GRAVITATION EXPERIMENTS AT THE UNIVERSITY OF VIRGINIA

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OUTLINE

GRAVITATION EXPERIMENTS AT THE UNIVERSITY OF VIRGINIA

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Jesse W. Beams was interested in precision laboratory experiments at Virginia as early as the 1920's. With the advent of quantum mechanics he had been interested, along with E. O. Lawrence, at Yale, in trying to split the photon with mirrors and high speed rotors. This ultimately led to the development of low friction magnetic suspension bearings and a technology of high speed (and at times, precision) rotations at Virginia, where he had done in 1928.

The tool consisting of low-friction precision rotors has evolved over the intervening time and is being used today for gravitational experiments, some of which are partly described elsewhere in this symposium.[1-5] In addition the method has found importance through centrifugation in isotope separation and also in certain biophysical applications.[5]

In this paper we discuss first the general status of precision in rotors, then several of Beams' experiments in gravitation and several experiments which embody the most recent evolution of the precision rotors.

I. History of Precision Magnetically-Suspended Rotors

The properties most sought in these rotors are constancy in the rotation speed and precision in the measurement of it. Vibrational, electrical, magnetic and thermal disturbances are the usual degrading mechanisms which have been studied in the context of many other kinds of precision measurement, and will not be taken up extensively here. Drags due to bearing friction and gaseous friction are the special problems of rotors which have been studied historically.

Fluctuations in rotor angular velocity and also in its measurement are the other special problems of rotors which would interfere with their ultimate precision. Precision of rotational period measurement, however, has to our knowledge not been studied previous to our recent reports.[6] Previously the rotational frequency was always the variable of concern.

Beams used small (few mm diameter) spheres as rotors with speeds from 10^4 to 10^6 Hz. His instrumentation allowed frequency measurements of the rotational speed. Although the direct frequency drift rate could not be followed instantaneously with highest precision, frequency measurements at sufficiently separated time intervals permitted the evaluation of the drag time τ^* of the rotor as defined by

$$\omega = \omega_o e^{-t/\tau^*}, \qquad (1)$$

where ω_o is the initial angular velocity. The stability of his measuring apparatus was insufficient[7] to measure drifts of the rotor angular velocity of such a type as could have indicated departure from behavior according to eq. (1). Such drifts might have been expected from centrifugal stress at these high speeds, as well as from other causes, some of which have been listed by Kenny.[8]

Beams, and later Kenny, Nixon[9] and Fremery[10] used similar methods--small spheres with frequency measurement. Their precision studies of the decay time constants were always at many Hz and used frequency measurements. The longest decay times reported were 10^9 to 10^{10} s by Beams and Fremery. The usual limitation was gas drag, even at the best obtainable vacuua, but Fremerey also confirmed an eddy-current drag mechanism which we have briefly discussed[1].

Our present rotors are larger and slower, and use measurement of the periods. Assuming the following differential equation for the "free" rotor we can see the potential advantage of this:

$$I\dot{\omega} + \alpha\omega = 0, \qquad (2)$$

where I is the moment of inertia and α is a drag coefficient consisting of two parts. Thus, we can assume,

$$\alpha = \alpha_g + \alpha_b, \qquad (3)$$

where α_g is the gas drag coefficient and α_b is the bearing drag coefficient. The latter term can include many things as bearing drag. For example, tidal effects on the earth would constitute a bearing drag when treating it as a rotor.

The decay time, from (1) and (2) is clearly,

$$\tau^* = I/\alpha, \qquad (4)$$

proportional to I if α is independent of it. For a ferromagnetic sphere that is not the case, but we use rotors in which $\leq$ 5% of the mass is ferromagnetic, in the form of a sphere or slug at the top of a rod.[1] There is still an actual dependence of α on I but it is slight, depending on complex details of the suspension.

Our rotors have I ~ 10^4 to 10^5 that of the earlier ones of ref. 7-10. In addition, we use small ω(~ 0.1 to 40 rad/s) in order to reduce dimensional change from centrifugal stress. This has permitted period measurements with various averaging strategies.[1] In addition it has opened up a new study of rotor fluctuations.[1,13] We have not attempted to push the limits of timing of single periods yet, being satisfied for the moment with errors $\Delta T/T \sim 10^{-7}$ to 10^{-6}, i.e. $\Delta T \sim 10^{-7}$ to 10^{-6} s. Soon, however, such limits will interfere with our measurement, even with optimum averaging strategies, including the Snyder algorythm[2], and we will pursue better timing methods. Present day optical and electronic technology should make it possible and not at all difficult to time the period of a smoothly running rotor to 10^{-9} s or better.

The basic problems of gas and bearing drag have been discussed at length.[13,14] The bearing drag is a complex function of the ferromagnetic suspension and any fields that penetrate the rotor shield.[15] The ideal bearing would seem to be a passive one to eliminate the tiny screw-sense interaction of the vertical suspension activity and the rotations. Active servoes are an essential feature of ferromagnetic suspensions as a consequence of what has come to be known as "Earnshaw's Theorem".[3] A diamagnetic, superconducting suspension would solve this, as well as essentially eliminating the tiny "Coriolis Torque" from eddy currents.[1] After sufficient experience with the more hospitable room temperature research this is surely the direction our research must take. Additional benefits to be expected would be improved shielding and reduction of rotor thermal noise $(\sim\sqrt{kT})^1$. The avoidance of excessive ac losses in superconducting rotors is not a trivial matter, but seems possible.[16]

The solution to the gas drag problem was suggested years ago by Beams, or perhaps Alvarez.[17] This is to corotate the gaseous atmosphere by corotating a chamber around the rotor. To avoid a miniature weather system from collective molecular motion the gas must be at the free molecule regime of pressure, below $\sim 10^{-4}$ Torr. Beams built a corotation system[17] but did not report on its properties.

For the corotation to be effective to an extremely high degree it is important that it be accurate. We have used two methods, one in which the outer chamber is kept at constant speed, being phase-locked to a cesium-beam clock,[18] and the other in which the outer chamber is servoed to corotate with the inner rotor.[2] The first version has been developed for several years and will be discussed below. Figure 1 shows the heart of such a system, in which an inner rotor, 1a) is magnetically suspended and freely rotates inside a quartz cylinder mounted on an air bearing, 1b). The second version is just being completed and the first primitive results were given in ref. 2.

II. Beam's Measurement of the Equivalence Principle

In 1970, Beams reported a measurement setting a limit on the difference of inertial and gravitational mass at very high inertial acceleration. In conventional terms the limit was not sufficiently sensitive to be strongly noticed, but it is a different and interesting scheme.

In Beam's method[19], precision of rotation was not so much of direct importance. The way he carried it out was to look for the tilting of a buoy floating in a fluorocarbon liquid as it was spun up. The schematic diagram is in Fig. 2. The cylindrical buoy, mainly of Dow-metal, had a hole drilled into which a platinum mass

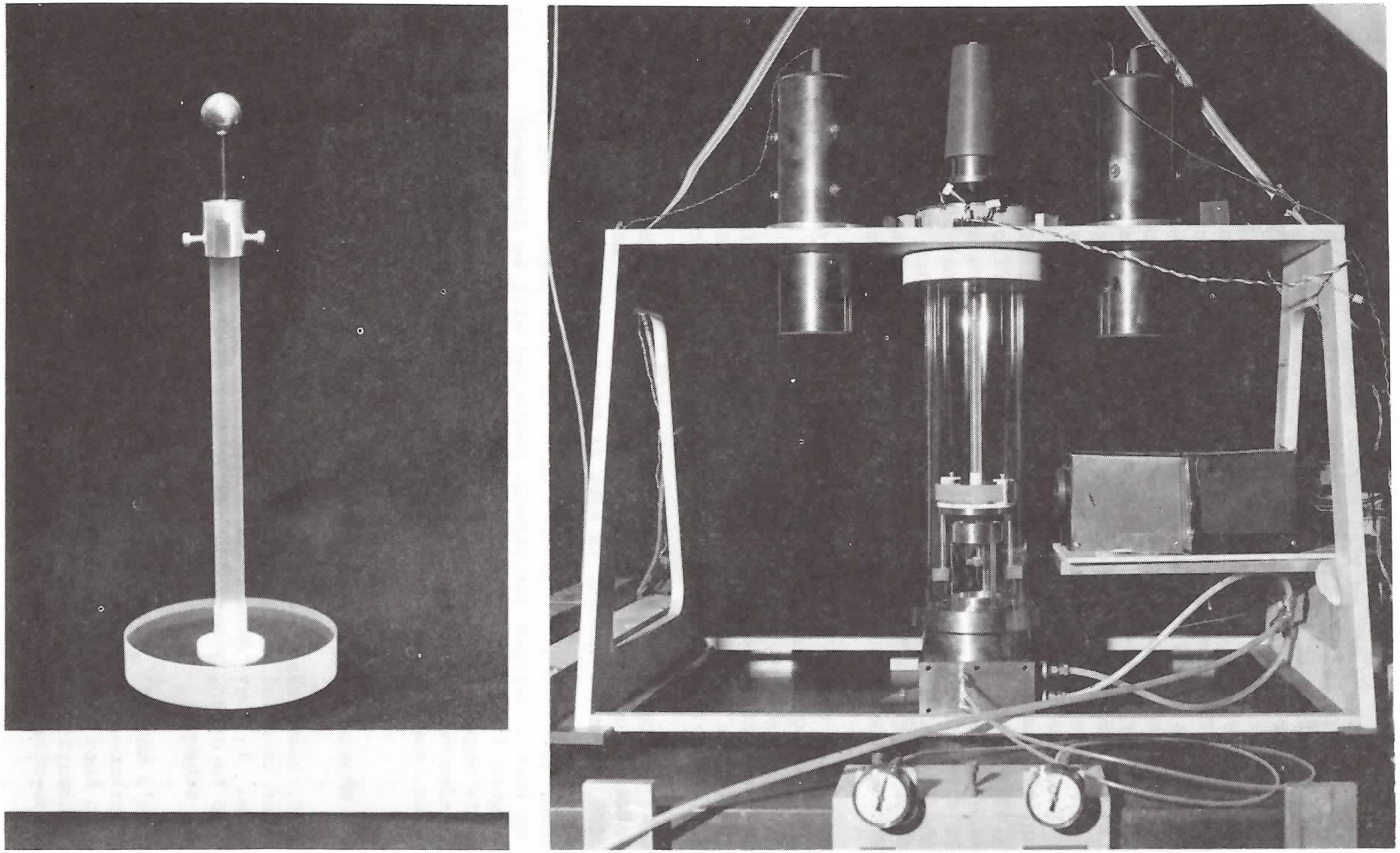

Figure 1. Corotation Systems. a) Inner rotor, b) System with outer cylinder on air bearing with magnetic suspension frame and angle sensor. Inner rotor here is on a moveable pedestal.

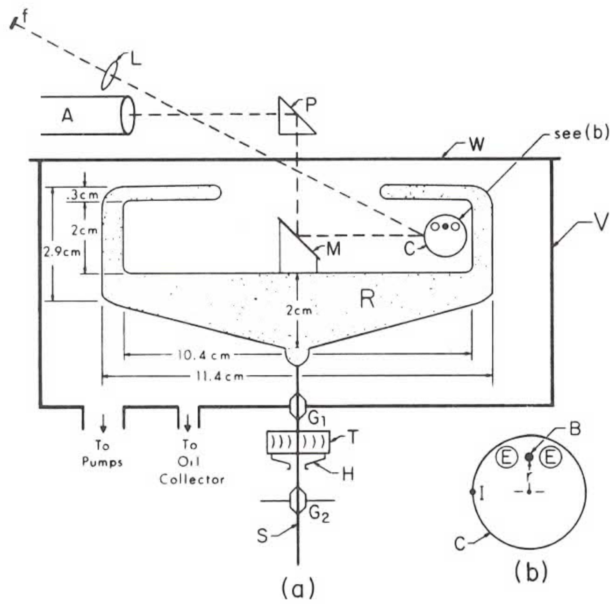

FIG. 2. (a) Schematic diagram of the apparatus. (b) Schematic cross section diagram perpendicular to the axis of the cylinder *C* showing location of platinum rod *B*.

was inserted. The empty part of the hole was such as to just account for the higher density of platinum over the lighter material it replaced. Thus, when sitting still, the buoy barely floated and its angular position was balanced in the earth's gravitational (and tiny centrifugal) field. This balance was observed with an optical system focussing on a fiducial mark. It was set up so that the mark could also be seen synchronously while the whole system was in rotation.

The flotation restoring couple could be calculated, but was measured by the oscillation period of the cylinder when floating in the fluorocarbon fluid outside the centrifuge. The platinum mass was 0.7 gm and the cylinder mass was 7.5 gm. The optical system allowed observation of float rotation to an effective value better than 10^{-3} rad when all known sources of error, including fluid density change under the centrifugal field, were taken into account.

All of this led to a limit for mass change of $\Delta m/m < 4 \times 10^{-5}$ in a centrifugal field of 1.5×10^6g. This could then be restated as $\Delta m/m < 3 \times 10^{-10}$ per g.

In other measurements of the equivalence principle[20,21] the limit was not stated in this way, but rather as

$$\eta(A,B) = \frac{(M/m)_A - (M/m)_B}{\frac{1}{2}\left[(M/m)_A + (M/m)_B\right]} , \qquad (5)$$

where M and m are the passive gravitational and inertial masses of materials A and B. In these experiments the inertial acceleration was essentially constant at about 1.6 cm/s^2, or about g/600, and the ~ 0.6 cm/s^2 variation of the gravitational field of the sun was what varied the ratio of the fields as the earth rotated.

If the ratio η were g-proportional, then the reported limit[20] of 3×10^{-11} would be ~ 1.8×10^{-8} per g. Such a dependence has not been suggested in this context, however.

III. Beam's Measurement of G.

There have been a huge number of measurements of G over the centuries.[22] None of these, until recently, was of absolute accuracy better than 10^{-3}, and the claimed accuracy of 10^{-4} for several recent measurements exceeds, considerably, their consistency with each other.

At such levels of accuracy, the primary uncertainty is probably due to the unwanted gravity gradients at the location of the experiment. Beams noted that a rotating experiment would average out the effect of these gradients and designed an experiment to do this, and more. It is pictured in Fig. 3. In effect it is an accelerating, servoed rotating torsion balance. It uses precision rotation in a different sense from some of the other experiments we will consider. The attracting, large masses sit on a table driven by a servo motor. The table rotates on command of a sensor which detects the movement of the attracted small masses toward the large ones. Thus, starting from rest the whole system accelerates at a constant angular rate which is in principle exactly proportional to G. The constants of proportionality are metrologically determined.

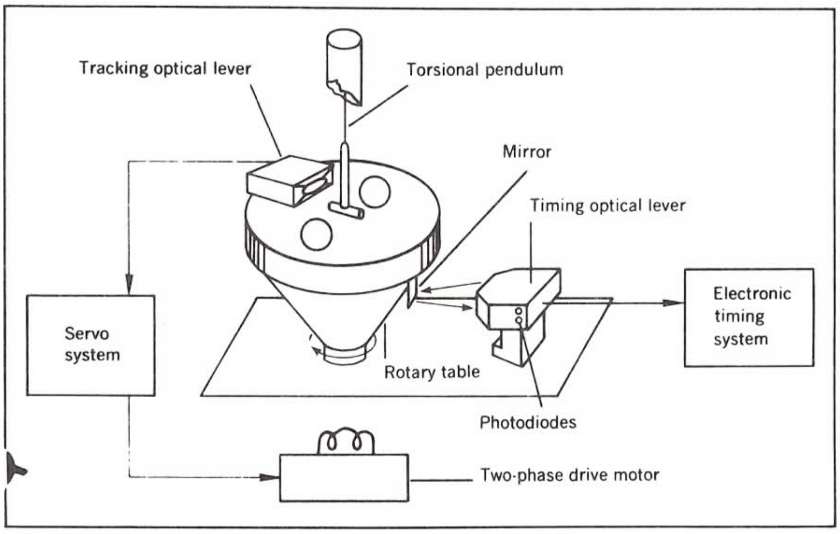

Figure 3. Beam's measurement of G. See text for explanation of rotational torsion balance method.

The results reported for this experiment[23] in 1969 conservatively claimed accuracy to 10^{-3}, and were arguably better than the results of Heyl[24], which claimed slightly higher accuracy but were afficted with seasonal variation.

The experiment of Beams was transferred to the NBS, Gaithersburg, where Luther and Deslattes improved it with more sophisticated instrumentation, etc. Results seemed to improve by something like a factor of 3, but inconsistencies appeared, which were ultimately traced to suspension fiber drift. This proved to be a continuing problem, in spite of an extensive testing of a variety of fiber materials.

The NBS experiment was then modified to use the oscillating torsion pendulum, rather than the rotating method of Beams. A series of innovations, including Reticon observation of the oscillations, permitted new levels of accuracy with the fibers. The gravity gradients are believed to have been treated sufficiently that an overall accuracy of 75 ppm has been reported[25] for their measurement $G=(6.6726\pm0.0005) \times 10^{-11}$ $m^3\text{-}sec^{-2}\text{-}kg^{-1}$.

IV. Proposed Measurement of $\dot{G}$.

When contacted by Dirac in the early 1970's Beams came to appreciate the need for a measurement of the time rate of change of G. He then reasoned that a shifting of priorities for the criteria of a torsion balance could lead to an experiment sensitive to changes in G at a rate as low as 10^{-10} per year--near the "Dirac rate" of -6×10^{-11} yr^{-1}. Absolute accuracy could easily be sacrificed for stability and sensitivity. Since it was expected to be a long experiment he sought assistance from the author.

In 1974 we seriously took up design studies for the experiment. What evolved was a symmetrized multiple-mass, rotating, cooled, feedback torsion balance.[26] Fig. 4 shows a much simplified schematization of the concept. While all these features seem necessary in a torsion balance measurement of G, and while they in principle solve the obvious problems in achieving the requisite sensitivity, it must be admitted that that design is short of true elegance. It has never been funded.

V. Matter Creation Measurement.

In the most discussed version of the Dirac cosmology,[27] a spontaneous, Machian, cosmological matter creation accompanies the change in G. Matter creation at the same rate has been part of other cosmologies, e.g. the one of Hoyle[28]. Thus, while in these ideas $G \sim 1/t$ and thus $\dot{G}/G)_o = -1/T_o$ where the subscript designates present time, $M \sim t^2$ and therefore $\dot{M}/M)_o = +2/T_o$, or about 1.2×10^{-10} yr^{-1} if we use the "popular" Hubble age of the universe of about 1.6×10^{10} yr.

There is no proposed mechanism or theory of how this matter is created, but three possible categories have been suggested by Dirac: 1) "additive", i.e. equally everywhere throughout the universe,

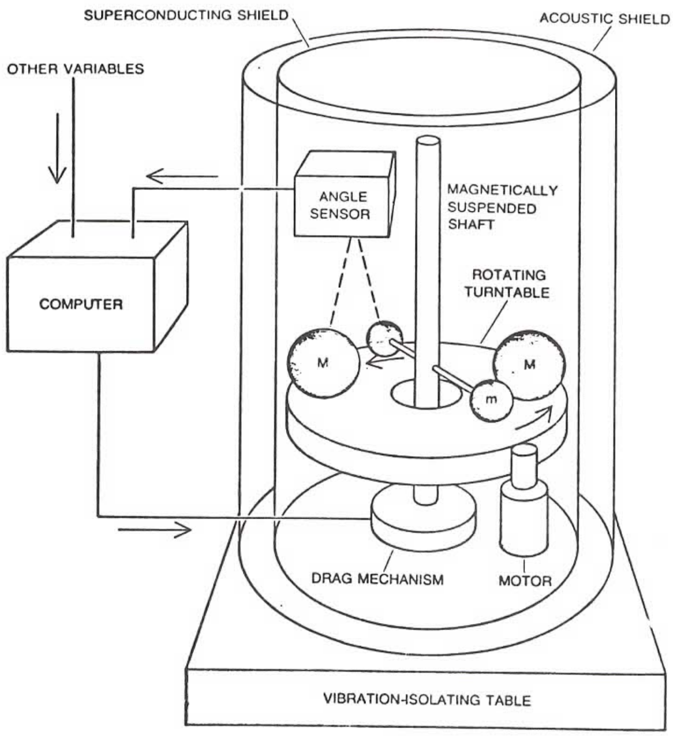

Figure 4. Simplified schematic drawing of method of rotating torsion balance measurement of time rate of change of G. Actual design had symmetrized small mass system with 8 equal masses.

2) "multiplicative", proportional to where matter already exists, and 3) in special places.

In the first category, it would imply a creation rate of ~ 10^{68} baryons per year, assuming there are 10^{78} baryons in our accessible universe out to the event horizon. Since this has a volume ~ 10^{81}-10^{82} cm^3, it would on the average be a rate of 10^{-13}-10^{-14} baryons/cc per year. Put another way, if our universe has a mean density of ~ 10^{-29}g/cc (assuming we will find the "missing mass"), then this scheme would have 10^{-40} g/cc created uniformly throughout the universe each year, or 10^{-47} g/cc each second.

The multiplicative category is the basis for this experiment. Each year would find a rotor increasing in mass by 10^{-10}, and its moment of inertia correspondingly. Searches in old crystals for such added matter have had controversial interpretation, and in fact there have been very few matter creation tests at all[27]. One clever test, by Cohen and King[29], sets a limit ~ 10^5 of the Dirac rate for the observation of hydrogen production in an evacuated pool of mercury.

Thus, proton creation in mercury, and presumably in other materials except possibly hydrogen, is ruled out in the multiplicative process.

What is needed, however, is a more general test. The spindown of an inertial rotor[27,30] is one such test. If sufficiently protected against conventional drag and disturbance mechanisms, it could exhibit a drag due to $\dot{I} \sim 10^{-10}$ I yr^{-1}, where I is the moment of inertia. The differential equations for such a system, with corotation protection, have been worked out[27], and give the result that a rotor would lag by an angle

$$\Delta \approx \frac{1}{2} \dot{I}/I \; \omega t^2, \qquad (6)$$

due to this drag in an observation time t. If $\dot{I}/I = 10^{-10}$ yr^{-1} = 3×10^{-18} s and $\omega \approx 10$ rad/s, then $\Delta \approx 1.5 \times 10^{-5}$ rad in 10^6 s (~ 12 days). This is easy to measure, if not masked by other disturbances. The central problem is in removing these and other drag mechanisms.

Our experiment for $\dot{m}$ is shown in Fig. 7-9 of ref. 5 of these proceedings. That Fig. 7 is reproduced here for reference, in slightly different form, as Fig. 5.

This employs our first scheme for corotation, (Fig. 1) in which the gas is corotated inside an outer cylinder which is going at a constant speed, phase-locked to a cesium-beam clock. The motor actually has temporary poles written on a stainless steel strip by the drive signal in the stator, and hence the phase lock is not absolute without period integration and control. In this scheme the signal from the motor period timer is continually added and then compared with the clock signal.

Since this motor-clock drive combination has potential for other precision uses it might well be worth a very sophisticated computer control means. We have devised several of these in principle, but it would be well to have short-term control as well as the overall phase lock mentioned above. This requires continuous position sensing of the motor and it has been very difficult at the level of accuracy of interest. Methods involving precision encoders and homodyne laser sensing have been tested and were not accurate enough.

A new method employing signals from rotational inertial sensing by piezo stacks has been built. Fig. 6 shows one of three pairs of piezo stacks on a rough, ball-bearing test turntable driven by a stepping motor. The two stacks are connected in opposition so vertical signals subtract but horizontal (tangential) signals add. The signals feed a high impedance preamplifier which rotates and its output is telemetered by FM conversion and a led transmitter to an optical receiver on the axis. This system has not yet been tested.

The method I corotation tests have exhibited features that might have been expected, at least in gross nature. An apparent torsional coupling to the inner rotor exists, which causes it to oscillate in the

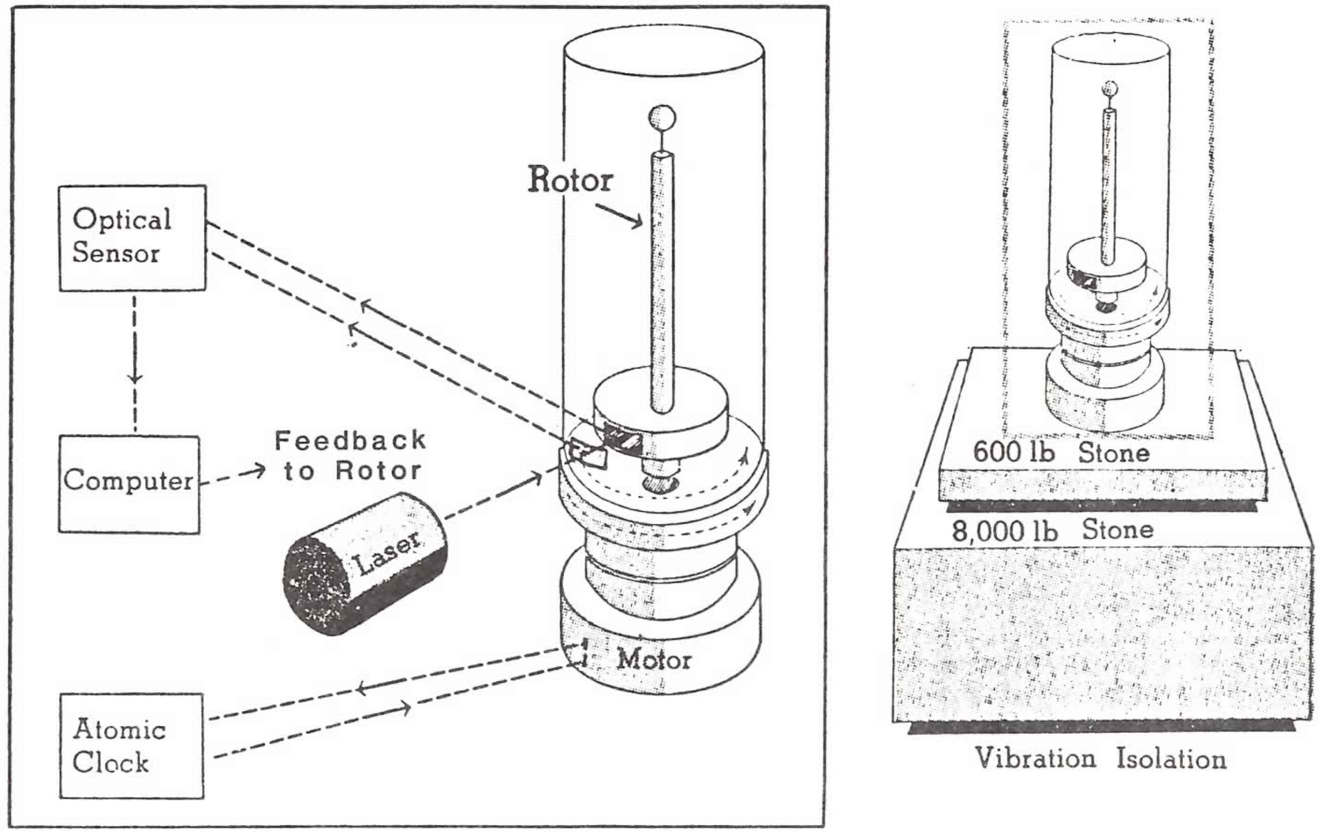

Figure 5. Schematic diagram of dynamic matter creation test involving spindown of precision rotor. At right, vibration isolation system.

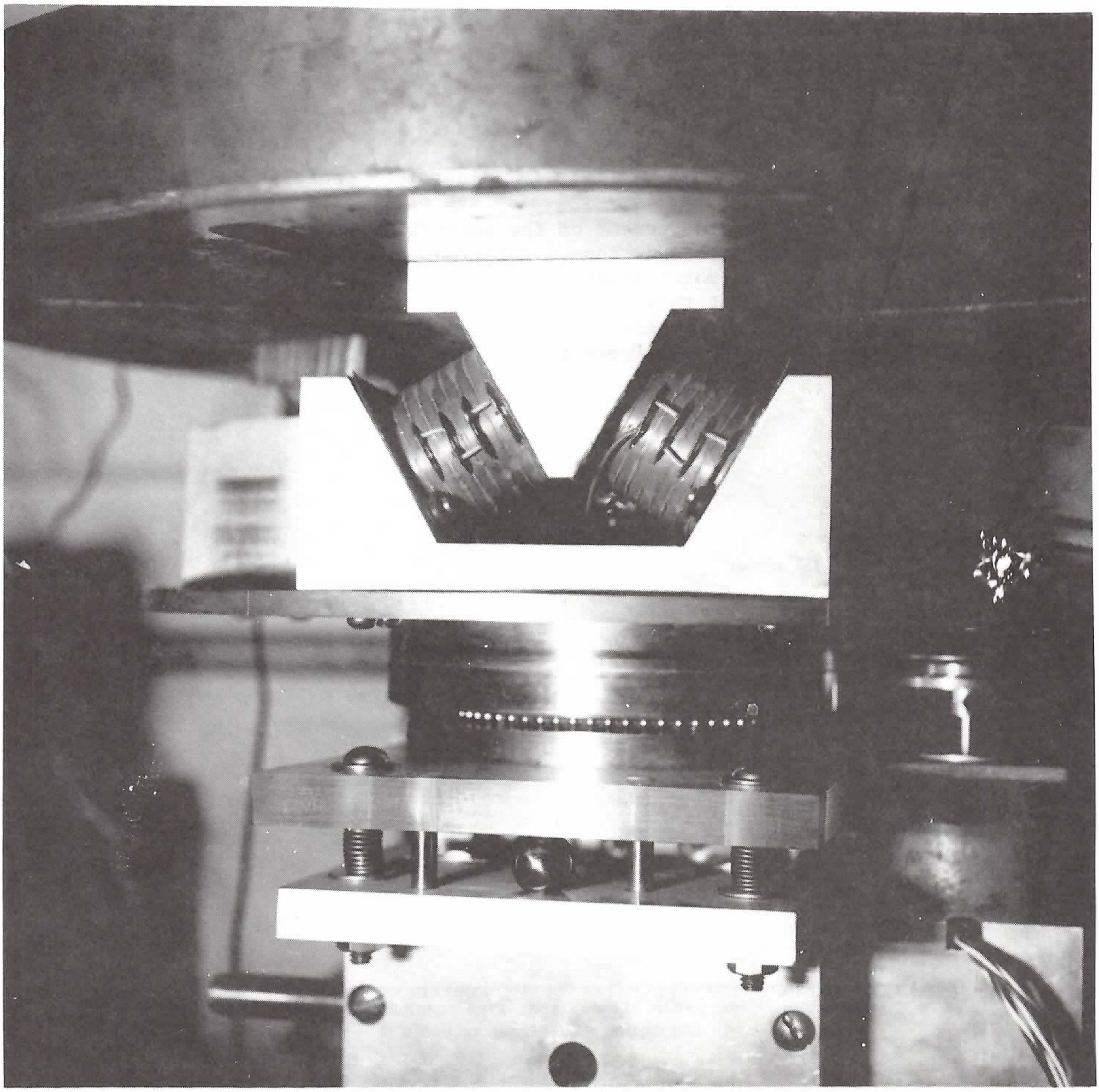

Figure 6. Test setup with piezo sensor for measuring instantaneous angular velocity of motor. See text for details of operation.

rotating frame.[14] Fig. 7 depicts the appearance of these oscillations in measurement of the rotor period. If the rotor period is T_o, the oscillation period is T_{os}, and the amplitude of oscillation is δT_R, it can easily be shown that the angle of amplitude oscillation with respect to an ideal rotation frame is

$$\delta\Delta_R = \frac{T_{os}\, T_R}{T_o^{\,2}} \quad . \tag{7}$$

This approximation is quite accurate for sinusoidal oscillations below 50° oscillation amplitude. Thus, we typically see oscillations of ~30 minute period and an amplitude dependent on the initial conditions (i.e. when the rotor falls into synchronous rotation with the outer cylinder). By manipulation of the motor speed we can pump the oscillation to a small initial value, but this grows to ~ 0.5° in a few hours. Whether this residual rotational "noise level" is due to excitation in the rotating frame or in the lab frame is still in question.

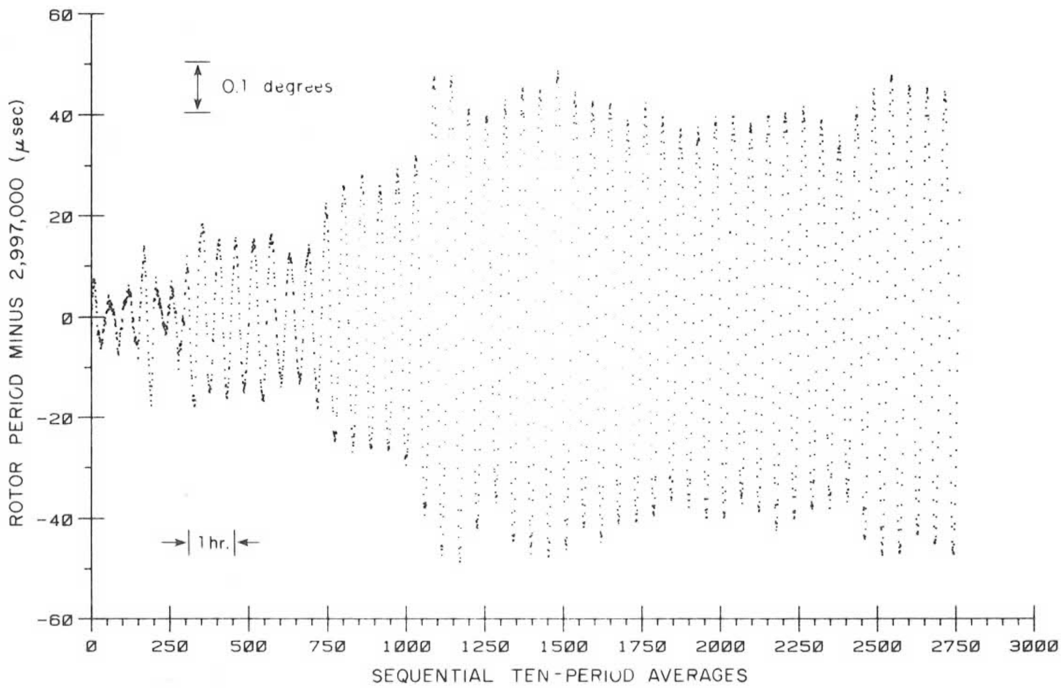

Figure 7. Oscillation periods of rotor in corotation showing tendency to build up to ~ 0.5° swings.

The above picture is oversimplified[14]. The period measurements of $\delta\Delta_R$ are in fact essentially the derivative of the position measurements. We usually use a coordinate system[27] in which Δ_R is the instantaneous departure of a fiducial point on the rotor from an ideal corotating reference frame. This can be measured by the difference between that timing signal and its counterpart coming from the cesium clock.

In practice we have measured differences between the rotor point and a point on the outer cylinder. This means that motor drift must now be accounted for[14]. In cases thus far this motor drift has been much smaller than rotor drift and was not yet a problem. Figure 8 shows a run with simultaneous measurement of the rotor-motor difference and of the motor-ideal difference. Slight drift of the motor is evident at one point, and is often seen in other runs.

The excess rotor drift in Fig. 8 is slight, in the scale shown, less than 0.4° in 10^5s. (This is nonetheless huge on the scale of our goal). By enclosing the experiment in a thermal and acoustic box, heating caused angle shifts up to ~ 0.5°, which could be correlated with suspension current shifts corresponding to height changes ~ 10 μm. We are further stabilizing the suspension but the potential advantage of a superconducting passive suspension in these respects is obvious.

The effectiveness of the gas drag reduction by corotation has been tested.[14] The differential equation for corotation[27] can be written in a way exhibiting dependence on the two coordinates (laboratory, θ, and rotating, Δ) as

$$I\ddot{\theta} + \mathring{I}\dot{\theta} + \alpha\dot{\theta} + \beta\dot{\Delta} + C\Delta = \Gamma(t), \quad (8)$$

where $\Delta = \theta - \omega_o t$ if ω_o is the constant angular velocity of the ideal rotating coordinate system. Clearly, in this formulation α is a drag coefficient in the laboratory frame, e.g. suspension drag, interaction with laboratory magnetic fields, etc. This is termed in an overall way as "bearing drag". The coefficient β signifies drag with respect to the rotating frame and is termed "gas drag". The two time constants are

$$\tau_b{}^* = I/\alpha, \quad (9)$$

and

$$\tau_g{}^* = I/\beta, \quad (10)$$

respectively.

The torsion coefficient, C, acts in the rotor frame, and whatever its origin can be used to model the oscillations described above. External torques, e.g. noise, are included in Γ(t).

For tests of corotation effectiveness we did a series of runs in which the rotor was at a given angular velocity ω_R and the motor driving the outer cylinder (and gas) was set at a variety of angular velocities, ω_o, in the same, and opposing directions. In the derivations and

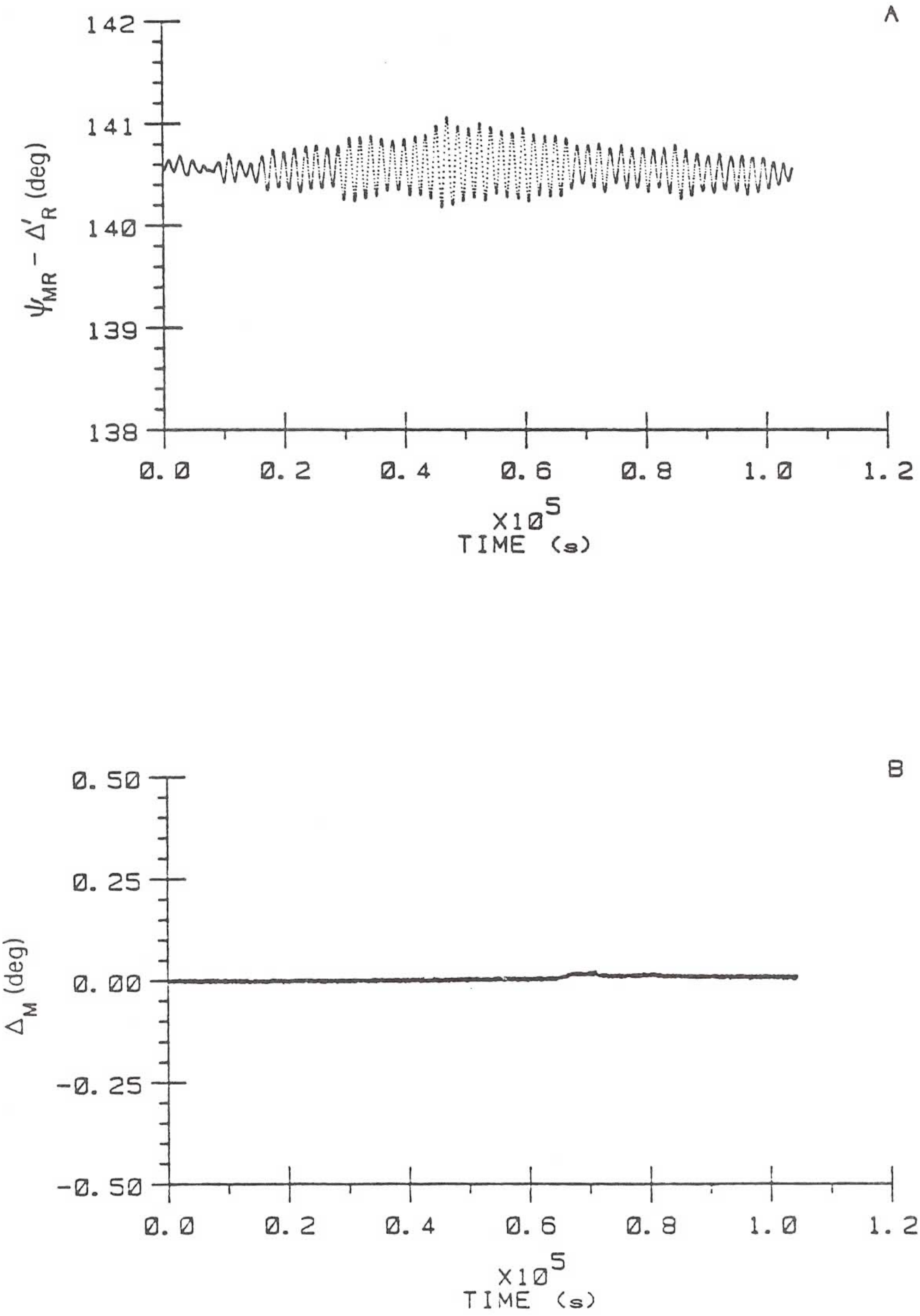

Figure 8. Corotation runs with angle departures from synchronous measured directly. A-rotor; B-motor. See text for discussion,

experiments which show how the gas drag is related to pressure and rotation, motion was always previously taken relative to a static laboratory frame. It can easily be shown that the relative velocity of the rotor and gas are what should be used and can replace the formly absolute ω in those derivations.

We summarize the overall situation, with this understanding included, for analysis of the tests as follows. The noise torque $\Gamma(t)$, torsion torque $C\Delta$, and moment of inertia change torque $\dot{I}\dot{\Delta}$ can reasonably be ignored on the basis of their sizes and the duration of these tests. Then

$$I\ddot{\Delta} + \alpha\dot{\theta}_R + \beta\dot{\Delta} = 0, \tag{11}$$

is the appropriate equation, where θ has been explicitly written as θ_R. Then $\dot{\Delta} = \dot{\theta}_R - \omega_o = \omega_R - \omega_o$, and $\ddot{\Delta} = \dot{\omega}_R$, so that the equation becomes,

$$\dot{\omega}_R + \frac{\alpha}{I}\,\omega_R + \frac{\beta}{I}\,(\omega_R - \omega_o) = 0. \tag{12}$$

With manipulation this is

$$\dot{\omega}_R = \frac{\omega_o}{\tau_g{}^*} - \left(\frac{1}{\tau_b{}^*} + \frac{1}{\tau_g{}^*}\right)\omega_R = a + b\omega_R. \tag{13}$$

Further manipulation and integration[14] leads to

$$-\frac{1}{\tau^*} = \frac{1}{\tau_g{}^*}\,\frac{(\omega_R - \omega_o)}{\omega_R} - \frac{1}{\tau_b{}^*}, \tag{14}$$

or

$$\frac{1}{\tau^*} = \left(\frac{T_o - T_R}{T_o}\right)\frac{1}{\tau_g{}^*} + \frac{1}{\tau_b{}^*}, \tag{15}$$

where T_o and T_R are the periods of the motor and rotor, respectively and τ^* is the observed decay time, $-\,\omega_R/\dot{\omega}_R$. This is of the form

$$y = mx + d, \tag{16}$$

where $x = (T_o - T_R)/T_o$ is the variable associated with setting the motor period.

Fig. 9 shows the results of two such test series at different time, called A and B. Points 1A and 1B are special ones corresponding to $T_o = \infty$, i.e. no corotation. The values of y are below the lines, signifying a higher decay time in this case. The presumption can be that other points have increased rotor drag from the small suspension bounce observed as synchronous current fluctuations when the outer cylinder rotates. This "excess drag" can be calculated from the difference but is not of interest here.

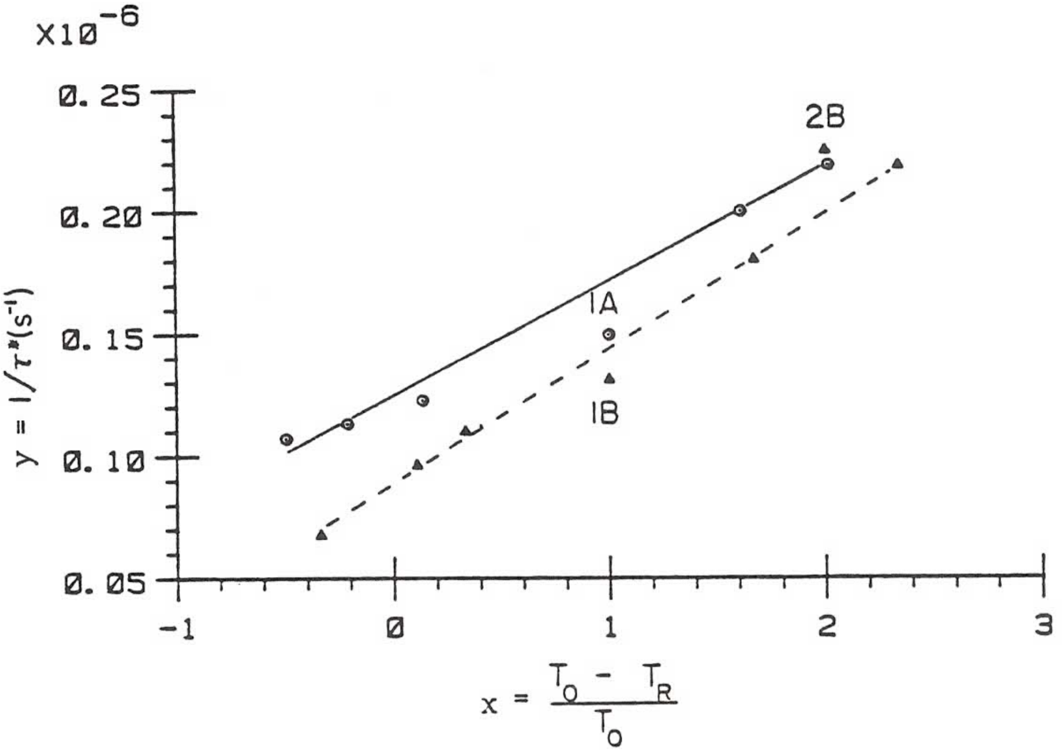

Figure 9. Decay time data plotted in the form of y = mx + d with $y = 1/\tau^*$, the measured decay time, $m = 1/\tau_g{}^*$, decay time due to gas friction, $d = 1/\tau_b{}^*$, decay time due to bearing friction, and $x = (T_0 - T_R)/T_0$. Run A is denoted by 0 and Run B by Δ. See text for derivation of linear equations and explanation of points 1A, 1B and 2B.

Point 2B (the triangle) is for $T_o = -T_R$, i.e. counter-rotation at synchronous speed. (The circle of run A in that vicinity was not actually at this "counter-synchronous" speed.) The high value of y at that point, meaning a decreased τ*, further suggests the notion of excess drag due, in this case, to increased synchronous suspension bounce.

The slopes of the curves are the reciprocal of the time constant due to gas drag, $\tau_g{}^*$. These can be compared with the theoretical value expected for gas drag[1,11]. For our rotor this is about

$$\tau_{gc}{}^* = 59/P, \qquad (17)$$

where P is the pressure in torr. We believe the error in pressure measurement and in the number 59 (related to rotor geometry) to be roughly 30%. The following table lists the results.

Table I

	$\tau_g^* \times 10^{-6}$, s	$\tau_{gc}^* \times 10^{-6}$, s	$\tau_b^* \times 10^{-6}$, s
Run A	22	15	10
Run B	18	11	13

The τ_b^* values listed have been corrected for excess drag from corotation bounce which can be removed. We see that even so, the bearing drag exceeds gas drag in these particular conditions. We have since greatly reduced the bearing drag by adding Helmholtz coils to cancel local non-suspension magnetic fields. With only slight care these can be "tuned" so that the total measured decay time is greater than τ_{gc}^*. Hence τ_b^* must be very small. The above tests for separating τ_g^* and τ_b^* are rather difficult, and have not yet been repeated.

Within the limits of accuracy of the tests it is seen that the notion of gas drag depending linearly on relative velocity of the rotor and gas is supported completely. Whether new effects occur at much longer overall decay times is yet to be seen, when bearing problems are more completely in hand.

VI. Rotational Inertial Clock

The use of an inertial clock for gravitational redshift comparisons has been discussed at length[2,31,32]. And the operation of a servoed version of a protected rotor acting in this fashion has been described elsewhere in this symposium.[2,5] The present discussion will concentrate on the features of such a system which may have intrinsic advantages in the pursuit of more precise rotations.

Servoed corotation offers additional control of the differential equation of motion (8). A passive corotation system such as the Matter Creation Experiment, method I, offers no way to cope with unwanted torques except by their reduction. The magnitude of the torque $C\Delta$, leading to oscillations for example, has been estimated[27] to be limited ultimately to no less than $10^{-13}\Delta$ dyne-cm from gravitational coupling of the rotor to outer cylinder due to machining accuracy limits even if all other couplings, e.g. magnetic and electrostatic, could be eliminated. For very small Δ this is sufficiently small, but the achievement of that as an initial condition and maintenance of it with a passive system are totally unstudied matters. In view of the above findings they are likely to prove exceedingly difficult.

A servoed system can, however, modify the equation[33] by adding controllable proportional, derivative and integral terms, acting on Δ. Even much more sophisticated approaches than that are possible with computer control. In practical terms, it is easy to see how a computer control can drive the outer, "shroud" rotor into synchronism with the inner, "proof" rotor. It can center the effective well (i.e. angular potential leading to C) in short times due to the feedback properties, and then adjust its own proprotional and other feedback factors appropriately, for example to cancel C, or most of it.

A number of other potential advantages, e.g. the added smoothness of double magnetic suspension, are just beginning to be tested and we look forward with considerable interest how these will affect the potential of precision rotations.

At the same time the intrinsic needs of the inertial clock are being considered. Even if the rotor clock achieves sufficient stability, say 10^{-15}, its use for gravitational red shift comparisons or other comparable experiments put certain demands on its interrogation. If daily variations are to be observed at this level, we must find ways to subdivide each rotation, say 10^{-5} of a day, into the 10^{10} parts needed for observing 10^{-15}. Vernier optical effects offer some hope, but are just now being considered in detail.

Conclusion

A series of precision experiments over the years, many but not all involving rotations, have been designed and worked on at the University of Virginia. Among other things they have led to increasing understanding of the behavior of precision rotors. Several clever experiments by Beams, and several recent experiments with rotors have marked particular efforts in this direction. A number of new effects have been observed and studied in this field, which has a remarkably sparse open literature. With what is found in the present two experiments, it is hoped that the technology can be sufficiently advanced that many other experiments that can be conceived will be feasible.

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