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PHOTOMECHANICAL LASER POWER MEASUREMENTS WITH MAGNETICALLY SUSPENDED ROTORS

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Magnetically suspended rotors with virtually no frictional losses could be useful for making high accuracy measurements of laser power. Two different approaches to this problem have been studied. The first involves measurement of the acceleration or deceleration of a spinning rotor due to the application of radiation pressure at its periphery. In the second, either the angle of deflection or the time of swing of a magnetically suspended torsion pendulum is measured as a function of the laser power. Preliminary experimental arrangements for both methods have been devised and are discussed here.

1. Introduction

As one of a series of experiments begun in 1947, Professor J. W. Beams of the University of Virginia Department of Physics focussed the beam of a 100 W arc lamp into a small spot on the periphery of a tiny magnetically suspended rotor. He found that the rotor, a 1.6 mm diameter steel ball bearing, could be made to accelerate or decelerate while levitated inside its vacuum chamber. This dramatic exhibition of the admittedly small yet non-negligible mechanical force that a light beam exerts caused him to note[1] that »...it might be possible to obtain a precise measure of the pressure of light...« with an apparatus such as he constructed.

This paper describes two types of *photomechanical* apparatus which have as their goal the eventual achievement of a one order of magnitude improvement in the precision of absolute laser power measurements. Such measurements are now made at the 10^{-3} to 10^{-4} level by beam calorimetry methods. Both new systems rely on the unusually high sensitivities of magnetically suspended bodies, specifically their sensitivity to mechanical disturbance.

After a brief review of the properties of magnetic suspension systems and an overvicw of the work of others, the techniques mentioned above will be discussed in detail and their state of development reported.

2. *Background*

A magnetically suspended body is one that is freely levitated in space by means of a servoed magnetic field. The obvious advantage of suspending a test mass in this way (as opposed to suspension by a quartz fiber, for instance) is that the suspended body is totally free of mechanical contact with its surroundings, except for atmospheric couplings which can be made extremely small.

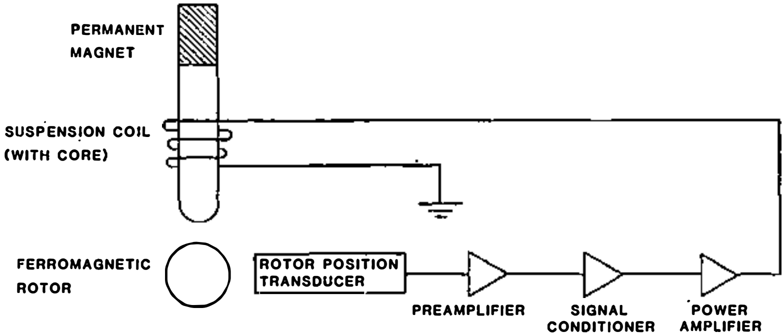

Fig. 1. The vertical position of the levitated rotor is controlled by the electronic feedback system which regulates the coil current. The permanent magnet provides a static lifting force; the electromagnet is used only to stabilize the rotor's height.

The operational diagram for such a suspension is shown in Fig. 1. The transducer converts the rotor motion into an electrical signal. The electrical signal is differentiated and amplified, then fedback to the electromagnet's coil. The magnetic lifting force produced by the coil is always just large enough to exactly offset the gravitational force of the earth. The net result is a stable balance of forces which keeps the body fixed in space at an adjustable position below the coil's pole place. A thorough discussion of the electro/magnetomechanics of such a system, as well as representative data for a simple optically sensed suspension are given elsewhere[2)].

Magnetic suspension systems are becoming more and more useful in a variety of industrial, aerospace and laboratory applications. These include high precision inertial guidance systems[3)], the Space Shuttle annular suspension and pointing system[4)], and the new spinning rotor friction gauges now used as gas pressure transfer standards[5)].

For use in laser power measurements, two properties of such suspensions are of particular interest: A suspended body set in free rotation has a very low background torque acting on it; and a suspended body undergoing small-angle oscillations about some zero-point has a very low restoring torque constant.

In the first case, this means that a torque-free rotor, protected from other forces, can be accelerated or decelerated by the pressure wave of a light beam, as demonstrated by Beams$^{1)}$. In the second case, this means that either the deflection angle or the period of a magnetically suspended torsion oscillator can be changed by the pressure wave of the incident light.

Both techniques can lead, ultimately, to an absolute measurement of the incident light beam's power, but at the present time, it is not clear which will be the most accurate.

A third alternative exists, and that is the production of torque on the rotor by the application of circularly or elliptically polarized light on the body's axis of rotation. The first observation of such an effect was made by R. A. Beth$^{6)}$ in 1936. A thorough discussion of the electromagnetic principles underlying the mechanism of this photomechanical torque transfer method has been published by Marston and Crichton$^{7)}$.

This last technique was not pursued in these efforts, however, since it depends on a much weaker phenomenon which has no macroscopic lever arm as in the other two cases.

The new techniques discussed in this paper have several distinct advantages over the existing photomechanical methods (see Refs. 16—18 below). The existing methods are based largely on the torsion pendulum principle, i. e., a balance beam suspended by a thin fiber which twists under the influence of incident light. Such methods are prone to several kinds of instrumentational drifts and all of these affect both the absolute accuracy and the precision (or repeatability) of the measurement. For example, the restoring torque constant of the fiber depends on its mechanical load in nonlinear and nonrepeatable ways. This leads to work hardenig of the fiber material and the resulting sensitivity shifts that constitute a well known source of error in torsion pendulum experiments. With a magnetic suspension system, the fiber is replaced by a magnetic field whose properties can be very precisely controlled by magnetomechanical feedback, as shown below. The feedback makes it possible to cancel out the various baseline drifts in the measurement, particularly when synchronous detection is used. Another advantage arises in that the size of the torsion constant can be adjusted by varying the gain, offset and corner frequency controls of the magnetic suspension system. This leads to a balance design having an appreciable amount of dynamic range. Additional advantages of magnetic suspension include its ability to support balance beams or rotors weighing anywhere from less than a gram to several kilograms, the relative ease with which the torsional couples of such suspensions can be calibrated, and their exellent vertical and rotational stabilities.

3. Operating principles of a spinning rotor power gauge

In Fig. 2 we see levitated a small steel cylinder. If it were painted with a totally absorbing coating and magnetically suspended a few millimeters beneath the pole piece of the suspension electromagnet, it could be used as a detector in a laser power measurement scheme as follows.

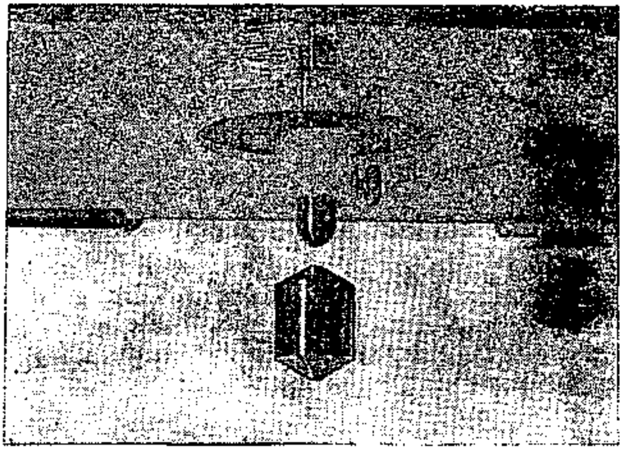

Fig. 2. A magnetically suspended cylinder shown floating stably a few millimeters below the coil's core.

If a beam of light strikes the absorptive surface of the rotor tangentially, each photon transfers linear momentum to the rotor about the axis of rotation. In such a scenario, the angular momentum of the rotor would then increase following the grazing incidence collision of each photon with the rotor. The time rate of change of the angular momentum during illumination is given by the product of the angular momentum itself times the photon flux rate. Integrating this quantity over the time interval required for the rotor to accelerate from rest to its maximum angular speed yields the following statement of the incident light power:

$$P = \frac{I c \omega}{r (\Delta t)}, \tag{1}$$

where P = laser power
I = moment of inertia of the rotor
c = speed of light
ω = angular speed of rotor
r = radius of rotor
Δt = time interval over which rotor accelerates to angular speed ω.

Clearly, the measurement of ω and Δt are time-based measurements, just as the measurements of I and r are length and mass based measurements, all of which can be made in terms of primary standards. The constant c is a fundamental constant of a well-known value. Therefore, we indeed have a new way of making absolute laser power measurements.

Two troublesome points, however, are the following: The quantity $\mathrm{d}N/\mathrm{d}t$ fluctuates. In addition to the random, statistical $\sqrt{N}$ fluctuations in output photon density, a variety of other much larger effects also cause drifts and fluctuations. Secondly, moments of inertia can sometimes be difficult to measure absolutely with high precision; although the seriousness of this problem depends on the rotor geometry and fabrication technique.

In order to judge the sensitivity and feasibility of this method, let us evaluate Eq. (1) for a particular example. Suppose our rotor is made of magnetically soft steel with a radius of 2 mm and a length of 5 mm, and that our averaging time is 100 s. Given this, we can rewrite Eq. (1) as

$$P \approx 1.4\,\omega\ \mathrm{W}. \tag{2}$$

This means that a laser whose output power was known to be, say, 100 mW would drive the rotor to 0.07 rad $\cdot$ s^{-1} or in this case a tangential linear speed of $v \approx 0.15$ mm $\cdot$ s^{-1} after 100 s.

The standard technique for monitoring the angular speed of small rotors has been to observe the scratch pattern (via reflected light) with a photomultiplier. This technique is usually useful only at high rotation rates, however, and m ight be totally invalid here since one want little or no other light falling asymmetrically on the rotor and driving it. Therefore, for low power lasers optical homodyne techniques, for instance, might be needed.

For the example given above, one would need a rotor speed resolution of ≈ 0.1 μm $\cdot$ s^{-1} in order to measure P to 10^{-3}. Obviously, this requirement becomes far less stringent at much higher laser powers. Also, as the laser power increases, the rotor size can be increased as well, with the advantage that at rotor radii of about 5 mm, it becomes possible to produce high resolution encodings on the rotor periphery, thereby facilitating angular speed readout.

In summary, while a workable scheme in principle at the low power ranges, this technique appcars to offer greatest promise in the range above 1 W, where the rotor can be driven to relatively large speeds in short times. Some competing effects and background disturbances will be mentioned later, and a thorough discussion of them is available elsewhere$^{8)}$.

4. Operating principles for an oscillating rotor power gauge

The idea of using a torsion oscillator as a laser power gauge is, of course, not new. The earliest work on such devices was reported by Neher$^{9)}$ and shortly thereafter by Cook, Flowers and Arnold$^{10)}$. Based on their calculation and preliminary experiments, Stimler, Slawsky and Grantham$^{11,12)}$ built a torsion pendulum photometer with a sensitivity of 2.55 ± 0.04 cm $\cdot$ J^{-1}. Braginsky, Minakova and Stepunin$^{13)}$ and Kokodii and Valitov$^{14)}$ were also investigating mechnical photometers at about this time. All of the above instruments were primarily intended for use with high energy pulsed laser beams. Pelepelina and Fedyushin$^{15)}$ have published a detailed error analysis of such instruments. More recently, Aida and Bouzidi$^{16)}$ and Roosen and Imbert$^{17,18)}$ have developed similar systems for use with cw lasers. Both groups of authors have derived the relationship between laser output power and mirror motion for their systems as a function of their various experimental parameters. Aida and Bouzidi claim that the useful range of their system is from 1 mW to 300 W (or more), while Roosen and Imbert have optimized their system for the power range of 1.0 to 10 W. They did this by using a stiffer torsion fiber than Aida and Bouzidi.

The principle of operation of torsion photometers is straightforward and the reader is referred to the earlier papers[16,17,18)] for the mathematical details. The method is as follows. A light ray is incident upon a mirror mounted on a balance beam which is supported horizontally by a slender fiber, usually about 10 μm in diameter and on the order of 0.5 m long. The radiation pressure produces a force that torques the system and causes a rotation through some angle which is then measured. This measured deflection angle is used, along with other system dependent parameters, to compute the laser output power.

The dependence of the laser power on the deflection angle, Θ, is given by

$$P = \frac{c\,C\,\Theta}{2r} \tag{3}$$

where P and c are defined as in Eq. (1) and

C = torsional restoring torque constant of the fiber
r = half the beam length.

In developing this expression, we assume only that the balance starts from its rest position, i. e., $\Theta = 0$, and that the laser beam is reflected backward with no loss of power.

Variations on this method, such as repeatedly illuminating the mirror over only fractions of its oscillation cycle, permit a dynamic rather than static measurement since the oscillator period is now changed. This means that some of the uncertainties associated with pure dc measurements (like baseline drift) can be reduced.

There are at least two alternative approaches to making dynamic measurements of the type mentioned above. In the first, the laser is used to synchronously pump the balance beam at its resonance frequency. This is accomplished by using a shutter to permit the illumination and the subsequent acceleration of the balance beam over a full half cycle of its swing. If the balance beam is initially at rest but develops a displacement which grows to some peak value, then the associated peak value of the laser power will be given by

$$P_{PK} = \frac{c\,I\,\omega_0^2\,\Theta_{PK}}{2r} \tag{4}$$

where

ω_0 = resonance frequency of the balance
Θ_{PK} = peak amplitude of motion.

A second dynamic approach to this problem involves timing the period of oscillation and the angular acceleration of the balance beam with and without laser illumination. In practice, it is difficult to determine the angular accelerations of a spinning body with high precision, so the second dynamic technique may not be as generally useful as the first.

By using a cleverly designed mechanism to shift the rotation axis of the balance beam a known distance with respect to its initial position, Roosen and Imbert are able to eliminate the need for measuring the oscillator's mechanical lever arm. This is important since the spatial distribution of the beam's energy on the target (the mirror) is not pointlike (unless very carefully focussed) and often consists of a complicated structure, as shown in Fig. 3. Without their technique, an absolute measurement of the distance between the beam-spot »centroid« and the axis of rotation can otherwise be made to perhaps only 1% thereby limiting the power measurement accuracy at the same level. Their technique also cancels out the uncertainty due to residual absorption by the mirrors of a small amount of the laser's radiant energy.

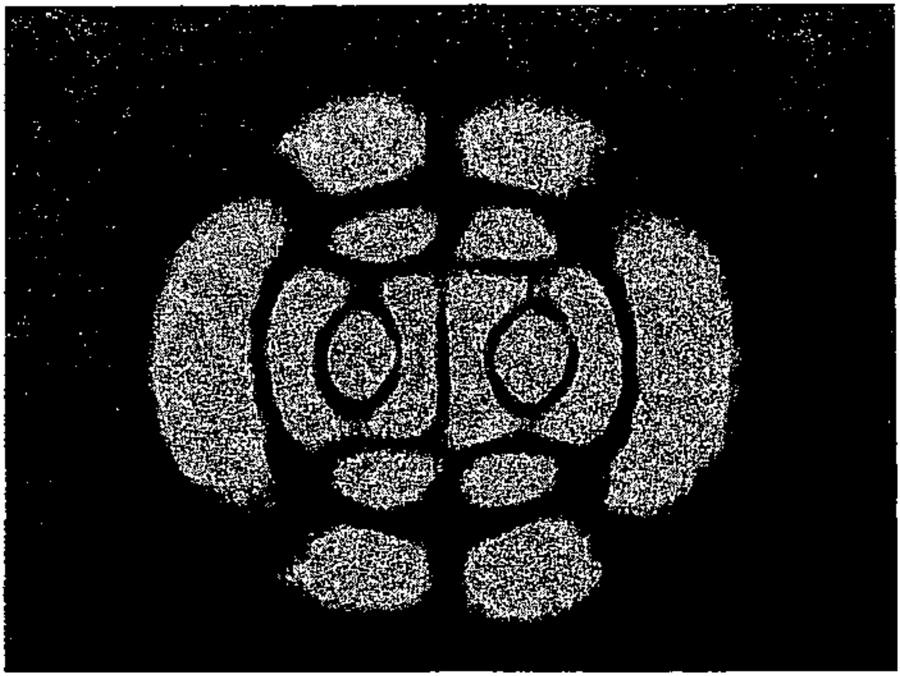

Fig. 3. The cross section of a multi-mode HeNe laser beam.

Ultimately, however, one is limited in both sensitivity and precision by the properties of the fiber. It is well known that the restoring torque constant of the fiber used in a torsion oscillator (whether it is made of quartz, tungsten, or some other material) is a function of time and load[19]. Drifts in the zero-point of the suspension also occur, although usually at rates quite slow compared with typical laser power measurement integration times.

An alternative to the fiber suspension is the magnetic suspension, and Fig. 4 shows such a system in operation. The magnetic field replaces the fiber, but the restoring torque constant for the system can still be modelled by the classical equation

$$C = I \left(\frac{2\pi}{T} \right)^2 \ \mathrm{N \cdot m \cdot rad^{-1}}. \tag{5}$$

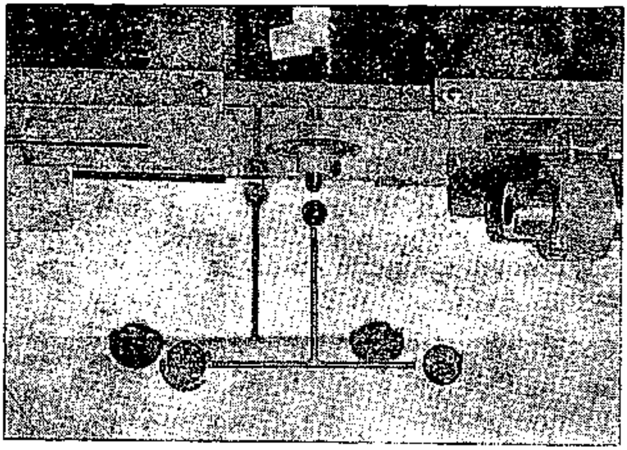

Fig. 4. The rotor used in the torsion oscillator technique is shown here, in suspension, with the mirrors in place.

Here, the parameter C and the other symbols in this equation play the same roles as they do in Eqs. (3) and (4) above.

The torsional restoring force acting on the beam is, ideally, given by the product of the torsional restoring constant, C, and the angular deflection of the beam from its equilibrium position. The constant C represents the second derivative with respect to angle of the mechanical potential well in which the balance beam finds itself. As such, the stability of its absolute value is very much dependent on how well behaved the potential itself is. Therefore, if there are extraneous dynamic effects which act on the balance in such a way as to mimic a variation in the size of the potential, then there will be a resulting variation in its curvature which manifests itself as a variation in the measured values of C. This problem applies to torsion balances suspended by either a material fiber or by a magnetic field.

Further analysis reveals an intrinsic advantage of the magnetic suspension over any material fiber, be it tungsten, quartz, or anything else. This is as follows. Although C can be found by studying the dynamical behaviour of the balance beam, as exhibited in Eq. (5), it can also be uniquely determined directly from the properties of the fiber itself. The appropriate expression is

$$C = \frac{\pi}{2}\left(\frac{G}{L}\right) r^4 \tag{6}$$

where

G = modulus of rigidity of the fiber's material

L = length of the fiber

r = radius of the fiber.

There is no way to guarantee in the manufacturing process that the value of G will remain constant over the length of the fiber. For instance, dislocations in the material might create highly localized points about which the torsion constant essentially vanishes. Moreover, C depends on the fourth power of the radius of the fiber, so even very small variations in r over the length of the fiber will result in very large variations in C. Fortunately, the character of C in a magnetic suspension is quite different. It is dependent on more easily controlled variables like the servo coil's current and the shape of the coil core's pole piece. Whatever variations in C magnetic suspensions might have they will most likely be due to microscopic inhomogeneities in the magnetic domain structure of the materials acted on by the magnetic fields.

If the magnetic field produced by the support coil is truly symmetric about the vertical axis (defined by gravity), and if the oscillator's ferromagnetic support slug is free of horizontal magnetic moments, the restoring torque constant can be made arbitrarily small. In practice, the suspension system shown in Fig. 4 has produced values of C as small as 7×10^{-10} N·m·rad^{-1}, which is between 2 and 3 orders of magnitude smaller than that reported by Roosen and Imbert$^{17,18)}$. It is important to note that this measurement was made at air pressure and without any special electrostatic shielding, and that one would expect far lower values of C after adding such shielding to an evacuated system.

The rotor shown in Fig. 4 has the following properties. The total mass is 40.86 g, the distance from the rotation axis to the center of either mirror is 78 mm, and the total moment of inertia is about 10^{-4} kg m^2. The front surface mirrors are aluminum coated glass discs with very high reflectivity in the red part of the visible spectrum. The inverted »*T*« structure is made of stainless steel tubing. The steel ball epoxied to the top of the structure is an unannealled chromium steel ball bearing. The rotor in its present state is inexpensive, and not of high metrological quality, but future versions will be improved as necessary.

In practice, the deflection of the rotor can be measured with any of the standard autocollimator techniques; or if used in the dynamic mode, its oscillation period changes measured with a high resolution digital counter using a fast time base and an appropriate input transducer.

5. *Experimental design considerations*

The biggest problem facing any absolute measurement is the elimination of systematic errors. Repeatibility of the measurement accuracy is an equally major concern. Some of the problems common to both systems will be discussed here, and some tentative solutions for them presented.

A stable magnetic suspension system makes these measurements possible. Several types of high precision suspension systems have been investigated by the author$^{8)}$ and his colleagues$^{20,21)}$ in recent years. Although they all involve active damping mechanisms in the electronic circuitry, the power exchanged between the suspension system and the rotor is (for these purposes) negligibly small. In fact, for certain rotational modes, a purely cylindrical rotor has exhibited a power loss of only 2×10^{-14} W$^{22)}$. This is several orders of magnitude below our target sensitivity. Its moment of inertia was approximately the same as the torsion oscillator rotor shown in Fig. 4. This means that at $\approx$ 1.0 mW power levels, a resolution of $\approx$ 1.0 nW in beam energy, as measured by such a device, would still be several orders of magnitude away from the point where the suspension system itself introduced uncertainties into the measurement.

Several kinds of thermal effects could be troublesome, but careful experimental design and procedure can alleviate them. For instance, thermal expansion or contraction of the rotor material changes the rotor's moment of inertia. This means that low expansion materials must be used whenever possible. If necessary, the rotor's housing can be temperature controlled, too. The radiometric forces are small at low pressures; and, in the case of the spinning rotor experiment, should not contribute any net torques anyway. Thermal noise poses the ultimate limit upon any measurement of this type, of course, but the long observing times used (for either technique) will average down the noise, and thereby increase the signal-to-noise ratio.

One newly discovered thermal effect, the Braginsky Rotational Ponderomotive Instability, competes directly with the signal in the spinning rotor technique. This effect produces a torque on a rotor (one entire half of which is illuminated) caused by the establishment of a temperature gradient in the rotor material[23]. To gain a deeper understanding of this phenomenom, consider the following scenario. Let a freely spinning body have a uniform optical field irradiate it from a direction perpendicular to its axis of rotation. As the body spins, the part of it bathed in light will increase in temperature compared to the part which is dark. The warmer part of the rotor experiences an increase in absorptivity. Therefore, as the warmer side rotates away from the light and into the darkness, there will be slight increase in the moment about the rotational axis acting such as to accelerate the rotor. Braginsky and Manukin[23] have used finite integral transformations to solve the integrodifferential equations for the angular velocity of rotation of a cylinder under the influence of this effect. Their results match well with measurements made on a hollow tin foil cylinder 1.5 cm high and 1 cm in diameter spinning diamagnetically suspended in vacuum. When illuminated with a flux of 500 $\mathrm{mW/cm^2}$, the rotor's angular speed changed by 2.5×10^{-2} rad/s over an averaging time of 1 800 seconds. The theoretical prediction was $\sim 3 \times 10^{-2}$ rad/s.

The photoelectric effect could lead to charging of the rotor surfaces, but coating them with a film whose work function is sufficiently high should eliminate this potential problem. Further, by making the rotor coating conducting, no net electrostatic torque can act on the rotor since large isolated charge distributions in the laboratory cannot couple to it. Strictly speaking, of course, this last statement is true only for rotationally symmetric rotors. For rotationally nonsymmetric rotors, a couple about the axis of rotation can develop and the resulting torques will produce variations in the angular speed or oscillation frequency of the rotor, as the case may be. This underscores the need to take great in care the design and fabrication of the rotor. Furthermore, it also implies that at some level of sensitivity, a Faraday cage may have to be installed around the apparatus to isolate it from any ambient charge distributions.

Previous studies have shown[24] that when rotors made of ferrites are allowed to make contact with the support coil's pole piece (due to suspension failure, for instance), the restoring torque constant for the system changes following the mechanical shock. Recent advances[21,25] in suspension technology have produced standoff mechanisms for ferrite rotors that can prevent this, however.

Many other types of disturbing effects have been investigated by Beams[26]. Estimates of the sizes of the more important disturbing effects which can accelerate or decelerate a rotor are available elsewhere[8].

6. *Experimental arrangement*

A typical[20,22,25] suspension circuit with optical sensing of the rotor height is shown in Fig. 5. A permanent magnet with a high energy product (alnico 9 or the equivalent) is placed above the suspension coil in order to provide most of the magnetic lifting force which supports the rotor. The servo system only supplies small correction currents to the coil thereby avoiding excessive heating. The use of a split diode as the rotor position detector insures adequate common mode rejection of noise and decreases the rotor height dependence on temperature changes of the position detector. The mass that can be supported with this system ranges from a small fraction of a gram to several kilograms. A thorough discussion of the design and operating feature of this suspension system have been published elsewhere[27]. Some of the early tests involving a freely spinning rotor used a single ended photodiode (rather than a split photodiode) as the position sensor. Such a system was, however, far less stable than that using the split-diode.

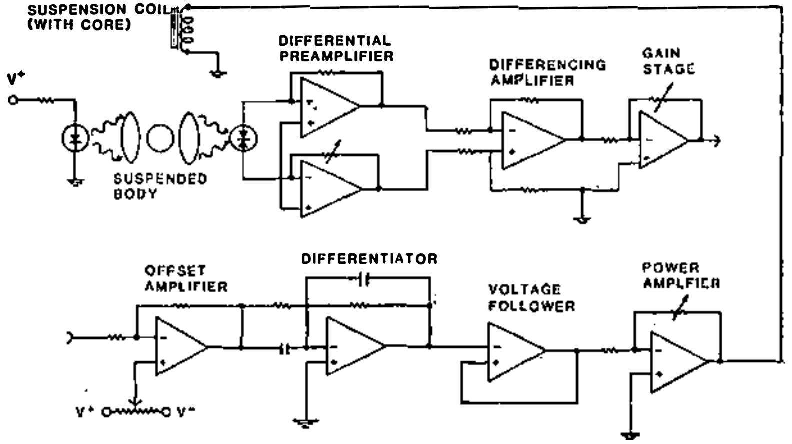

Fig. 5. The circuitry used in these experiments is shown here in detail, including the optical position transducer. The active differentiator damps and stabilizes the vertical motion of the rotor.

7. *Results and discussion*

It has been shown that even relatively massive rotors with small laser drive-torque/drag torque ratio's are sensitive to tangential HeNe laser radiation at the milliwatt level. Changes of up to 3.5% in the angular speed decay time constant of a rotor have been detected, but non-optical systematic effects which might also be operating to produce such changes are not yet fully understood.

Several studies of spin-up from rest of a suspended cylinder at various gas pressures have been done with the recently developed »corotation« system[8,28], but these have all been for purposes of studying the strength of inter-rotor couplings which play important roles in other experiments[29].

Quantitative studies on the spin-up from rest of a laser-driven rotor, i. e., tests of Eq. (1) are yet to be completed.

More substantial progress has been made on the second technique, i. e., the torsion oscillator method. The principle goal so far has been to increase the sensitivity of the measurement by exploring ways in which the restoring torque constant acting on the rotor can be made even smaller.

Table 1 shows a step forward in this area. Steel spheres, similar to those used as support slugs for the torsion oscillator shown in Fig. 4, were put into magnetic suspension in both the annealed and the unannealed states. The heat treatment reduces the size of the permanent magnetic moment in the sphere, thereby, reducing the residual »background« torque that has to be overcome by the laser beam driving the oscillator. The reduction of the background torque is also important when attempting to improve the sensitivity and stability of magnetically suspended spinning rotor temperature gauges[30,31,32].

TABLE 1.

sphere mass g	unannealed sphere torque constant $N \cdot m \cdot rad^{-1}$	annealed sphere torque constant $N \cdot m \cdot rad^{-1}$
3.4	3.5×10^{-9}	7.4×10^{-10}
16.0	7.6×10^{-8}	9.1×10^{-9}

Restoring torque constants acting on magnetically suspended spheres with and without annealing, as measured by application of Eq. (8) to the experimental apparatus.

Absolute mechanical calibration of such a system operated in a feedback mode will be possible. One version of this kind of feedback system under consideration here has one of its mirrors replaced by a conducting disk. This arm of the balance is inserted between the plates of a capacitor which exert an electrostatic force that maintains the balance at a null position. These types of systems further reduce the effects of drift.

Techniques for producting a spatially uniform magnetic field with a gradient just sufficient to insure stable support are also under study, as are investigations into the optimum shape of the rotor. It may be that a rotor with three or more mirror bearing arms each sustaining multipass reflections of the laser beam being measured will provide greater sensitivity and better repeatibility.

Finally, the role of reflections in these experiments must be treated. It is clear that if the laser beam is aimed directly at the mirror in, say the torsion pendulum arrangement, then the reflected beam would fall back upon the incident beam and be at least partially re-reflected by the laser's output mirror. This means that the detector, i. e., the susspended rotor, would in fact be monitoring the power due not only to the primary beam, but also that due to secondary and higher order reflected beams. This problem would be compounded by any additional reflections from beam steering or refractive optical elements between the laser and the detector. In the worst case, at very high laser powers, the reflected beam might damage the laser itself upon reentry into the gain tube or resonant cavity. Fortunately, there are several ways to deal with these problems and still preserve the precision and absolute accuracy of the method. For instance, most commercially available low power lasers produce a polarized beam. By placing a highly transparent and anti-reflection coated polarizing filter (like a thin film pellicle) in the path between the laser and the detector, the reflected beam could not recycle itself back into the apparatus. In the case of unpolarized light, a calibrated semi-reflective pellicle beam splitter might be used to monitor a well-known fraction of the beam's energy which has been redirected perpendicular to the original beam, thereby preventing backreflections from the laser mirrors. Acousto-optic beam deflectors could also be introduced into the measurement to reduce the number of reflective beam steering elements needed in a particular application. Where necessary, Faraday rotation or electro-optic modulation could also be used to extinguish unwanted ghost reflections. In general, unwanted reflections would contribute a systematic error to this mehtod of absolute determination of laser power. The incorporation of one or more of the suggestions listed above will certainly be helpful in reducing the size of such errors. Nevertheless, very careful characterization studies will be necessary to ensure that the effects of any residual or unavoidable beam ghosts are well understood and can be rigorously accounted for as necessary.

8. Conclusions

Although still in their infancy, the techniques discussed above, when fully developed, will provide a new, independent way of making absolute laser power measurements[33]. It will be very interesting to compare them directly with the existing high accuracy beam calorimeters and stabilized solid state detectors.

These magnetic suspension based methods will allow us to make laser power measurements in terms of purely mechanical variables while reducing the problem of drifts which arise in other photomechanical techniques.

The use of magnetic suspension technology will provide the basis for previously unachieved sensitivities and this type of power meter, in either form, should have a relatively long service life.

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FOTOMEHANIČKO MJERENJE LASERSKE SNAGE POMOĆU MAGNETSKI OVJEŠENIH ROTORA

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Magnetski ovješeni rotori sa zanemarivo malim gubicima mogli bi se primijeniti za mjerenje laserske snage visokom točnošću. U ovom radu proučavaju se dva pristupa tom problemu. U prvom mjerilo bi se ubrzanje vrtnje rotora pod djelovanjem radijacijskog tlaka na rub rotora. U drugom pristupu mjerio bi se ravnotežni kut otklona ili vrijeme njihanja magnetski ovješenog torzijskog njihala. Načinjene su prethodne mjerne postave za oba pristupa i u radu se raspravljaju teškoće i mogućnosti predloženh metoda.