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Chapter

Keeping the Dream Alive: Is Propellant-less Propulsion Possible?

James F. Woodward

Abstract

"Breakthrough" advanced propulsion can only take place with a correct understanding of the role of inertia in general relativity. Einstein was convinced that inertia and gravitation were the obverse and reverse of the coin. The most general statement of the principle of relativity, captured in his Equivalence Principle and the gravitational induction of inertia. His ideas and how they have fared are reprised. A rest mass fluctuation that is expected when inertia is gravitationally induced is then mentioned that can be used for propulsion. Recent work supported by National Innovative Advanced Concepts Phase 1 and 2 NASA grants to determine whether thrusters based on gravitationally induced inertia can actually be made to work is presented. A recent design innovation has dramatically increased the thrust produced by these Mach Effect Gravity Assist (MEGA) impulse engines.

Keywords: origin of inertia, general relativity, gravitational induction of inertia, Mach effect mass fluctuations, Mach effect gravity assist (MEGA) impulse engines

1. Introduction

The dream of getting to the stars is at least as old as it has been understood that the stars are Sun-like objects at vast distances. A dream because of the vast distances; 4 light years being the distance to the nearest star. No technology that is widely accepted is presently known that will get us to the stars in some preferably small fraction of a human lifetime. The mainstays of current space access are chemical rockets for heavy lift and electric propulsion for in-space propulsion. They both require the transport of propellant that is accelerated as it is ejected from the spacecraft to produce thrust. Much less than getting to the nearest stars, even getting to the outer Solar System quickly requires prohibitive amounts of propellant. This problem has led to a number of speculative solution suggestions within well understood physics – none of them convincingly practicable.

Some years ago, I pointed out that were Einstein correct in claiming that inertia is an inductive gravitational phenomenon, as he asserted in his general relativity theory, then one could predict that masses of bodies with changing internal energies subjected to proper accelerations should transiently change their rest masses by much larger amounts than the simple E/c^2 contribution due to the changing internal energy, owing to its "amplification" by the interaction with local gravitational field due to distant matter that Einstein identified, following Mach, as the cause of inertia. These rest mass fluctuations are "Mach effects". Laid out in a series of research papers over the years, and in 2012 this culminated in *Making Starships and Stargates: the Science of Interstellar Propulsion and Absurdly Benign Wormholes* [1]. Here I update the first five chapters of that work.

2. Inertia, gravity, propulsion and Mach effects

Before Einstein, it was assumed that significant gravitational effects are only produced by astrophysical scale objects. Planets. Stars. And larger mass concentrations. Gravity was not viewed as part of the solution of the propulsion problem. It was/is the propulsion problem. Aside from using the gravitational interaction with astrophysical objects as slingshot "gravity assist" encounters, this belief is still held essentially universally. Einstein's elaboration of the principle of relativity changed this. He called his theory of gravity "general relativity" (GR), not his theory of gravity. Why? Because GR is a theory of gravity *and* inertia, which are coupled by the *principle* of relativity expressed at the most elementary level by his Equivalence Principle (EP). The EP consists of the observation that you must look out the window of a rocket ship to determine whether you are accelerating (smoothly) at one gee in deep outer space, or at rest on a launch pad on Earth. Before the EP, the principle of relativity was restricted to inertial systems. First invented by Galileo, and then codified by Newton in his laws of motion, it says that if you are moving according to the first law, you must go to a window to determine whether you are moving with respect to other objects in different inertial frames of reference. Inertia in Newtonian mechanics is a (magical) property of material objects conferred on them by their existence in absolute space. And when such objects are given (proper) accelerations by the application of external forces, absolute space springs to life to produce the force that opposes the acceleration, acting through the object on the accelerating agent. This conception of inertia is still widely believed, notwithstanding Einstein's efforts to change it.

Einstein, with his theory of Special Relativity (SR), started the changes in the concept of inertia that are still with us today. The first was a paper in 1905 where he asked if the energy content of a body contributed to its inertial mass? [2]. The answer, of course, is the most famous equation in human history: $E = mc^2$. The vacuum speed of light, c, is the important factor in this equation. In SR, c, is a constant with the same numerical value for all observers everywhere/when, a speed that cannot be exceeded by any observer. The fact that c is a constant means that space and time are not physically distinct and independent as they are in Newtonian mechanics. The interdependence of space and time is captured in the Lorentz transformations that take one from one inertial frame of reference to another moving with respect to the first with some non-zero velocity. His next step, taken two years later, was the Equivalence Principle (EP). About the time that Einstein was discovering the EP, his former instructor, Hermann Minkowski, was reconstructing the absolute space and time of Newton into the modern conception of relativistic spacetime. Still absolute though, as inertia therein is still a magical property of space that confers inertial mass on its material contents and springs to life to provide the force that opposes proper accelerations of the massive contents. This conception of spacetime has long carried Minkowski's name. In a sense, it is the culmination of Newtonian physics – the last Newtonian word on space and time where gravity is treated as just another of the forces of nature akin to electricity and magnetism.

The conception of spacetime that Einstein was adumbrating in his speculation on the equivalence of inertia and gravity was motivated by Mach's observation that local inertial frames do not rotate with respect to the "fixed stars" [cosmologically distant matter]. Mach had suggested that distant matter acts through a long-range interaction with local matter. This was fundamentally different conceptually from Minkowski's spacetime. Einstein put down his speculations on inertia and gravity in an invited paper for an annual review of medicine in 1912: Is There a Gravitational Effect Which is Analogous to Electrodynamic Induction? [3]. In particular, he was interested in the interaction of a test mass located at the center of a spherical shell of matter when they were relatively accelerated – a situation considered by a number of relativists since the early 20th century, though recently in the context of "frame dragging". Inductive of effects of the sort Einstein was interested in are not present in scalar theories of gravity like Newton's; they only appear in vector and tensor theories like electrodynamics and GR. So, Einstein was reduced to fudging with his relationship between energy and mass to get the result he wanted. Namely, that the gravitational potential energy of the test particle contributes to its mass. And if the mass shell were sufficiently massive, producing a Newtonian potential inside the shell equal to the square of the vacuum speed of light, the entire mass of the test particle could be accounted for. Noting Mach in this connection, he opined, "The degree to which this conception is justified will become known when we will be fortunate enough to have come into possession of a serviceable dynamics of gravitation."

Einstein went on to consider the gravitational force produced by relative acceleration of his test particle and mass shell, finding that the gravitational potential energy of their interaction produces a force that tends to drag the test particle with the motion of the shell proportional to the gravitational potential energy divided by c^2. He did not note that were the potential roughly equal to c^2, the test particle would move rigidly with the accelerating shell. And were the particle held stationary by an external force, the accelerating shell would produce the inertial reaction force felt by the agent holding the test particle in place.

The serviceable dynamics of gravitation that Einstein sought turned out to be GR, the correct field equations being found by him in November of 1915. Prediction of the anomalous advance of Mercury's perihelion, together with Eddington's confirmation of Einstein's prediction of deflection of light passing close to the Sun in the 1919 solar eclipse catapulted Einstein and his theory to international popular acclaim. Shortly after the initial publication of GR, Einstein mooted his ideas about "Mach's principle", the assertion that inertia was due to the gravitational action of mostly matter at cosmological distances. This led to an exchange with Willem deSitter – who showed that Einstein's field equations were consistent with several solutions thereof that were obviously inconsistent with Mach's principle – that convinced Einstein to abandon the principle. It is now widely thought that this meant that Einstein had abandoned the idea that inertia was gravitational in origin. This is not correct. While he had abandoned the most extreme version of the principle, which requires an "action-at-a-distance" field theory, Tullio Levi-Civita had reminded him that inertia is an integral part of GR, and like gravity, satisfies the EP. Einstein retreated from full-blown Mach's principle to what he called "the relativity of inertia". Still a Machian conception of inertia.

Einstein advanced his ideas first in an address at Leiden in 1920 where he analogized his evolving view of spacetime to the "aether" of the turn of the century theory of electrodynamics. And then he extended his view in remarks in a series of lectures at Princeton in 1921 [4]. There he calculated the action of some nearby, "spectator" matter on a test particle of unit mass (at the origin of coordinates) in the weak field limit of GR. He found for the equations of motion of the test particle (his Eqs. 118):

$$\left(\frac{d}{dl}\right)\left[\left(l+\bar{\sigma}\right)\mathbf{v}\right]=\nabla\bar{\sigma}+\frac{\partial\mathbf{A}}{\partial l}+\nabla\times\left(\mathbf{A}\times\mathbf{v}\right), \tag{1}$$

$$\bar{\sigma} = (\kappa / 8\pi)\int(\sigma / \mathbf{r})\mathbf{dV}_{\text{o}}, \tag{2}$$

$$\mathbf{A} = (\kappa / 2\pi)\int(\sigma\mathbf{dx} / \mathbf{dl})\mathbf{r}^{-1}\,\mathbf{dV}_{\text{o}}. \tag{3}$$

The second and third of these equations are the expressions for the scalar ($\bar{\sigma}$) and vector ($\mathbf{A}$) potentials of the gravitational action of the spectator masses with density σ on the test particle. l is coordinate time and v is coordinate velocity of the test particle. The first equation is just Newton's second law. After writing down these equations, Einstein noted approvingly that,

> *The equations of motion, (118), show now, in fact, that*
>
> *The inert mass [of the test particle of unit mass] is proportional to 1 +* σ, *and therefore increases when ponderable masses approach the test body.*
>
> *There is an inductive action of accelerated masses, of the same sign, upon the test body. This is the term dA/dl.*
>
> *Although these effects are inaccessible to experiment, because* κ *[Newton's constant of universal gravitation] is so small, nevertheless they certainly exist according to the general theory of relativity. We must see in them strong support for Mach's ideas as to the relativity of all inertial interactions. If we think these ideas consistently through to the end we must expect the whole* $g_{\mu\nu}$*-field, to be determined by the matter of the universe, and not mainly by the boundary conditions at infinity.*

The way J.A. Wheeler would later, repeatedly put this was, "mass there *rules* inertia here". (He used this remark as the frontispiece for his book with his former student Ignacio Ciufolini, *Gravitation and Inertia* in 1995 [5]).

The above quote was not Einstein's last explicit word on gravity, inertia, and spacetime. In 1924, he again addressed these topics in a paper, "Concerning the Aether" [6]. In it he quickly asserted that by "aether" he did not mean the material aether of turn of the century electromagnetism. Rather, he meant a real, substantial, but not material entity that *is* spacetime, and that spacetime *is* the gravitational field of material sources. No material sources, no spacetime. This was his way of getting rid of the Minkowski and other metrics that de Sitter had shown to be anti-Machian. As he put it toward the end of his article:

> *The general theory of relativity rectified a mischief of classical dynamics. According to the latter, inertia and gravity appear as quite different, mutually independent phenomena, even though they both depend on the same quantity, mass. The theory of relativity resolved this problem by establishing the behavior of the electrically neutral point-mass by the law of the geodetic line, according to which inertial and gravitational effects are no longer considered as separate. In doing so, it attached characteristics to the aether [spacetime] which vary from point to point, determining the metric and the dynamical behavior [sic.] of material points, and determined, in their turn, by physical factors, namely the distribution of mass/energy.*
>
> *That the aether of general relativity differs from those of classical mechanics and special relativity in that it is not "absolute" but determined, in its locally variable characteristics, by ponderable matter. This determination is a complete one if the universe is finite and closed.*

Arguably, Einstein is the most profound physical thinker yet produced by our species. His physical intuition garnered him the *only* rank zero classification in Lev Landau's ranking of physicists where Galileo, Newton, Faraday and Maxwell were only first rank. One may reasonably ask, if Einstein was convinced that GR, correctly interpreted, encompassed the gravitational induction of inertia, why today is it widely believed in the community of relativists and beyond that inertia is **not** gravitationally induced? That inertia is no better understood than it was in the absolute systems of Newton and Minkowski? Carl Brans. And his "spectator matter" argument.

Brans did his doctoral work at Princeton in the late 1950s. His doctoral supervisor was the noted experimentalist, Robert Dicke. After passing his qualifying exam, Dicke tasked Brans with investigating the question of as the origin of inertia in GR as Dennis Sciama had made "Mach's principle" a central question in GR several years earlier. When Brans read Einstein's remarks on Machian inertia in Einstein's 1921 comments mentioned above, he noted a problem. As Brans later wrote in 1977 [7]:

> *Over the years, many and varied expressions of Mach's principle have been proposed, making it one of the most elusive concepts in physics. However, it seems clear that Einstein intended to show that locally measured inertial-mass values are gravitationally coupled to the mass distribution in the universe in his theory. For convenience I repeat the first order geodesic equations given by Einstein to support his argument:*
>
> *[Brans inserted here Einstein's equations displayed above.]*
>
> *... Einstein's claim is that "The inertial mass is proportional to* $(l+\bar{\sigma})$*, and therefore increases when ponderable masses approach the test body.*

Brans pointed out that having the masses of local objects, the test particle in this case, depend on their gravitational potential energies acquired by interaction with spectator matter must be wrong. Were it true, then the electric charge to mass ratios of elementary particles for example would depend on the presence of nearby matter. Were this true, gravity could be discriminated from accelerations without having to check for the presence of spectator matter by going to the window in a small lab and looking out – a violation of the Equivalence Principle. From this, Brans inferred that

> *... global, i.e., nontidal, gravitational fields are completely invisible in such local standard measurements of inertial mass, contrary to Einstein's claim... Einstein ought to have normalized his local space-time measurements to inertial frames, in which the metric has been transformed approximately to the standard Minkowski values, and for which distant-matter contributions are not present [Emphasis added.]*

This is the "coordinate condition" required by Brans' work: that the coordinates be compatible with the assumed approximate Minkowski metric applicable in small regions of spacetime. Since the absence of gravity is presupposed for Minkowski spacetime, this amounts to the assumption that the Newtonian potential due to exterior matter in such small regions of spacetime is effectively everywhere/when equal to zero. That is, the locally measured value of the total Newtonian gravitational potential is universally zero. This certainly makes the localization of gravitational potential energy impossible in GR, a now widely accepted fact. And where there is effectively no gravity, there can be no gravitational induction of inertia. Accordingly, it would seem that the spectator matter argument makes Machian gravitationally induced inertia incompatible with general relativity.

One might think that assuming the locally measured invariance of the Newtonian gravitational potential, since it allegedly requires that it effectively be zero, deprives the potential of its physical meaning, for if it is everywhere/when measured to be the same, how can it have the variations in spacetime – gradients and time derivatives – that characterize local gravitational phenomena? Physically speaking, the answer to this question is informed by the consideration of the vacuum behavior of light. In SR, the vacuum speed of light is constant. It is measured everywhere/when to have exactly the same value by *all* observers. As such, it never has non-vanishing derivatives of any sort. In GR, this changes. The vacuum speed of light remains a *locally* measured invariant. But the vacuum speed of light measured by observers who are not *local* does not have the locally measured invariant value. The vacuum speed of light in the vicinity of a black hole with its strong gravity field, as measured by a distant observer where the local gravity is weak, is slower than the distant observers measurement of the value at his/her location. This is *not* the consequence of some material-like medium being present in the vicinity of the black hole. It is the consequence of *time* running more slowly in strong local gravity fields when measured by distant observers far from strong local sources of gravity. This *fact* about the vacuum speed of light in GR used to be called the *coordinate* speed of light. Since it is not an invariant, global or local, its derivatives do *not* vanish.

Brans' argument led to the adoption of the coordinate condition mentioned above where gravity is effectively absent in sufficiently small regions of spacetime. But the argument actually does not require the adoption of this coordinate condition. If, however, the Newtonian gravitational potential is to have any value other than effectively zero, then it must be a locally measured invariant so that charge to mass ratios of elementary particles do not depend on local gravitational conditions to avoid violations of the EP as Brans showed. But to accommodate real local gravitational phenomena, we must assume that, like the vacuum speed of light, the Newtonian potential has varying *coordinate* values that are not invariant.

Since the gravitational induction of inertia depends on the presence and motions of "matter" (everything that gravitates) chiefly at cosmological distances, the obvious question is: is the needed stuff out there doing what it must do to produce inertial effects? Einstein was clever enough to know that the knowledge of cosmology in the 1920s and beyond was insufficient to make such a determination backed up with observational evidence. Friedmann and Lemaitre made initial explorations of cosmology in the '20s, discovering that sensible solutions of Einstein's equations dictated expanding universes for simple models with homogeneity and isotropy of sources of the field. Their work was elaborated by Robertson and Walker shortly thereafter, leading to so-called FLRW cosmology. Modern cosmology is far better informed by observations and concomitantly more detailed and complicated – though no one has a clue as to what "dark energy" is, it certainly exists. For our purposes, however, the features of cosmology needed to address the gravitational induction of inertia are already present in FLRW cosmology, for recent observations do not call into question the assumptions of homogeneity and isotropy. And a simple argument made by Dennis Sciama in 1953 [8] makes possible knowledge of the motions of cosmological sources important to inertia induction.

Sciama developed his early ideas on the origin of inertia in terms of a vector theory of gravity modeled on Maxwell's equations for electrodynamics. Like Einstein in 1921, he obtained a term in his gravelectric force equation that involves the time derivative of the vector potential of the gravitational field. The vector potential, **A**, depends on the integration over the matter currents in the observable universe, that is, ρv, where ρ is the matter density in an integration volume element and v its velocity relative to the point where **A** is evaluated. Sciama noted that all of the various motions that stuff out there in the universe engage in, on average over sufficiently large distances go to zero. So, to calculate **A**, all we need do is imagine that, say, a test particle is moving with velocity v with respect to some cosmic rest frame. The principle of relativity allows us to view the test particle as at rest with the universe moving rigidly past it with velocity $-v$. All of the "peculiar" motions of the stuff out there is irrelevant as they average to zero. This means that the velocity can be removed from the integration over the matter currents, leaving an integration over the matter density. That integration returns the total Newtonian gravitational potential, customarily written as ϕ. As Einstein observed in 1912, up to a factor of order unity, if this potential is equal to the square of the vacuum speed of light, then the entire inertia of the test particle can be attributed to its gravitational interaction with the rest of the universe. And inertial reaction forces are gravitational forces – arising from the $d\mathbf{A}/dt$ term in Einstein's equation of motion above since $d\mathbf{A}/dt = (\phi/c^2)\, d\mathbf{v}/dt = a$ provided that $\phi/c^2 = 1$ always and everywhere.

Is ϕ actually equal to c^2? At least up to a factor of order unity, the answer to this question is yes. For example, Sultana and Kasanas did a calculation assuming all of the features of modern general relativistic cosmology several years ago and got the "right" answer [9]. But there is an even more compelling reason to accept that Mach and Einstein were right about gravitationally induced inertia. *As a matter of observation*, spacetime is spatially flat. In terms of the FLRW cosmological models with their homogeneity and isotropy, cosmic scale spatial flatness is just a curiosity attached to arguably the simplest FLRW model characterized by the exact balance of gravitational potential energy and "kinetic" energy, that is, non-gravitational energy characterized by $E = mc^2$ where m is the inertial mass of the matter in the cosmology. The general FLRW metric can be written introducing a "curvature index" k with values plus or minus 1 and zero. Plus 1 gives the metric for positive curvature spacetime where kinetic energy exceeds potential energy and is "closed". Minus 1 gives the metric where the roles of the energies are reversed and is "open". Closed universes expand and contract whereas open ones expand forever. For k = 0 the energies are exactly the same and spacetime is spatially flat. It expands forever, but with decelerating speed, just stopping at cosmic temporal infinity. In this spacetime we have for material particles:

$$m_g \phi = m_i c^2 \tag{4}$$

where the subscripts g and i identify gravitational and inertial masses of the material particle. This is true everywhere/when in the cosmos. Another peculiar property of the k = 0 solution is that the condition of spatial flatness does not change as cosmic expansion takes place. So, if we apply the EP to cancel the masses in Eq. (4), we find that $\phi = c^2$ obtains universally. The remarkable properties of the spatially flat, k = 0 FLRW cosmology were first formally identified as a problem by Dicke in lectures in 1969, and then in an article written with James Peebles in 1979. He called this the "flatness paradox" because spacetime in even casual observations is obviously spatially flat, but the k = 0 cosmology is "unstable". Small fluctuations in the matter density should drive spacetime quickly into either k = plus or minus 1 behavior – which is not the steady decelerating expansion asymptotically to infinite extent of the k = 0 solution. Why, Dicke asked, is our aged cosmos spatially flat? Alan Guth was in the audience of the 1969 lectures and eventually proposed "inflation" to solve the flatness and other problems.

By 1979 intense discussion of Mach's principle and the gravitational induction of inertia had almost entirely abated. Hoyle and Narlikar had published an action at a distance version of GR. It did not attract much interest. John Wheeler continued to say "mass there *rules* inertia here". His later book *Gravitation and Inertia* with I. Ciufolini [5] makes plain that he was an advocate of a limited version of Einstein's "relativity of inertia", that is, the gravitational induction of the inertial properties of spacetime, but not the gravitational induction of the inertial properties of matter per se. But Brans' spectator matter argument had banished Einstein's version of the gravitational induction of inertia. Was Einstein simply wrong about the gravitational induction of inertia? No. The k = 0 FLRW cosmology does more that allow one to assert that $\phi = c^2$ when the inertial and gravitational masses are canceled in our test particle equation above as they are the same according to the EP. And the fact that this cosmology evolves preserving this condition – notwithstanding Dicke's paradox – means that FLRW k = 0 cosmology automatically makes ϕ a locally measured invariant like c ensuring that the coefficient of the acceleration in the $d\mathbf{A}/dt$ term in the equation of motion is always 1. This is not true in k ≠ 0 cosmologies where the potential and kinetic energies are not equal. So, the answer to Dicke's flatness paradox is not inflation. Inflation may explain *how* flatness comes about. But it is that k = 0 cosmology obtains *because it is required by Newton's third law, the equality and opposition of applied and inertial reaction forces that singles out k = 0 as the correct cosmology.* In other cosmologies ϕ is not equal to c^2 and action does not equal reaction. This makes Brans' spectator matter argument – which locks in the necessity of ϕ being a locally measured invariant equal to c^2 – one of the most consequential developments in general relativity of the past century.

Why bother about what the correct origin of inertia is? After all, if ϕ is a locally measured invariant it is everywhere the same and it seems that it can have no effects beyond pushing back when we try to accelerate massive objects. We live in an enormous gravitational field that we can only detect when we try to change our states of inertial motion. That is, when proper accelerations of material objects are involved. So, to couple to the gigantic gravitational field in which we live, we must accelerate stuff. The question then is, does accelerating stuff do anything other than excite an inertial reaction force? To answer that question we need the gravitational field equation for the inertial force. Since we are looking for relatively large, lowest order effects, we do not need the full formalism of GR. The Newtonian approximation is good enough. But it must be modified to Lorentz invariant form to be realistic. As it happens, George Luchak wrote out the relativistic Newtonian approximation field equations in 1951 when doing an investigation of Patrick Blackett's conjecture on the origin of stellar magnetic fields being the mass currents arising from stellar rotation [10]. The field equation he found was:

$$\nabla \bullet \mathbf{F} + \frac{1}{c}\frac{\partial q}{\partial t} = -\ 4\pi\rho \tag{5}$$

With

$$\nabla q + \frac{1}{c}\frac{\partial \mathbf{F}}{\partial t} = 0 \tag{6}$$

and

$$\nabla \times \mathbf{F} = 0. \tag{7}$$

q is the rate at which the field does work on its local source density. Since the field is irrotational [$\nabla \times \mathbf{F} = 0$], **F** can be written as the gradient of a scalar potential ϕ. q is $\partial E_o/\partial t$ where E_o is the proper source energy density, so the second term in Eq. (5) is just the second time derivative of the proper energy density. The time-dependent term in this equation is where rest mass fluctuations are to be sought. The proper energy density E_o is just the proper matter density ρ_o times c^2. But the gravitational induction of inertia lets us write c^2 as ϕ, so $E_o = \rho_o\phi$. Using this relationship and several pages of algebra (see chapter 3 of [1]) yields:

$$\nabla^2\phi - \frac{1}{c^2}\frac{\partial^2\phi}{\partial t^2} = 4\pi G\rho_o + \frac{\phi}{\rho_o c^4} + \frac{\partial^2 E_o}{\partial t^2} - \left(\frac{\phi}{\rho_o c^4}\right)^2\left(\frac{\partial E_o}{\partial t}\right)^2 - \frac{1}{c^4}\left(\frac{\partial\phi}{\partial t}\right)^2 \tag{8}$$

The left-hand side of this equation is the d'Alembertian of the potential ϕ, a wave equation for ϕ with sources on the right-hand side. Since the time-dependent terms on the right-hand side of Eq. (8) originate on the field side of the equation, they do not carry the coefficient $4\pi G$. To be treated as massive sources (and multiplied by $4\pi G$ like ρ_o in the first term on the right-hand side of Eq. (8)) they must be multiplied by the factor ($1/4\pi G$). The time-dependent source terms thus become:

$$\delta m_o = \frac{1}{4\pi G}\left[\frac{\phi}{\rho_o c^4}\frac{\partial^2 E_o}{\partial t^2} - \left(\frac{\phi}{\rho_o c^4}\right)^2\left(\frac{\partial E_o}{\partial t}\right)^2 - \frac{1}{c^4}\left(\frac{\partial\phi}{\partial t}\right)^2\right] \tag{9}$$

The first of the terms on the right-hand side of this equation is the largest in most circumstances – and the term on which MEGA impulse engines depend. The second term can be triggered by the first term in special circumstances, but is almost always negligible (see chapter 9 of [1]). The third term is inconsequential.

3. MEGA impulse engines

To excite these rest-mass fluctuations all we need do is make the internal energy density of a massive object change while it is undergoing a proper acceleration. An energy density fluctuation of the sort required is easily produced by charging/discharging a capacitor. The required proper acceleration of the capacitor can be produced with an electro-mechanical actuator – in particular, a device comprised of lead-zirconium-titanate, PZT, elements that expand/contract when a voltage is applied to them. The actuator must be affixed to a "reaction" mass in order for its motions to communicate accelerations to the capacitor undergoing internal energy changes to produce the MEGA mass fluctuations wanted. Since PZT actuator components are also capacitors, the actuators can play the role of both actuator and capacitor simultaneously. One then only needs a stack of PZT disks affixed to a reaction mass to generate mass fluctuations. To make this device into a MEGA impulse engine all we need do is provide for a second mechanical acceleration at the frequency of the mass fluctuations that acts so that this acceleration of the PZT stack is in one direction when the stack is less massive and the opposite direction when it is more massive. This, in effect, makes the PZT stack the propellant of the engine, and the mass fluctuation that arises from the coupling to the cosmic gravitational potential allows one to indefinitely recycle the propellant, Not exactly propellantless propulsion. But you do not have to keep throwing new PZT stacks overboard to produce propulsion. A device of this sort is displayed in **Figure 1**.

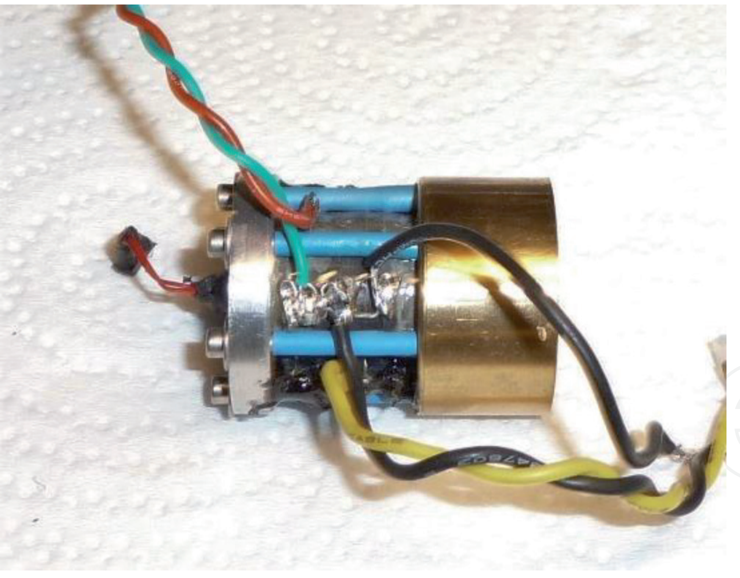

Figure 1.
A stack of 8 PZT crystals 19 mm in diameter by 2 mm thick is clamped between a brass reaction mass and an aluminum cap with 6 4–40 cap screws. A thermistor is embedded in the cap to monitor the temperature of the device and two thin crystals are embedded in the stack near the cap.

The first laboratory test devices of these engines were made in 1999. To make mounting of the devices on a torsion balance possible, a bracket was attached to the back of the reaction mass, as shown in **Figure 2**. A simple L shaped piece of aluminum, initially this bracket was bolted directly onto the reaction mass. The devices hardly worked at all. When a thin rubber pad was placed between the bracket and reaction mass (the black tabs seen in **Figure 2**) the devices sprang to life. It did not take long to figure out that the pad was not damping the vibration of the device. Rather, it was decoupling the device from the mounting bracket at the high (tens of KHz) frequencies of operation, allowing it to vibrate more vigorously as the vibrational energy was not being as strongly sinked into the mounting bracket and beyond. An important change was made in the devices made from 2011 on from the first devices made in 1999. Instead of using Edo Corp material EC-65, Steiner-Martins material SM-111 was substituted. The motivation for this change was the dissipation factor for the SM-111 material is about an order of magnitude smaller than that for EC-65, leading to a much-reduced heating rate in the SM-111 material. An unintended consequence of this material change was that instead of driving the devices with a voltage waveform with both first and second harmonics to get the

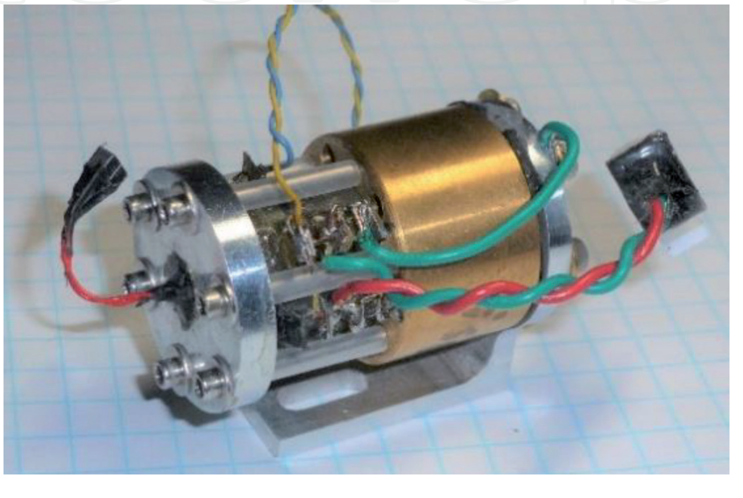

Figure 2.
*A device of the type shown in **Figure 1** with an aluminum "L" braket attached for suspension on a torsion balance. Note the black rubber tabs peeking out at the interface of the bracket and the reaction mass.*

desired mechanical response, the new devices can be driven with a single frequency sine wave (with a special step-up/isolation transformer) and the SM-111 material generates the higher harmonics needed to produce thrust when operated near an electro-mechanical resonance of the device.

A quantitative discussion of thrusts generated in these devices when excited with a suitable sine wave voltage is given in [1], pages 174 to 178. In general terms, δm_o is:

$$\delta m_o \approx \frac{1}{4\pi G}\left[\frac{\phi}{\rho_o c^4}\frac{\partial^2 E_o}{\partial t^2}\right] = \frac{\phi}{4\pi G \rho_o c^4}\frac{\partial P}{\partial t} \tag{10}$$

where P us the instantaneous power, that is, in an ideal capacitor, the product of the instantaneous voltage and current across the capacitor. This is the product of two sinusoids of the same frequency and returns a sinusoid of the double frequency, that is, at the second harmonic frequency. If the capacitor is ideal, there is no energy dissipated as the voltage signal is applied and δm_o has no DC offset – and δm_o time-averages to zero. To extract a steady thrust from this mass fluctuation we must provide for a force and mechanical excursion of the capacitor at the second harmonic frequency of the excitation voltage frequency. The second harmonic excursion produces an acceleration with the same frequency, and this acceleration multiplied times δm_o gives the force produced in the capacitor. This is a product of two sinusoids of the same frequency resulting in an AC component with a frequency of 4 times the base frequency plus a DC component that depends on the relative phase of δm_o and the second harmonic acceleration. The DC part of this product is the Mach effect force that can be used for propulsion.

Devices of the sort shown in **Figure 2** were used in work on the Mach effect project until Hal Fearn wrote successful applications first for a Phase 1 (2017) and then Phase 2 (2018) NASA Innovative Advanced Concepts (NIAC) grants from NIAC to support this work. (See [11] for the final report of the Phase 2 grant.) During the Phase 1 and early part of the Phase 2 grants, work focused on a voltage scaling test and issues of vibration and calibration. Typical thrust signals were in the tenths of a micronewton to a micronewton or so, detected with a sensitive torsion balance built with the help of Thomas Mahood a decade earlier shown in **Figure 3**. The device being tested is located in a Faraday cage mounted on a

Figure 3.
The torsion balance used in this work for small thrusts on its 500 pound granite vibration isolation table. The vacuum chamber is clear plastic, making careful examination of the operating conditions with a Polytech laser vibrometer easy.

special vibration isolation yoke attached to the near end of the balance beam. One of the aims of the funded work on these grants was to increase the magnitude of the thrusts produced by the tested devices. Other issues just mentioned diverted attention from the increased thrust goal until late 2019 and early 2020. When attention was focused on thrust improvement, the decision was taken to make incremental improvements to the existing devices, rather than go to a radically different design. The obvious design feature to address was the rubber pads that had made the devices work at all. A plan of varying several other design features that might be optimized was also initiated. Shortly after this plan was initiated, COVID-19 struck. Weekly Zoom meetings of the team continued, but at CSUF lab access was restricted to HF, and JFW was restricted to building apparatus to be tested by HF in the lab.

If one understands the role of the rubber pads to be the high frequency decoupling of the device from its support structure, rather than damping the high frequency vibrations, several modifications are straight forward. First, instead of just using a pad between the reaction mass and L bracket, since the pad acts as a spring, pads should be put on both sides of the L bracket. Second, materials other than rubber are surely better candidates. For example, nylon, phenolic, PEEK and Vespel. And these materials can be fabricated with carbon fibers to increase their strength and improve their thermal conductivity. Third, the thickness of the material can be adjusted. An example of one of the devices used in this test campaign is shown in **Figure 4**. The washers on the mounting screws are PEEK in this case. There were, of course, variations in the performance of the various materials and configurations. But all the dielectric washer systems suffered from heating problems that were not resolved even with carbon fiber filling. The thermal problem led to the exploration of metal washers, Belleville washers in particular. Commercial Belleville washers with dimensions similar to the washers in **Figure 4** and the correct stiffness were not available. Washers available in this size had to be glued together to get the correct properties. They solved the thermal problems with the dielectric washers.

In late spring, Paul March and Michelle Broyles began investigating alternate ways of using Belleville washers. They envisioned clamping the reaction mass with a flange at the interface with the PZT stack with big, clunky Belleville washers. This was not the way to go. The flange would not be exactly at a node of all of the vibrations in the device, and clamping it with heavy Belleville washers would doubtless

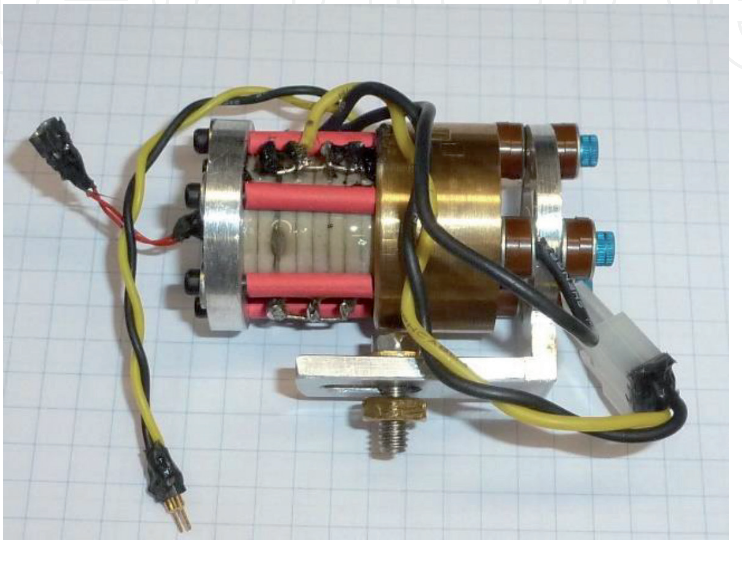

Figure 4.
A standard device with double thickness PEEK washes on the mounting screws.

at least screw up the pattern of higher harmonic vibrations on which thrust production depends. But a small flange at least near a node of the principal vibration as a mounting point was an appealing idea as the L bracket mounting design was clearly less than optimal. But instead of clamping with clunky Belleville washers, three equally spaced holes were drilled in the flange and lined with Teflon. A support structure with three steel dowels to pass through the holes in the flange was built. When tested, it worked.

This mounting system had a precursor. Several months earlier the L bracket had been replaced by a "sledge" as the part of the L that attached to the Faraday cage. A sledge that was free to move on a small mounting plate bolted to the cage provided with steel dowels on which the sledge rode. That too had worked. But its importance had not been fully appreciated at the time. The flange and dowel mounting scheme made the device itself into a sledge. A number of technical details had to be addressed. The chief detail, however, was that Teflon sleeved holes in the flange were far from frictionless; and frictionless-ness was clearly the ideal if unfettered motion of the device was the goal. With an essentially frictionless mounting system we could approach the ideal of an in space propulsion test. Josė Rodal remarked that what we needed were miniature linear ball bushings instead of Teflon sleeves. But they were likely prohibitively expensive. All of the team members on the call had experience with linear ball bushings and immediately apprehended the significance of Josė's observation. Paul and Chip Akins were on it instantly. Before Josė concluded his remarks about linear ball bushings, they had independently tracked down a source of suitable bushings. They were not prohibitively expensive. The next most important detail was how to extract a very low frequency to stationary force from a device vibrating on dowels with frictionless bearings? Chip and Michelle had the answer: very soft springs that would not transmit the high frequency vibrations to the support frame and would not mess up higher harmonics in the device by applying undue pressure on the "ears" of the flange carrying the bushings. Michelle and Paul eventually tracked down suitable springs.

Tests were done to find the best detailed design for the reaction mass and parts of the supporting frame. The reaction mass design eventually adopted has a flange 3.5 mm thick so that the 5 mm long bushings protrude to center the springs on the dowels that position the device on the dowels. The reaction mass diameter and length were chosen to be 22 mm, making the center of mass of the device lie in the plane of the flange. The PZT stack and aluminum preload cap are those of the L bracket design. A bare assembled device is shown in **Figure 5**. The complete assembly has a mass of 150 gm. It is shown mounted in its supporting aluminum frame in **Figure 6**. The thermistor, strain gauge and power leads are all stress relieved by attachment to the frame. Two of the six springs that position the device on the 2 mm diameter dowels are visible at the top of the picture.

In principle, if the linear ball bushings are functioning correctly, no pseudo force arising from a slip–stick mechanism in the device per se can be transmitted to the support structure owing to the conservation of momentum and the frictionless-ness of the bearings. So, one does not really need the torsion balance with its vibration isolation yoke that ensures slip–stick effects are not transmitted to the bearings of the balance where they might register a false positive "force". Since our vacuum chamber is made of clear plastic, investigating vibration in the parts of the balance with a Polytech laser vibrometer is straight-forward. So, to be doubly certain that real forces are generated in these devices, at first Hal Fearn adapted mounting hardware to place the new style devices on the torsion balance, notwithstanding that the balance acts as a low pass filter for forces with any time dependence. This is shown in **Figure 7**. In addition to recording the voltage and current applied to the device,

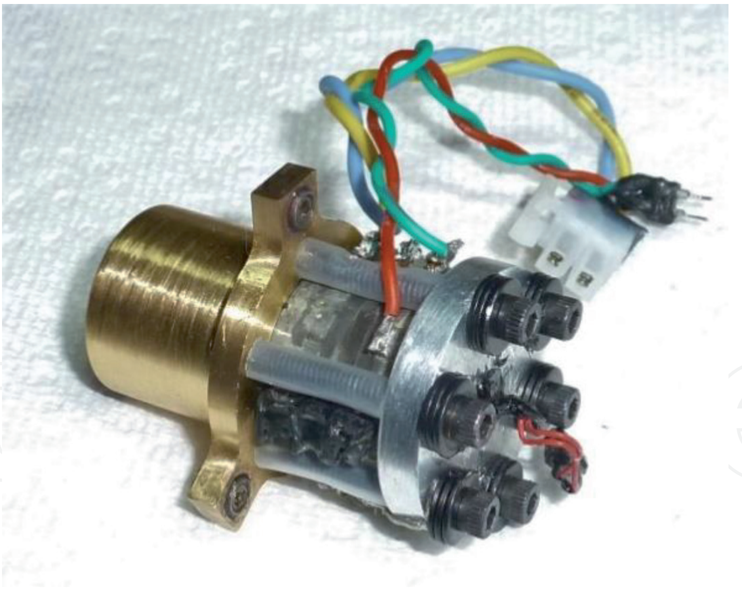

Figure 5.
A bare device of the sledge design. The cap is 4.5 mm thick and 28.6 mm in diameter. High strength steel 4–40 cap screws provide the stack preload. Electrical conections are positioned to minimize drag on the motion of the parts.

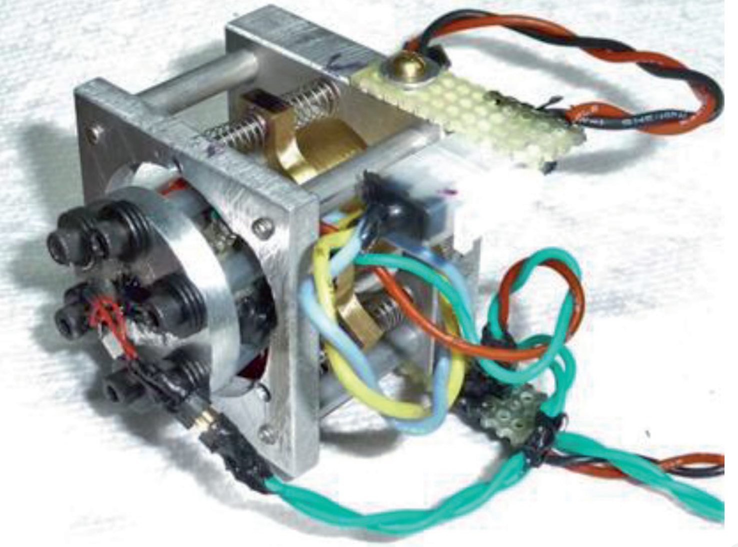

Figure 6.
The device in its supporting frame.

the mechanical activity with the embedded strain gauge, and the temperature with the thermistor in the cap, movies of the device were recorded with a Logitech Brio webcam as the forces produced visible motion of the device on the dowels.

After a few weeks, the Philtech position sensor used with the torsion balance to record its position (and thus force producing any deflection from rest) was removed from the vacuum chamber and repurposed to measuring the position of the sledge mount device on the rods supporting it as shown in **Figure 8**.

The four data signals – voltage, current, strain gauge, and temperature – were captured (along with the movie of the device) by three Picoscope oscilloscopes and displayed on a monitor. One Picoscope was dedicated to the production of a strip chart recoding of the voltage (blue trace) and position (red trace with scale factor 250 microns per volt) and temperature (green trace calculated to a degrees Celsiu8s scale) displayed in the upper left part of the monitor screen. The Picoscope data file of this

Figure 7.
A sledge mounted device on hardware on the torsion balance in the clear plastic vacuum chamber.

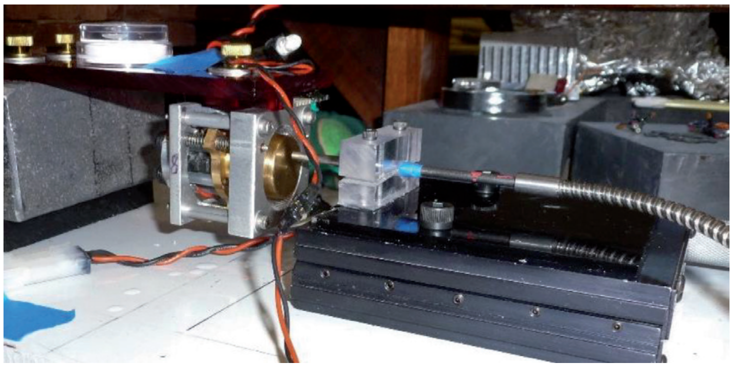

Figure 8.
The device mounted on a cantilever (with bubble level to adjust the levelof the cantilever). The Philtech optical probe is clamped to a micrometer stage for positioning and calibration. It records the distace from the probe to the free end of the reaction mass a millimeter or so away.

display was saved for each run on completion of the run. The second Picoscope was dedicated to the real time capture of the voltage (blue, 100 volts per volt), current (black, one amp per volt), and strain gauge (red, not absolutely calibrated) waveforms during a run. The total power (i X V, green, 20 watts full scale) was computed and displayed in real time. This display is in the lower right of the monitor screen. The third Picoscope, a very fast 2 channel device, was dedicated to the real time display of the FFT power spectra of the voltage (blue) and strain gauge (red) signals located in the lower left part of the monitor screen. The webcam movie was displayed in the upper right of the screen. A picture of the monitor display for a completed run is shown in **Figure 9**. Since our power amplifier was not equipped to track and lock on to signal behavior at or very near resonance, and the thrust resonances for these devices are temperature dependent and – by design – very high Q, frequency sweeps were used to detect the thrust events expected. A typical run would consist of a 20 KHz sweep in 20 seconds (so the frequencies of events could be read off from the time of their occurrence) followed by a 5 second sweep back to the start frequency followed by another 20 second sweep. **Figure 10** shows the monitor screen at the peak amplitudes of the waveforms at resonance transit for the run displayed in **Figure 9**. Note the presence of higher harmonics in the waveforms and power spectra, especially the second harmonic component in the current waveform. If the second harmonic is absent or out of phase, there is no thrust. Just before and after the resonance event,

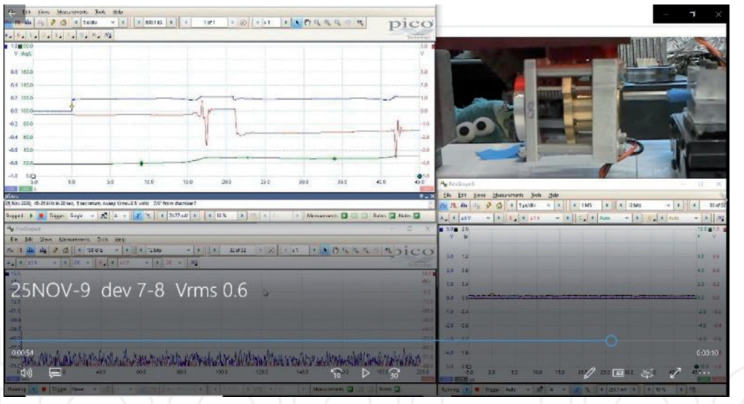

Figure 9.
The monitor display for a completed run. From the position data the velocity and acceleration of the device on the dowels can be computed.

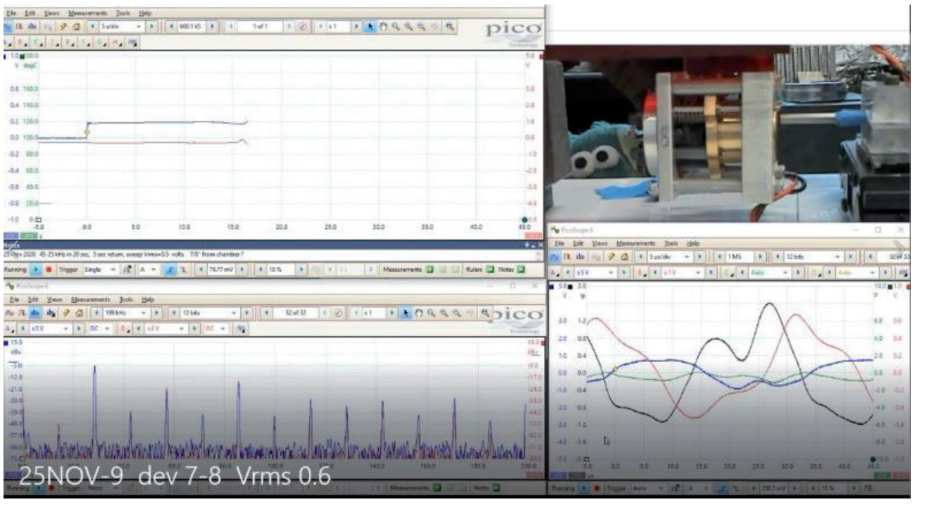

Figure 10.
The monitor screen at transit of the first thrust resonance in the run displayed in ***Figure 9.*** *Note the higher harmonics in the waveforms and power spectra, especially the second harmonic in the current waveform.*

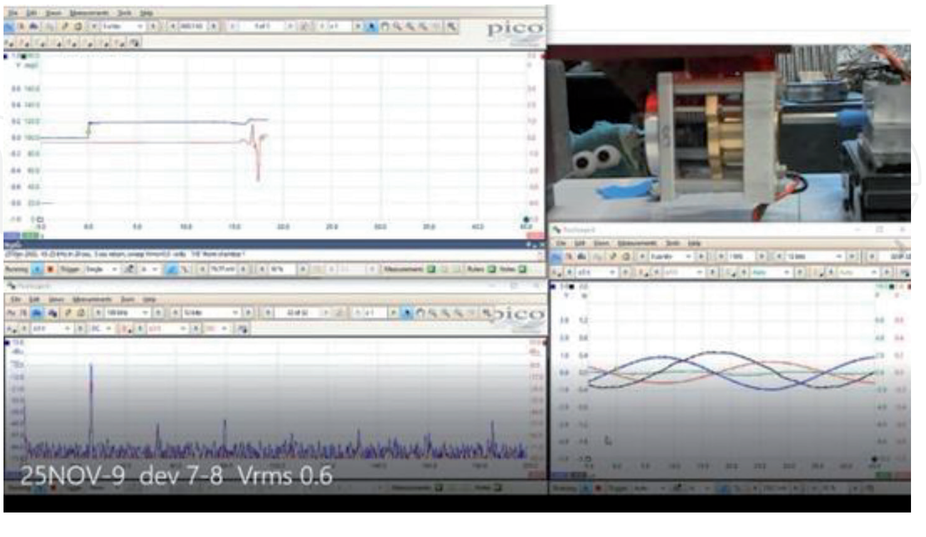

Figure 11.
The monitor screen immediately after the thrust resonance.

the signals look like those in **Figure 11**. The second and higher harmonics are gone. But the strain gauge waveform shows that strong first harmonic vibration is still present. That vibration ensures that the device moves frictionlessly on the support dowels. The thrust impulse is sufficiently large to initiate the displacement recorded in the strip chart display (red trace) in **Figure 9**. The positioning springs on the dowels convey the thrust to the support frame while arresting the motion of the device and returning it to its rest position. Evidently, these devices work as expected.

4. Conclusion

Many people over the now many years this project has been underway have contributed to its progress in a variety of ways. In my grad student days, those most helpful were Malvin Ruderman, Wolfgang Yourgrau, Allen Breck, Alwyn van der Merwe, James Barcus and Laurence Horwitz. At CSU Fullerton I have enjoyed the tolerance and support of the History and Physics Departments' faculties, especially Ronald Crowley, Dorothy Woolum, Allan Sweedler, Keith Wanser, Mark Shapiro, and Stephen Goode in the Mathematics Department. A number of the formal publications related to this topic (see the technical references in ref. [1] here) were published in *Foundations of Physics*, in part because lists of a half-dozen suggested referees were solicited. I invariably recommended people familiar with both gravity and Wheeler-Feynman action at a distance theory, world class physicists all. And accompanied the lists with the suggestion that the manuscripts be sent to all of my suggested referees. Their comments proved helpful. John Cramer's mention of this work in his *Analog* Alternate View column in the mid-'90s brought this project to the attention of a wider audience. Thomas Mahood through his Master's program and beyond helped in many ways to advance the project. About this time Jim Peoples, Graham O'Neill, Paul March and Sonny White, all then at Lockheed-Martin took interest in the project. As did Frank Meade and Kirk Goodall, and Gary Hudson of the Space Studies Institute (which still supports this work). Others include Nembo Buldrini, Greg Meholic, Marc Millis, Martin Tajmar, Tony Robertson, Paul Murad, John Cole, George Hathaway, and Dennis Bushnell. Peter Milonni and Olivier Costa dé Beauregard made helpful suggestions. Jack Sarfatti, Paul Zielinsky and Nick Herbert contributed by sharpening the arguments related to Einstein's views on the gravitational induction of inertia, as has Lance Williams. Anthony Longman was in no small way responsible for bringing the project to the positive attention of the management of NIAC, Jay Falker, Jason Derleth and Ron Turner. David Mathes, and then Gary Hudson wrote the first and then second unsuccessful NIAC grant proposals. A few years later Heidi (now Hal) Fearn wrote the successful Phase 1 and 2 proposals. Since joining the project in 2012, Hal has been chiefly responsible for advancing the project in many ways. New and improved instrumentation. Data acquisition and analysis. Writing of reports and papers. Giving presentations of on-going work. Organizing workshops and seeing to the publication of their proceedings. Other than Hal, the members of the NIAC grant teams included Marshall Eubanks and José Rodal for Phase 1. In Phase 2 they were joined by Chip Akins, John Brandenburg, Michelle Broyles, Max Comess, David Jenkins, Dan Kennefick, Paul March, and Jon Woodland. The NIAC grants made several advances – notably, thrust increase of two to three orders of magnitude – that otherwise would not have happened possible. To make sure the thrust increase is real, the SSI has engaged George Hathaway to do a replication now in progress. And NIAC has engaged Mike McDonald at NRL to do a replication next year. So, soon we will know if this propulsion scheme really works. Several physicians, Ann Mohrbacher, Ching Fei Chang, Jerold Shinbane, and others at the University of Southern California, have kept me alive these past 15 years.

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