THE TECHNICAL END OF MACH'S PRINCIPLE

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ABSTRACT:

The theoretical motivation for the prediction of mass fluctuations in accelerated objects based on Mach's principle is reviewed. It is pointed out that one of the two predicted fluctuations, normally hopelessly below the level of detectability, can be made quite large in "just so" circumstances. Since this fluctuation is always negative, when driven as a periodic fluctuation, its time-average is non-zero and negative. As such, this effect holds out the possibility of inertia manipulation at a scale with practical consequences. Results of recent experiments with lead-zirconium-titanate (PZT) devices where evidence for the predicted mass fluctuation was sought as a weight shift are reported, together with a description of the check protocols used to eliminate spurious sources of the signals seen. Those results, if not conclusive, are at least promising.

KEY WORDS: Mach's principle, mass fluctuations, wormhole

INTRODUCTION:

Although many issues of scientific interest surrounding Mach's principle are yet to be resolved, I argue here that core features of the principle are sufficiently well understood to justify their exploration with an eye to possible technological applications. What might those technical applications be? Well, should inertia turn out to be manipulable by some means, one might be able to do things presently regarded as the stuff of science fiction and science fantasy. In particular, one might be able to facilitate rapid spacetime transport in several ways, the most extreme involving the induction of large amounts of "exotic" matter. Although not yet advanced to the stage of straightforward technical implementation, I relate results of some experiments now in progress, following strict scientific protocols, that suggest such manipulation may one day prove feasible. It goes without saying, of course, that all this depends on the ultimate outcome of those experiments. And they may eventually reveal this to be nothing more than wishful thinking – a foolish pipedream.

What is it that we know about Mach's principle and the origin of inertia that makes experiments with a technological orientation possible? Well, perhaps the most important and fundamental thing we know is that in a universe like ours – with essentially isotropic matter distribution (at cosmological scale anyway) characterized by a Friedman, Robertson, Walker (FRW) cosmological model – inertial reaction forces are a consequence of the *gravitational* action of chiefly distant matter on local objects when they are accelerated. There are those who will try to tell you that inertial reaction forces are not so caused, that they are caused by the action, say, of the electromagnetic quantum vacuum zero point field (EZPF). Aside from the fact that the EZPF conjecture on the origin of inertial reaction forces is deeply flawed, the fact of the matter is that it has been known since the work of Derek Raine in the mid-1970s that inertial reaction forces in FRW cosmologies are caused by gravity (Raine, 1975). Equally important, owing to the work of Dennis Sciama, dating back to the early 1950s, we know that inertial reaction forces are the result of a *radiative* interaction, as one would expect from the analogous case in electrodynamics where *accelerations* of electric charges produce propagating electromagnetic waves that carry the chief interaction with distant electric charges (Sciama, 1953; see also J.-F. Pascual-Sanchez, 2000).

The radiative nature of the gravitational forces that yield everyday inertial reaction forces poses something of a problem: Inertial reaction forces are instantaneous. When you push on something, it pushes back immediately. How can that be if the interaction that produces the reaction force is communicated to the thing you push from chiefly the most distant matter in the universe at the speed of light in vacuum? Some have tried to deal with this by claiming that inertial reaction forces can be attributed to "constraint" equations on "initial data" that, being elliptic rather than hyperbolic, act instantaneously across arbitrarily large distances. The only plausible alternative to this scheme is to regard inertial reaction forces as forces of radiative reaction. As is well-known in the case of electrodynamics, since the work of Wheeler and Feynman in the 1940s on "action-at-a-distance" electrodynamics, radiation reaction forces can be accounted for by invoking advanced as well as retarded propagating wave solutions of the field equations where an accelerated local charge interacts with a large, isotropic, distant absorber (Wheeler and Feynman, 1945). This, of course, is precisely the sort of behavior that one should expect for the gravitational interaction that produces inertial reaction forces if Mach's principle is correct. (Appreciation of the importance of Wheeler-Feynman style action-at-a-distance electrodynamics in physical phenomena, including gravitation, is not new. It was noted long ago by Hoyle and Narlikar, 1974.)

Now, one may think: There is a problem with the radiation reaction picture of inertial reaction forces if they are gravitational in origin. The gravitational radiation given off by any accelerated local object of reasonable mass is incredibly minute. Newton's third law then suggests that the reaction force produced by launching this radiation should be correspondingly minute. Inertial reaction forces are, by comparison, however, gigantic – many, many orders of magnitude larger. Since inertial reaction forces are gravitational forces in general relativity theory, Sciama's analysis reveals them to be radiative, and their instantaneity requires that they be seemingly minuscule radiation reaction forces, we seem to be faced with an insuperable paradox. The problem here, I think, lies not in the consistency of the mathematical formalism. Rather, it is a problem of visualization.

If we take the customary view of the distant matter in the universe as being at rest (ignoring cosmological expansion) and local objects as accelerated with respect to the distant matter, then it is easy to believe that inertial reaction forces cannot be gravitational radiation reaction forces because the gravitational disturbance launched by any acceleration is so small. If, instead, we adopt the view made explicit in Sciama's 1953 paper on Mach's principle and the origin of inertia, where the accelerated local object is regarded as (instantaneously) at rest and the external force on it causes the distant matter in the universe, as viewed from the local object, to appear to accelerate rigidly, then it is quite reasonable to assume that the gravitational action of all of that distant stuff accelerating will produce a force on our local object of the order of magnitude of typical inertial reaction forces. In any event, I am going to assume that inertial reaction forces are forces of gravitational radiation reaction communicated by a gravitational field interaction that displays the action-at-a-distance character of Wheeler-Feynman absorber theory. Why? Because in absorber theory there are phase lags and small time delays that, at least in principle, hold out the hope of getting some purchase on inertia. That purchase may allow us to test Mach's principle. And if we are truly fortunate, it may open the way to technological applications of some interest.

A BIT OF THEORY:

Radiation reaction in electrodynamics is not automatically included in Maxwell's equations. Considerations of conservation of energy and momentum, however, require that it be dealt with since the electromagnetic waves predicted by the theory carry energy and momentum. The launching of such waves by accelerating electric charges, therefore, must produce a reaction force on the charges that preserve the conservation principles. In electrodynamics this problem has been dealt with in several ways: the deformable extended electron model of Lorentz where the reaction force arises from propagation delays as parts of the electron communicate with each other during the acceleration; the point electron of Dirac where the reaction force is computed by demanding that the conservation laws obtain; and the already mentioned action-at-a-distance absorber theory of Wheeler and Feynman with its phase shifts and time-delays. The counterpart of the time-delays in the treatments of Lorentz, and Wheeler and Feynman for Dirac's theory is "pre-acceleration" – electrons begin to accelerate some small time before the force that produces the acceleration acts.

As a soon to be superannuated experimentalist, I do not propose to tackle inertial reaction forces in an elaborate, formal way. So, rather than try to solve the field equations of general relativity theory to recover inertial forces as forces of radiation reaction, I will approach things differently. What we are interested in, given our presumed technological bent, is: Can we affect the masses of things by local operations on them? Ultimately, the only thing we can do locally is to apply forces on objects. Thus, the question to be answered can be restated as: Does the application of forces on objects cause their inertial masses to change? If the forces cause accelerations, inertial reaction forces arise. The inertial reaction forces are caused by the action of the gravitational field of chiefly distant matter, so our question becomes: Does the action of the gravitational field, in generating inertial reaction forces, cause the inertial masses of accelerated objects to change? The simple, if a bit unorthodox way to answer this question is to write the field that produces the inertial reaction force as that inertial reaction force per unit local charge (inertial/passive gravitational mass) and take its divergence to get the local source charge density (active gravitational mass density). If the local source charge density changes as a result of the applied force that produces the acceleration, then the Equivalence Principle insures that the local inertial mass density changes too.

We must do this in a relativistically correct way, so we use the four-vector force to obtain the field strength and take the four-divergence to get the local source charge density. We can simplify the expression produced in this way by noting that the field that causes the inertial reaction forces that arise in response to elementary accelerations is irrotational. One cannot "wind up" the effects. Consequently, the three-vector part of the field can be written as the gradient of a scalar potential. The result of these operations (which – up to a typographical sign error in Equation (3.10) – can be found spelled out in "Twists of Fate: Can We Make Traversable Wormholes in Spacetime" available at <http://chaos.fullerton.edu/~jimw/Twists.pdf>) is the following equation:

$$\nabla^2\phi - (1/\rho_o c^2)(\partial^2 E_o/\partial t^2) + (1/\rho_o c^2)^2(\partial E_o/\partial t)^2 = 4\pi G\rho_o \qquad (1)$$

In this equation ϕ is the scalar potential of the field, ρ_o the rest-mass density of the material in the volume element of the accelerated field source and E_o the corresponding rest-energy density. G is Newton's universal constant of gravity. It must be included on the right hand source side to scale *passive gravitational* mass into *active gravitational* mass. I should also mention that this equation is only exactly true in the instantaneous frame of rest of the local matter that is being accelerated where all of the Lorentz contraction factors are equal to one, and thus disappear. This is not an approximation. But it does mean that if you want to see what the field equation looks like in any other reference frame, these factors must be restored explicitly.

Equation (1) almost looks like a normal inhomogeneous field equation where the d'Alembertian of some quantity, usually a potential, is equated to a local source charge density (or a source current in the case of a vector potential). So it is natural to ask: Is there some way to express the local rest-energy density E_o that will allow us to put Equation (1) into this customary form? Well, if we invoke the strong form of Mach's principle – which says that the inertial masses of things *per se* arise from their gravitational interaction with chiefly the most distant matter in the universe – then we can do this. Note that it is the strong form of Mach's principle that is used here, not the weak form that only requires that inertial reaction forces arise from gravitational interactions. The strong form of Mach's principle allows us to assert that the local energy density E_o is just the total *gravitational* potential energy of the local matter, or:

$$E_o = \rho_o\phi. \qquad (2)$$

Is there any reason to take such an assertion seriously? After all, one normally learns that the gravitational potential ϕ is arbitrary up to an additive constant. Clearly, E_o cannot have this property. And in FRW cosmologies it does not. ϕ turns out to be a *locally measured* invariant in those cosmologies, just like the vacuum speed of light c. Indeed, not only does ϕ have the same invariance property as c, it must be equal to c^2 if inertial reaction forces are to be accounted for as gravitational forces (as Sciama [1953] showed now nearly a half-century ago). In consequence, we can re-express Equation (2) in the form:

$$E_o = \rho_o c^2 \tag{3}$$

which we immediately recognize as the well-known relationship between mass and energy that is a consequence of *special* relativity theory.

Using Mach's principle as embodied in Equation (2) we can separate the variables in Equation (1) by substituting $\rho_o\phi$ for E_o. When the time derivatives are computed and we take account of the fact that we may take $\phi = c^2$, after a modest amount of algebra we find that:

$$\nabla^2\phi - (1/c^2)(\partial^2\phi/\partial t^2) = 4\pi G\rho_o + (\phi/\rho_o c^2)(\partial^2\rho_o/\partial t^2) - (\phi/\rho_o c^2)^2(\partial\rho_o/\partial t)^2 - c^{-4}(\partial\phi/\partial t)^2. \tag{4}$$

Now we have the d'Alembertian of ϕ equal to a source charge density. But the source charge density has several time-dependent terms in it. It is the time-dependent terms that are the ones of interest. Before discussing them, however, we simplify Equation (4) by taking note of the fact that $\phi = c^2$ in the coefficients of the time-dependent terms and setting $c^{-4}(\partial\phi/\partial t)^2 \approx 0$ since, with a c^{-4} coefficient, it will always be minuscule. Equation (4) becomes:

$$\nabla^2\phi - (1/c^2)(\partial^2\phi/\partial t^2) \approx 4\pi G\rho_o + (1/\rho_o)(\partial^2\rho_o/\partial t^2) - (1/\rho_o)^2(\partial\rho_o/\partial t)^2. \tag{5}$$

Note that if ρ_o is a constant (as well as an invariant), then the time-dependent terms on the right hand side of Equation (5) vanish and we are left with a classical wave equation for ϕ of standard form; and if we assume that all time derivatives vanish, we recover Poisson's equation for ϕ. So, it would seem, we haven't done anything seriously foolish so far.

Since it is the local, instantaneous passive gravitational/inertial matter density that we are interested in, we note that the right hand side of Equation (5) can be written as $4\pi G\rho(\mathrm{t})$, where $\rho(\mathrm{t})$ is that matter density. From Equation (5) we have:

$$\rho(\mathrm{t}) = \rho_o + (1/4\pi G)[(1/\rho_o)(\partial^2\rho_o/\partial t^2) - (1/\rho_o)^2(\partial\rho_o/\partial t)^2]. \tag{6}$$

For convenience of calculation we'll use $\rho_o = E_o/ c^2$ to write Equation (6) as:

$$\rho(\mathrm{t}) = \rho_o + (1/4\pi G)[(1/\rho_o c^2)(\partial^2 E_o/\partial t^2) - (1/\rho_o c^2)^2(\partial E_o/\partial t)^2]. \tag{7}$$

While the mathematics that has led us to the time-dependent terms in Equations (6) and (7) may be fairly straight-forward, one may wonder if there is any plausible physical basis for them. In view of the small time-delays/phase lags that typically occur in radiation reaction processes, I would argue that these time-dependent terms might reasonably be expected. They must be quite small in all normally encountered circumstances in order not to conflict with experience. Substitution of realistic values for ρ_o and E_o into these equations bears out this expectation.

EXPERIMENTAL AND PRACTICAL MATTERS:

Just because the time-dependent terms in Equations (6) and (7) are normally negligibly small does not mean that they cannot be engineered to be quite large. For example, consider a capacitor made with a highly polarizable dielectric like barium titanate. In titanate materials, the ions in the lattice undergo large excursions when they are subjected to strong electric fields. So, if we apply an AC voltage signal with an amplitude on the order of hundreds of volts at a moderately high frequency to such a capacitor, the lattice ions will undergo large accelerations. And, from the point of view of the predicted effects, the accelerations will be accompanied by large fluctuations in the stored internal energy in the capacitor. To estimate the magnitude of the expected effects in our capacitor we need merely note that $\partial E_o/\partial t$ in Equation (7), when integrated over the volume of the capacitor, is just the instantaneous power P being delivered to the capacitor. (P is just the product of the voltage V and current i in the circuit containing the capacitor.) If we assume P to be a simple sinusoidal signal with an amplitude P_o of, say, a hundred watts and a frequency of 10 kHz, the first transient term (with the second time derivative of E_o) turns out to yield a mass fluctuation with an amplitude of a few milligrams. At higher frequencies and powers the amplitude of the mass fluctuation becomes larger still. Indeed, running in the 60 to 80 kHz range with a power amplitude of several hundred watts, the amplitude of the mass fluctuation rises toward the gram range.

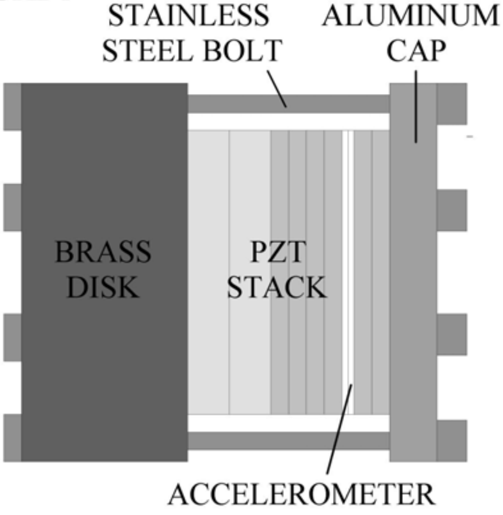
Although there may be a way to take advantage of the large mass fluctuations expected on the basis of the first transient term in Equation (7), for experimental and simple practical purposes it has an intrinsic drawback: Its time-average is zero. This means that in order to detect an effect based on this term you must be able to "weigh" a device in which it is driven as quickly as the mass fluctuates. An experiment of this sort, the work of John Cramer and one of his graduate students, is now in progress at the University of Washington. They have found that the "weighing" speed constraint limits them to less than one kHz operating frequency. Since the first transient term effect scales with the square of the operating frequency, the amplitude of the mass fluctuation they will be able to generate will be quite small, making detection of the effect difficult.

The zero time-average of the first transient term effect doesn't apply to the second transient term, for, being quadratic in P, it is positive definite. From the practical point of view, this is the term of greater interest too, because, being positive definite, it is always negative. That means, if we can excite an effect based on this term to practical levels, since its time-average is not zero we might be able to drive a *stationary* state of reduced, perhaps even negative mass in our capacitor with an AC applied voltage signal. The mundane, technical problem here is that the magnitude of effects expected on the basis of the second transient term in Equation (7) are usually many orders of magnitude smaller than those predicted with the first transient term. For example, if we assume that ρ_o in the denominator of the coefficient of the time derivative can be treated as a constant of order unity – that is, we assume that any mass fluctuation is only a very small perturbation of the total mass – then we will discover that the second transient term effect is down by 15 orders of magnitude or so from the magnitude of the first transient term effect. Need I say that this does not appear to be very promising?

We have ignored an important property of Equation (7). It is non-linear. And if we do not make the small perturbation approximation assumption, we find that the second transient term effect – normally negligibly small – can rival, indeed outstrip, the first transient term effect. You will find this remarkable property of Equation (7) already mentioned in "Twists of Fate" [1997] and its precursor "Making the Universe Safe for Historians" [hereafter, MUSH, 1995, pp. 19 – 20, which also suffers from the same typographical sign error in the derivation of the effect as Twists]. As Ronald Crowley and Stephen Goode pointed out (in a thesis defense) a couple of years ago, the significance of the second transient term is easily shown. One simply substitutes the *ansatz* $\rho_o = \rho \cos(\omega t)$ into the transient terms in Equation (6) and computes their derivatives. This *ansatz*, of course, is not an exact solution of Equation (6). But this computation shows that when the ρ_os in the denominators of the coefficients of the transient terms are not treated as constants, the two terms turn out to be of about the same magnitude. Since the first transient term is linear in the applied power and the second is *quadratic*, when enough power is applied to make the amplitude of the first term transient effect a non-negligible fraction of the total unperturbed matter density *we may reasonably expect the second transient term effect to manifest itself*. And, as discussed in MUSH and *Twists*, in extreme circumstances, if the bare masses of elementary particles are negative and hideously large (as they likely are), it may be possible even to drive wormhole formation with this effect. For that reason, I will call this the "wormhole" term/effect, notwithstanding that some will doubtless find this hopelessly romantic, or perhaps even delusionary.

Evidently, in order to try to detect the predicted effects we need a capacitative device that stores large amounts of internal energy and produces large, bulk accelerations in its dielectric material. The obvious material that answers these requirements is lead-zirconium-titanate, so-called PZT, that is routinely used to make electromechanical actuators and ultrasonic devices. Depending on the sign of the applied voltage to a PZT crystal, it will either expand or contract. So if it is subjected to an AC voltage signal, it will oscillate at the applied voltage frequency. To optimize the operation of a device made of PZT crystals, we will want to put them together, interleaved with electrodes, into a stack and mount the stack on a reaction mass so that the oscillation induced by the applied voltage signal produces the largest possible acceleration of the stack where the largest stored energy fluctuation is taking place. That is, we will want to build a device that looks, schematically, like that shown in longitudinal section in Figure 1.

FIGURE 1

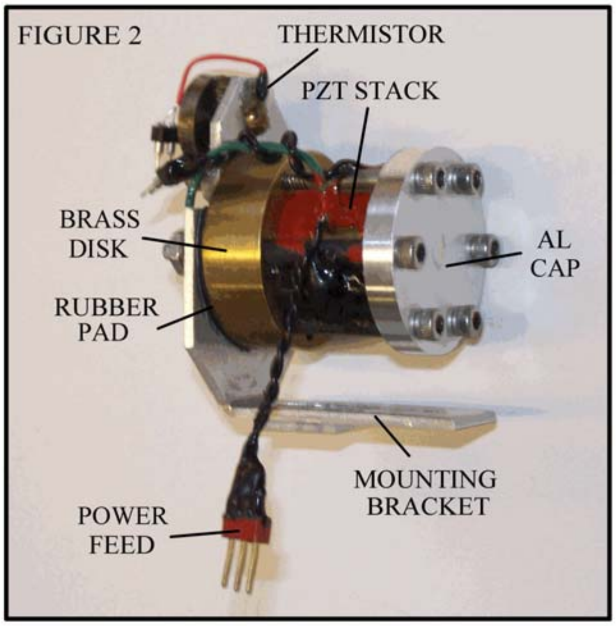


THE TEST DEVICE:

The device shown in Figure 1 is a stack of PZT disks about 2 cm. in diameter (actually, 0.750 inch) glued together (with special epoxies) fitted with electrodes and then clamped between a thin aluminum cap and a brass disk about one cm. thick with six (4-40) machine screws. (Such clamping to produce a preload is needed to improve the performance of the mechanical oscillation and to keep the stack from tearing itself apart when operated at high power.) Since the largest accelerations will occur at end of the PZT stack next to the aluminum cap, the PZT crystals there are thin (about 1 mm. thick) so that most of the energy stored in the stack will be stored there. The PZT crystals next to the brass disk are thicker (about 3 mm. thick) since they only serve to carry the acoustic wave generated in the active end of the stack to the reaction mass (and thus should be of the same material as the active end of the stack to avoid an acoustic impedance mismatch that might degrade the performance of the device). Note that a pair of very thin PZT crystals (about 0.25 mm thick) are included in the end of the stack where the largest effect is expected. They are used as a passive accelerometer to monitor the accelerations in this part of the stack. (A more elaborately instrumented device would include more such accelerometers.)

The device must be mounted on the stage of a weigh system. One might be inclined to think that how this is done will not make much difference; and were we chiefly concerned to observe the first transient term effect, that might actually be the case. Experience, however, teaches that if one seeks the second transient term effect *everything* matters, for to bring it to detectable levels *everything* must be *just so*. In the case of mounting the PZT stack/reaction mass assembly I used the aluminum bracket shown in Figure 2, for when first built the device was to be suspended from the beam of a torsion pendulum. In an attempt to reduce the vibration generated in the stack communicated to the beam, I inserted a thin rubber pad between the bracket and the reaction mass. The communicated vibration was reduced, as expected. But an unexpected consequence of the rubber pad was dramatically improved performance of the device. The performance of the device even depends on the presence of the 1 cm square by 1 mm thick plastic pad glued to the arm of the bracket (visible in Figure 2 below the bracket just to the right of where the power feed crosses it) and the torque on the nut on the mounting stud in the weigh system stage that passes through it (not shown in Figure 2). (The arm of the bracket was slotted at the outset to

FIGURE 2



allow for adjustment. When the attachment point was fixed, the plastic pad with a centering hole was added to make mounting on the weigh stage easily repeatable.) Even the type of mounting stage on the weigh sensor matters. In retrospect it is clear that all of these things affect the propagation of acoustic waves in the device, and such quirkiness should be expected. But before the fact, this was not obvious.

The behavior of the PZT crystals in the stack depend quite sensitively on their operating temperature. In part, this is a consequence of the fact that the thermal expansion properties of the crystals and the materials in the stack preload clamp are not the same. The brass reaction mass, stainless steel bolts, and aluminum cap all have higher coefficients of thermal expansion than the PZT crystals. So, as the device heats up during operation, the preload changes, and with it the mechanical behavior changes too. In order to get reproducible behavior the device must be run only for short intervals in a fairly narrow operating temperature range. So the device must be equipped with a thermometer. Originally, when the preload dependence sensitivity was not fully appreciated, a thermometer was included only to insure that the device was always operated well below the Curie temperature of the PZT crystals so that they would not be depoled when run. The first thermometer used is the spiral bimetallic strip thermometer mounted on an aluminum ear bolted to the brass disk (visible in Figure 2 to the left of the thermistor). When it became clear that more precise temperature monitoring was required, a thermistor was glued to the aluminum ear to monitor the device temperature.

THE WEIGH SYSTEM:

The core measurement in an experiment to determine whether the mass fluctuation effects predicted by Mach's principle are present is the measurement of the weight of the device in which the effects are driven. Since a fast response, high resolution weigh system is needed, commercial devices, with their long integration times, are unsuitable. A proprietary weigh system was therefore built using a Unimeasure U-80 position sensor fitted with a stainless steel diaphragm spring to transform it into a force sensor. It works on the basis of a magneto-resistive effect in Hall probes that move in a magnetic field of known configuration. It is shown with its protective case removed in Figure 3.

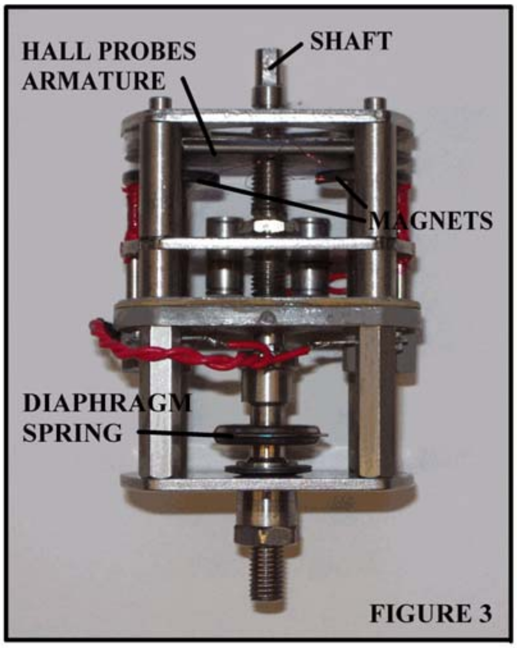


FIGURE 3

Since the U-80, especially operated at high sensitivity, is susceptible to electromagnetic interference, great care must be taken in shielding the device and its associated circuitry. The U-80 used in the experiment described below was encased in a steel shielding container one centimeter thick, shown in Figure 4. The leads to the electronics a few tens of centimeters away were a shielded, twisted pair of conductors

(Trompeter Twinax cable with gold-flashed Trompeter connectors). And the “remote” electronics were enclosed in cast aluminum circuit boxes, all of them then being located in a double wall steel box. While these measures sufficed to eliminate all routine electromagnetic interference (tests were done to insure this), the system remained sensitive to 100 mHz radio transmissions. Fortunately, the distinctive nature of this intermittent interference made it easy to identify and suppress either by data correction, or by data elimination. Another important feature of the weigh system can be seen in Figure 4: the three tensioned fine steel guy wires that stabilize the central shaft against lateral motion. This ensures that only motion along the axis of the central shaft can take place. Thus, lateral forces of spurious origin are not mistaken for a weight signal.

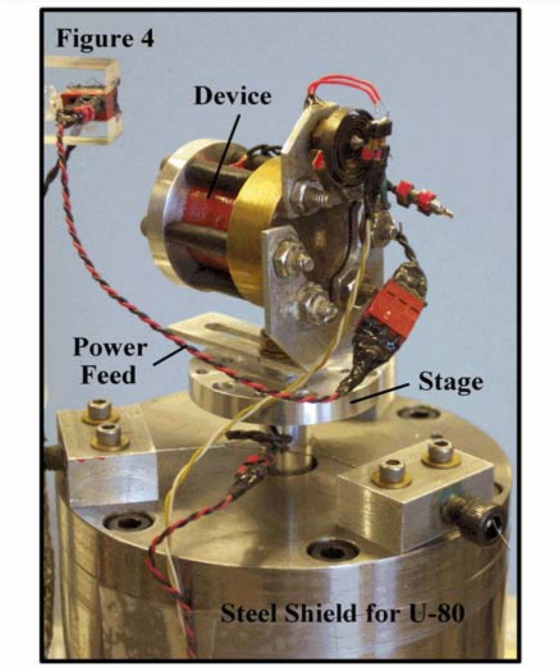


Figure 4

OTHER APPARATUS:

The rest of the apparatus needed to do the experiment is straight-forward. A sinusoidal signal generator equipped with voltage controlled frequency modulation for automatic frequency sweeps produces the signal that is amplified by a power amplifier. (A Carvin DCM-1000 run in bridged output mode, capable of driving nearly a kilowatt into a 4 Ohm load up to nearly 100 kHz, is a well-suited power amplifier.) Since the peak output swing voltage of inexpensive commercial power amplifiers is about 60 to 70 volts, a stepup transformer is required to bring the peak voltage up to the several hundred volts range. (The transformer used was wound on an Amidon T-300 powdered iron [mixture 26] torus with a 6 to 1 turns ratio.) The secondary circuit, that includes the driven device, is wired with sense resistors to monitor the voltage and current. These signals are then multiplied with a four-quadrant multiplier chip

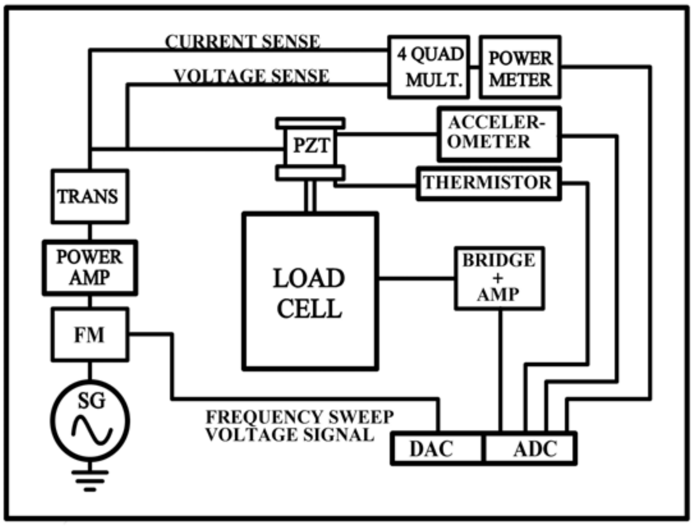


Figure 5: A schematic diagram of the chief electronic circuits used in this experiment. The DAC and ADC are computer controlled.

(an Analog Devices 633 chip) and its output is rectified and filtered (with an Analog Devices 630 synchronous demodulator chip) to give a voltage signal that tracks the real-time amplitude of the power wave in the driven device.

Switching and frequency modulation (when used) of the power circuit is accomplished with the digital-to-analog part of a PC based data acquisition and control board, which also acquires data from several channels during data acquisition cycles. The weigh signal, power, and thermistor on the device were routinely monitored. And a fourth channel was used to monitor either the accelerometer embedded in the PZT stack, or an accelerometer attached to the weigh stage (to monitor vibration communicated to the weigh system during operation of the device). A schematic diagram of these circuits is displayed in Figure 5. Each channel was equipped with an anti-aliasing filter. The standard data acquisition protocol was to take data at a rate of 50 Hz during a 14 second interval. The first and last several seconds of each data cycle were quiescent conditions, the device only being operated for a few seconds in the middle of the cycle. Data acquisition and subsequent data reduction was done with proprietary software specially created for the tasks.

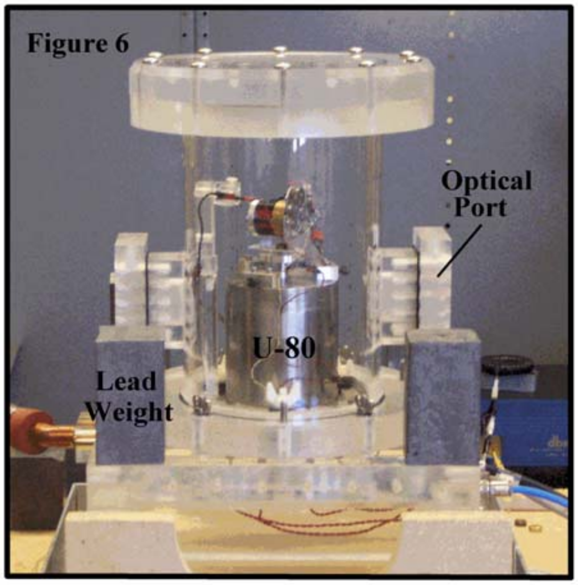


Figure 6

The only other things worth mentioning are vibration isolation and the vacuum system. The U-80 with the device mounted on it was placed in a plexiglass vacuum chamber. (See Figure 6.) A rotary vane vacuum pump was used to achieve vacua of a few tens of milli-Torr or better in the chamber. While this is not a hard vacuum, it is sufficient, when compared to operation at atmospheric pressure, to insure that any effect seen with the weigh system is not due to acoustic and/or discharge effects. Vibration produced by the vacuum pump and other ambient seismic noise, given the sensitivity of the weight measurement attempted, mandates that significant vibration isolation be used. This was done with inner tubes and massive lead weights, Barry Stablevel devices and more lead weights, and finally layers of Sorbothane and yet more lead weights.

SOME RECENT RESULTS:

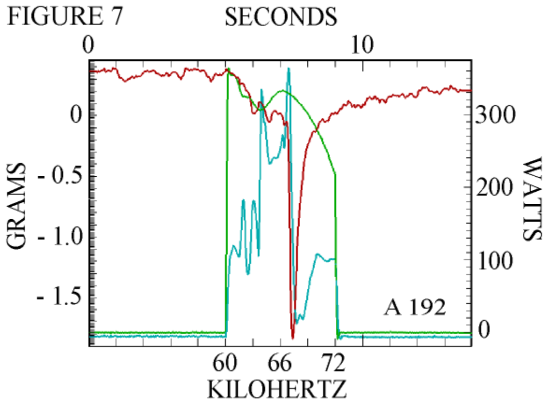
Although it is tempting to present here secure results that have "aged", perhaps it is more interesting and instructive to relate what I have been getting with this system in the recent past. The objective here is simple: To drive large accelerations accompanied by large, rapid changes in internal energy in a titanate material, the aim being to get everything "just so" so that a stationary wormhole term effect manifests itself at a detectable level. The problem is not to produce apparent weight changes in the system described here. Indeed, given that a small device mounted on a very sensitive differential weigh system is being driven at high power, exciting strong ultrasonic vibrations in the vicinity of a mechanical resonance of the system (to get the large accelerations), it would be quite surprising if apparent weight fluctuations were not produced. The real problem is showing, once such weight fluctuations have been detected, that they are the effect sought, not just some spurious signal attributable to mundane origins.

As one proceeds in this sort of investigation, one develops an arsenal of tests that allow one to detect spurious signals, and a variety of protocols that eliminate or stabilize behaviors that can compromise the quality of the data obtained. Tempting though it is to load up with illustrative data related to the tests and protocols I have developed in the course of the past year and a half (and more), I will merely mention several of them.

Since the weigh system is based on the amplification of a rather small electrical signal and the device being tested is run at a power typically of several hundred Watts, perhaps the most obvious source of spurious signals is electromagnetic pickup in the weigh system of the power signal. A simple test can be done to make sure that the shielding of this weigh system circuit is adequate, and the weigh signals are not so contaminated. One puts a small shorting loop of wire at the device sitting on the weigh system and places a nearly identical device elsewhere in the high voltage circuit. Run in this configuration, the electromagnetic fields normally present are mimicked, but no sought effect is produced. Other electromagnetic tests that can be done include placing strong permanent magnets near the system to check for coupling to the Earth's magnetic field. Strong electric fields that can be expected in the system can induce dipoles in nearby dielectrics, and if the fields have strong gradients, forces can arise. The electric fields, of course, will be alternating given the ultrasound frequency of the applied voltage signal. But the induced dipoles will oscillate too, so stationary forces may be produced. The magnitude of such forces can be checked by the simple test of applying a static voltage to the device. None of these tests revealed the presence of spurious signals that might account for signals reported here.

What sort of signals are we talking about? Ones like that displayed in Figure 7. There three traces are displayed. The red trace is that for the weight sensor; the green trace tracks the power applied to the device; and the light blue trace is that for the accelerometer glued to the bottom of the mounting stage of the weigh system which tracks vibration present in the weigh system. As mentioned above, data are taken during a 14 second interval where power is applied during the center four seconds while the frequency of the voltage signal is swept, in this case, through a range of 12 kHz centered on 66 kHz. The weight and power scales are shown on the left and right hand sides of the figure respectively. The full-scale range of the accelerometer signal is given in ADC counts in the lower right hand corner of the figure. (No attempt at absolute calibration of this accelerometer was made.)

FIGURE 7



Very obviously, something interesting happens at about 67 kHz. The weight of the device appears to decrease by in excess of a gram. Considering that the active PZT material in the stack has a mass of about 10 to 15 grams, this weight fluctuation, *if real*, is enormous. It approaches 10 percent of the active mass. We must, therefore, try to show that the effect in Figure 7 is attributable to mundane causes. Perhaps the vibration induced in the weigh system at the mechanical resonance of the device (see the mounting stage accelerometer trace) might cause flash heating of the spring, and its transient expansion might generate a brief apparent weight reduction. In fact, thermal effects of this sort are present. Their time-constants, however, are far too long to produce the prompt part of the sort of effects seen. And one might reasonably expect to see a similar weight effect at the first accelerometer spike were we dealing with a simple vibration induced thermal effect.

If the weight spike in Figure 7 (and other results like it) can't be written off entirely to electromagnetic or transient thermal causes, only a few other candidate causes of spurious signals remain. Those most easily dealt with are corona and "sonic wind". Given the presence of several hundred volts in and around the device during operation, one may expect that coronal discharge might take place. Careful construction and insulation should be sufficient to suppress corona. To make sure that it is absent the device can be operated in total darkness and observed with a night-vision scope. And the system can be operated at various levels of vacuum, which should change any coronal effects present. Sonic wind is commonplace in ultrasonic systems. It is a consequence of the fact that ambient gas cannot follow the motion of solid devices operating at high frequency since their excursions exceed the speed of sound in the gas. Sonic wind effects can be quite pronounced all the way down to about a Torr. But they largely disappear below, roughly, 100 milliTorr. So operation in the range of less than a few tens of milliTorr is sufficient to eliminate sonic wind effects. And as a further check, runs can be done at atmospheric pressure to compare with those done in the 10 to 30 milliTorr range.

The most troublesome source of spurious signals is mechanical vibration in the weigh system. Accordingly, the obvious thing to do is to try to attenuate the vibrations generated by the operation of the device before they reach the weigh system. And vibration isolation devices were implemented to accomplish just this end. Using them it is possible to reduce vibration in the weigh system to levels undetectable with the accelerometers normally employed. Do weight fluctuation signals like that shown in Figure 7 disappear when this is done? No. They can be sharply reduced in amplitude; but signals on the order of a few tens of milligrams persist. You may be wondering why I haven't shown you smaller signals of this sort instead of that in Figure 7. Because the situation is more complicated than one might like. The conditions needed to produce large wormhole term effects, as I have said, are "just so". And there is reason to believe that some significant part of the weight signals like that in Figure 7 *may* be due to a real Machian effect that depends on "just so" conditions that require the participation of vibratory motion in the weigh sensor.

If you are deeply skeptical of what I have just said, you should be. Until recently I simply dismissed this possibility. But not long ago, quite fortuitously, I encountered behavior that forced me to reconsider my belief that vibration in the weigh system could only produce spurious signals. In particular, after extended operation of the system, I succeeded in slowly driving down the amplitude of a weight fluctuation signal I was studying to an undetectable level. As a check, I decided to operate the system with the device bolted directly to the weigh stage, that is, with the vibration isolation device removed from the system. As expected, even directly bolted to the weigh stage, no signal was present, notwithstanding that the device continued to operate “normally”. (Both the thermistor and the accelerometer embedded in the PZT stack showed that the device continued to produce mechanical excursions of normal operation.) This result was obtained late on a Friday afternoon. The following Monday I set out to pursue this apparent null result. To my amazement, however, the weight signal that I extinguished the previous Friday had returned. It persisted even when the system was “warmed up” to the operating conditions of the previous Friday. Relaxation of the system over the weekend had restored “just so” conditions that I had compromised by extended operation the previous week. Knowing that the sort of system relaxation that could take place in the space of 60 hours or so could not substantially change the vibration present in the weigh system, I was forced to consider the possibility that a real effect might be present in the results. (After the fact, though, an engineer friend tracked down work on PZT devices where precisely the sort of relaxation effect with a time-scale of tens of hours, evidently present, had been systematically studied.)

How does one discriminate a real from a spurious signal in these circumstances? One way is to check for promptness of the effect seen. A real wormhole term effect, given operation at a fixed frequency for an interval short enough so that heating doesn’t appreciably change the conditions of operation, should simply switch on and off with the applied power. Vibration induced effects, especially thermal effects induced by vibration, one might expect not to show such prompt switching behavior. Rather, steady secular evolution should characterize effects of this type.

Since programming for a short fixed frequency pulse had been done long before, switching to this simple switching protocol was trivial. Results of this sort are presented in Figure 8. The peak-to-peak thermistor and mounting stage accelerometer readings in ADC counts are given in the lower right hand corner of the figure. “Upright” refers to the orientation of the weigh system and vacuum case. The weight trace (red), as expected, shows both a prompt change at switch-on and switch-off of the power and a secular drift during the powered interval that only very slowly decays after the power is shut off. The thermistor trace (blue) records the steady input of energy to the system. But the heating it records is in the device assembly, whereas the thermal drift in the weight trace arises from the heating of the diaphragm spring caused by vibration.

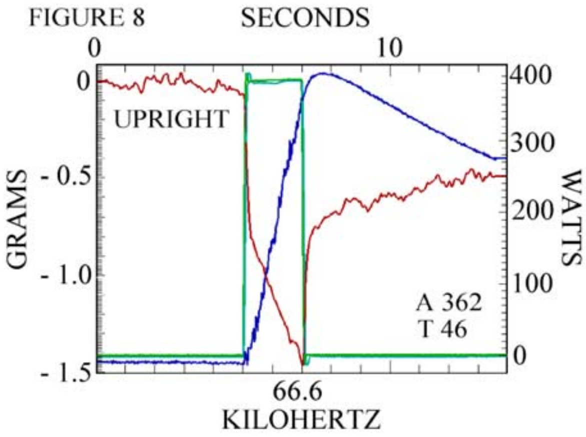
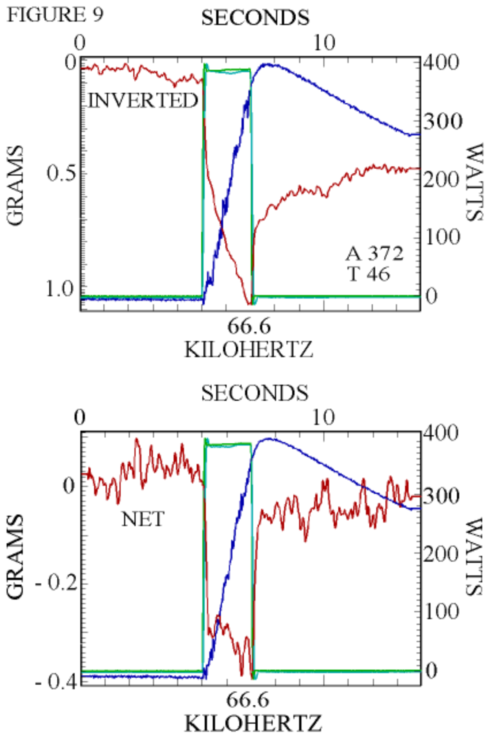


FIGURE 8

While it is tempting to interpret the prompt part of the weight signal in Figure 8 as the Machian effect sought, it would be premature to do so. The reason why is that ultrasonic vibration in the diaphragm spring might change its properties in such a way as to mimic the effect sought. There are two ways in which this might happen. One is that the vibration might induce a stationary distortion in the spring. Given the sign of the effect in Figure 8, such a distortion would have to be an induced distension of the spring. The other is that the vibration might cause the static spring constant to change, creating, as it were, a "dynamic" spring constant. (My engineer friend tracked down a study done within the last few years purporting to show precisely this sort of effect. See: Slotwinski, J.A. and Blessing, G.V. [1999].) I choose to call this the "meringue effect". Can these effects be checked for? Yes. The distortion effect can be isolated by simply inverting the entire system and doing another data run. Inversion, when allowance is made for the possibility that the static spring constant may change in the inverted configuration, will not change the direction of the distortion effect. A real weight effect, however, will reverse direction under inversion (accommodated by reversing the signs of the weight scale relative to zero in the displays).

The results for inversion corresponding to Figure 8 are displayed in the top panel of Figure 9. Since the direction of the effect is the same as in Figure 8, evidently we are dealing with a spring distortion effect. The amplitudes of the effects, nonetheless, are different, signaling the presence of a contributory effect that does reverse direction when the system is inverted, as a real Machian effect would. That part of the signal is easily isolated by subtracting the inverted weight trace from the upright weight trace, yielding the net weight trace displayed in the lower panel of Figure 9. The weight fluctuation that presumably contributes equally to the upright and inverted signals should have an amplitude half of that for the net signal in Figure 9, that is, on the order of 125 milligrams. Although this signal is down by about an order of magnitude from the naïve interpretation of the signal in Figure 7, having passed the weigh sensor inversion test, it is a much more reliable result.

FIGURE 9



Before proceeding, I should say a word about errors in the data presented here. The precision of the data can be estimated directly from the results (which are typically the average of a half-dozen to a dozen cycles). The signals of interest, very obviously, are much larger than the quiescent variability of the traces on any time-scale. The accuracy of the data is another matter. It depends on the accuracy of the absolute calibration of the weigh sensor and voltage and current measurements in the driving circuitry. I won't subject you to a long discussion of the calibration methods employed. Suffice it to say that the accuracy of these measurements were better than ten percent of the full-scale signals recorded, which is more than adequate for our present purposes.

GETTING LUCKY:

Far and away the most common activity of any experimentalist is repeated reconfirmation of Murphy's Law (and its various corollaries). But every once in a while dumb luck strikes and everything works far better than one has any right to expect. After the data in Figures 8 and 9 were obtained, through a "foolish mishap", the system was seriously degraded and had to be opened up and minor tweaking done in an attempt to restore reasonable behavior. Nothing major. Just checking that the nut on the stud on the mounting stage was secure; that the leads were properly dressed; that the tension of the steel guy wires that stabilize the mounting stage hadn't been compromised; that sort of thing. Since interesting behavior was most easily detected when the system was run in the inverted orientation, that is the way the system was put it back together. The first cycle taken after reassembly was completed looked very much like the average of inverted cycles shown in the center panel of Figure 10. At first the significance of the structure of the weight trace didn't register. I thought I had further fouled up the system. Only slowly did it dawn on me that I was looking at *quintessentially* "just so" data. Although the secular thermal effect present in Figures 8 and 9 is still prominent, a prompt weight *reduction* that outstrips any spring distortion effect in the opposite sense is plainly in evidence.

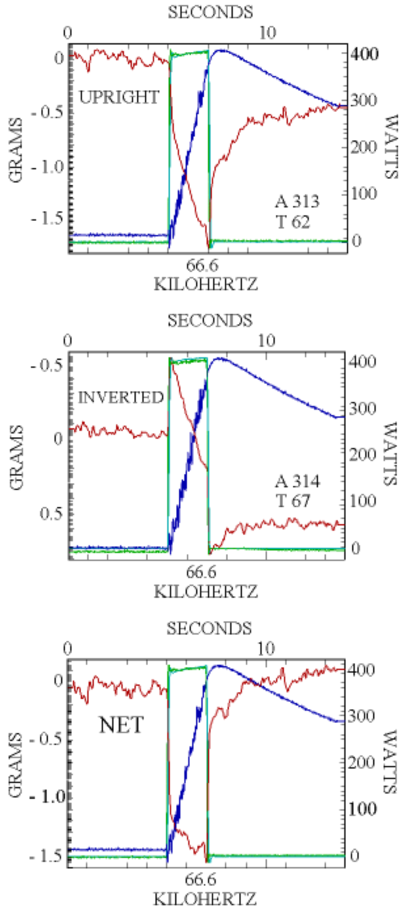


FIGURE 10

After taking several more inverted cycles (to ensure that I wasn't just looking at flukey data), I restored upright orientation and held my breath while the first cycles were acquired. They looked like the average of several cycles in the top panel of Figure 10. I had not loused up the system. Quite the opposite. Subtraction of the inverted results from the upright results yields the net weight signal displayed in the bottom panel of Figure 10. Comparison on the amplitude of the mounting stage accelerometer signal for this and the prior system configuration reveals that it is exceedingly unlikely that the change in the amplitude of the prompt weight signal – by a factor of about five – can be attributed to a change in the vibration in the weight sensor – the only plausible spurious source of anomalous prompt weight signals. Perhaps one day the discipline of "gravinertial engineering" will grace the curriculum of this and other institutions after all.

CLOSING COMMENTS:

You may, at this point, be thinking that this is all just ridiculous, far, far too "good" to be true. After all, the principle of the preference for the most prosaic result would seem to suggest that the "just so" conditions that produced the data displayed in Figures 7 through 10 must be "just so" conditions of mechanical vibration generating a subtle meringue effect in the weigh sensor spring, notwithstanding that the magnitude of the effect is essentially uncorrelated to the amplitude of the vibration present in the weigh system – as indicated by the mounting stage accelerometer readings for Figure 10 compared with those for Figures 7 through 9. Taking the contrary point of view, one might argue that the most prosaic result is not some weird meringue effect in the spring; rather, it is the Machian effect sought. Although the Machian effect is surprising and unexpected, no "new physics" beyond acceptance of the relativity of inertia – Mach's principle – is needed to produce its prediction. Accordingly, one might argue that we should be amazed were the predicted effect *not* to be found when sought. But perhaps that is just wishful thinking. In any event, I think it fair to say that the experimental results presented here merit an at least modest further investigation. Gravinertial engineering will never happen if we don't ask questions and take risks.

I think it fitting that my last remarks be acknowledgement of the contributions of others, for even small, table top efforts like this are not done completely alone. For many years now I have enjoyed the tacit, and occasionally overt, support of my colleagues at CSU Fullerton. Given the "speculative" nature of this research, I do not think I can overstate how important that support has been. I have also enjoyed some modest support from folks in a major American corporation. (When I asked if they wanted to be identified, they told me to say that were I to tell you who they were, I'd have to kill you. They were, of course, joking. I think that they were really concerned about the reaction of their stockholders were their support of such "speculative" work to be made public.) Of my colleagues I owe a special debt to Ronald Crowley and Stephen Goode, both of whom went through the derivation of the effect with considerable care on more than one occasion. Indeed, it was Ron's insistence that I do a particular calculation exactly, instead of making a simplifying approximation, that brought the wormhole term to light in the first place. And both of them, in Thomas Mahood's masters thesis defense, went out of their way to call attention to the fact that the wormhole term could have consequences as large as the other time-dependent term in laboratory circumstances – an eventuality that I had not seriously considered hitherto. I have also profited significantly from many conversations with John Cramer and Keith Wanser. Both are masters of both theory and experiment, and I know that they will see the imprint of their comments in the work I have reported here.

I would be remiss were I not to mention the contributions of Thomas Mahood and Paul March. Tom worked with me from the spring of 1997 through the end of 1999. Always ready with good, often inspired ideas about how to deal with the problems one encounters in doing experiments, he also went out of his way to insure that tests that needed to be done actually got done. He also kept pushing to forward innovations in the work. Paul, at a distance (he lives in Texas), has also kept prodding to keep the work moving forward. Recently, Tom and Paul have been joined by Kirk Goodall. Should gravinertial engineering ever come to be, I expect it will be in no small part due to the interest and efforts of all these people (and those not known to me who also may be pursuing this effect).

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