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A PROPOSED ROTATIONAL PYROMETER FOR USE IN PRECISION TEMPERATURE MEASUREMENTS

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A rotational pyrometer for high precision relative temperature change measurements is proposed. The system employs a magnetically suspended ferromagnetic sphere as the rotor whose angular speed decay ratio is measured as a function of rotor temperature. Competing effects are discussed, and calculations of the system's predicted sensitivity are given. Preliminary work on a magnetic suspension system for use in this experiment is reported, along with isothermal rotor decay ratio data from a previous experiment. Data on the case of interest, i. e., for a non-isothermal rotor are not yet available and will be presented later.

1. Introduction

Although freely suspended spinning rotor pressure gauges were first developed several years ago[1] and recently proposed for use as pressure transfer standards[2], there has been little parallel work done on the use of such rotors for precision temperature measurements.

The rotational speed constancy of an undriven, rapidly spinning, magnetically suspended rotor is ultimately limited by the stability of its moment of inertia. Therefore, if the rotor diameter varies due to thermal expansion or contraction, its angular speed must vary inversely with that change so as to keep the total rotor angular momentum constant.

The inherent advantage of such a system is that the rotor acts as a »temperature to frequency converter«. This lets us compare temperature, a physical quantity which is relatively difficult to measure with high precision, directly with frequency which we can measure far more precisely than anything else.

This paper describes research into the design and construction of such a »rotational pyrometer«. It was motivated by recent work which adopted the Beams double magnetic suspension[3)] to new areas of precision measurement[4)], and by the thought that there might be better ways to monitor spinning rotor temperatures than those previously developed[5)].

Calculations of the system sensitivity and of the sizes of the competing effects will be given, along with proposed calibration techniques. Details of the magnetic suspension circuitry will be discussed, and typical operating parameters for maintaining stable rotor support will be presented.

2. *Background*

Suppose that we have a magnetically suspended rotor spinning in some thermally conducting fluid in contact with a heat source. Further, let angular momentum be conserved for this torque free spinning rotor. If L is the total rotor angular momentum, then

$$L = I\omega \tag{1}$$

where I is the rotor moment of inertia and ω is its angular speed. Using the fact that L is conserved, we find

$$\frac{\mathrm{d}L}{\mathrm{d}T} = \left(\frac{\mathrm{d}I}{\mathrm{d}T}\right)\omega + \left(\frac{\mathrm{d}\omega}{\mathrm{d}T}\right)I = 0 \tag{2}$$

or

$$\frac{\mathrm{d}I/\mathrm{d}T}{I} = -\frac{\mathrm{d}\omega/\mathrm{d}T}{\omega}. \tag{3}$$

where T is the rotor temperature. For a spherical rotor of mass M and radius R, the moment of inertia is

$$I = \frac{2}{5}MR^2 \tag{4}$$

and

$$\frac{\mathrm{d}I}{\mathrm{d}T} = \frac{4}{5}MR\frac{\mathrm{d}R}{\mathrm{d}T} \tag{5}$$

providing that $\mathrm{d}M/\mathrm{d}T$ vanishes, which for rotors spinning in inert gases is a good approximation. Let R expand linearly with temperature according to the familiar law

$$R(T) = R(1 + aT). \tag{6}$$

Differentiating with respect to temperature, we find

$$\frac{\mathrm{d}R}{\mathrm{d}T} = Ra \tag{7}$$

and

$$\frac{\mathrm{d}I/\mathrm{d}T}{I} = 2a \tag{8}$$

where a is the rotor linear expansion coefficient. Combining (3) and (8) we find

$$\frac{\mathrm{d}\omega}{\omega} = -2a\,\mathrm{d}T \tag{9}$$

where $\mathrm{d}\omega/\omega$ is often called the rotor angular speed decay ratio. Solving for $\mathrm{d}T$, we finally obtain

$$\mathrm{d}T = -\frac{1}{2a}\left(\frac{\mathrm{d}\omega}{\omega}\right). \tag{10}$$

This simple expression states that a knowledge of the rotor thermal expansion coefficient, a, and a measurement of its angular speed decay ratio would be sufficient to establish the rotor temperature change (barring competing effects).

The results of one experiment reported by Beams(6) can, in fact, be interpreted as a verification of Eq. (10). He found that a small steel sphere spinning at 10^6 rotations per second undergoes a speed fluctuation of $\mathrm{d}\omega/\omega \approx 2 \times 10^{-5}\,\mathrm{K}^{-1}$. This implies from (10) a thermal expansion coefficient of $a \approx 10^{-5}\,\mathrm{K}^{-1}$ for his rotor, a typical value for the types of steel he used.

Rotor decay ratios as small as $\mathrm{d}\omega/\omega \approx 5 \times 10^{-10}$ have been reported by Spitzer(7), and electro-optical systems capable of measuring rotor speed drift at the 10^{-10} (and below) level are available(8). So in principle, if a rotor with $a = 10^{-4}\,\mathrm{K}^{-1}$ were used, one could measure a temperature drift of $\mathrm{d}T = 10^{-6}\,\mathrm{K}$; again, providing that the rotor decay ratio depended only on its temperature.

Typical competing effects which would act to change the rotor speed include floor vibrations and seismic noise, atmospheric drag, and eddy current loss mechanisms. Several others are catalogued by Beams(3). The last two mentioned here are of special concern because they can lead to rotor self heating which, if large enough, might mask the rotor decay ratio-signal arising form the real rotor heating source to be studied.

Both effects, however, can be minimized by spinning small rotors at low speeds. Eddy current drag torques have been shown by Fremerey(9) to dominate atmospheric drag torques at pressures below 10^{-7} Pa, but they will still lead to Ohmic heating of the (conducting) rotor. It is possible to suspend a rotor made such that only a few percent of its moment of inertia could sustain eddy currents(10), and Ritter(11) has suggested servoing the position of the magnetic suspension pole piece to compensate for rotor motions which lead to eddy currents. It seems, therefore, that when eddy current losses become a limiting factor, recent advances in magnetic suspension technology could be brought to bear on them.

A rotor spining in high vacuum is not, of course, able to receive very much heat from its surroundings via conduction. Therefore, in order to more realistically asses the rotor's thermal coupling to an evacuated chamber and the resultant effects on its angular speed decay ratio, we must consider the effects of radiation.

If ω is slowly varying, as it will be, we can differentiate (10) with respect to time and obtain

$$\frac{\mathrm{d}T}{\mathrm{d}t} = -\frac{1}{2a}\cdot\frac{1}{\omega}\cdot\frac{\mathrm{d}\omega}{\mathrm{d}t} = -\frac{1}{2a}\frac{\dot{\omega}}{\omega}. \tag{11}$$

The rotor temperature change, $\mathrm{d}T$, and the change in its heat content, $\mathrm{d}Q$ are related by

$$\mathrm{d}Q = Mc_p\mathrm{d}T \tag{12}$$

where M is the rotor mass and c_p is its specific heat at a constant pressure. Differentiating (12) with respect to time, we find

$$\frac{\mathrm{d}Q}{\mathrm{d}t} = Mc_p\frac{\mathrm{d}T}{\mathrm{d}t} = Mc_p\dot{T}. \tag{13}$$

Now, following Spitzer[7] we note that the thermal power, p, radiatively exchanged between the rotor and its chamber is given by

$$p = \frac{\mathrm{d}Q}{\mathrm{d}t} = Aa\sigma(T_c^4 - T^4) \tag{14}$$

where $A = 4\pi R^2$ is the rotor surface area, a is the rotor absorptivity, σ is the Stefan-Boltzmann constant and T is the temperature of the rotor chamber walls (assumed to be uniform).

Equating (13) and (14) we find

$$\dot{T} = \frac{Aa\sigma(T_c^4 - T^4)}{Mc_p}. \tag{15}$$

Now combining (11) and (15) we find

$$\frac{\dot{\omega}}{\omega} = -\frac{2aAa\sigma(T_c^4 - T^4)}{Mc_p}. \tag{16}$$

It should be pointed out that (16) correctly replaces the original erroneous result derived by Spitzer[7]. Further, (16) suggests that we can calibrate the rotational pyrometer in terms of the temperature of the chamber wall (which can be measured by other means), providing that the constants of the rotor material can be adequately determined. The process of calibration would consist of obtaining a family of decay ratio versus chamber wall temperature curves and fitting (16) to them in order to evaluate $(T_c^4 - T^4)$.

For a given rotor, we can simplify (16) by combining the constants such that

$$n = \frac{2aA\alpha\sigma}{Mc_p}. \tag{17}$$

This leaves us with

$$\frac{\dot{\omega}}{\omega} = -n(T_c^4 - T^4). \tag{18}$$

Equations (9) and (18) become then the appropriate expressions to use when analyzing results from a rotational pyrometer at high and low temperatures, respectively; although near thermal equilibrium ($T_c \approx T$), there is little difference between their predictions. This is supported by Beams result (quoted earlier$^{6)}$) which was, in fact, obtained at high vacuum near thermal equilibrium.

Let us now consider the behaviour of a rotational pyrometer in some limiting cases.

As we approach absolute zero, thermal expansion coefficients vanish. The rotor decay ratio, as given by either (9) or (18) would also vanish implying that this instrument would not yield useful temperature data at very low temperatures.

The upper limit would correspond to the Curie point of the material, beyond which magnetic suspension could not be maintained.

The response time of the rotor to, say, a thermal step change would depend on the thermal conductivity of the rotor, the rotor volume, and the pressure of the atmosphere in which it spins. A ferromagnetic, conducting rotor spinning at some pressure in the viscous regime would reach its equilibrium more rapidly than a permanent magnet of equal volume spinning in an ultra high vacuum (free molecular flow).

In the above example, it must be clearly pointed out that the thermal step must be sufficiently large to insure that the resulting decay ratio would not be masked by the usually dominant exponential rotor speed decay caused by gas friction.

Since the rotor absorptivity, a, (see equation (14)) is wavelength dependent, a rotor could be designed to be more sensitive to some sources than others thereby making it essentially a bandpass device, too.

The next section describes an apparatus now in the early stages of development which (when finished) will be the working prototype rotational pyrometer.

3. *Apparatus*

Clearly, the most important part of this work involves the development, of a bearing for the rotor which is virtually friction free. Magnetic suspension of a ferromagnetic rotor is the easiest way to achieve such low friction. Frictional drag torques as low as 10^{-17} Nm have been produced$^{12)}$, and more recent work$^{13)}$ with relatively massive rotors ($M = 250$ g) have shown energy dissipation as low as $\approx 10^{-18}$ W. The latter result has been made possible by the use of the corotation scheme first reported in Ref. 3 and then developed in Ref. 10. In this system, the rotor vacuum chamber corotates around the rotor itself thereby bringing the residual atmosphere in the chamber into motion with the rotor. The gas friction otherwise due to the rotor-chamber relative velocity difference is thereby reduced significantly.

Such techniques should only be necessary though if one intends to push the method to its ultimate limits of sensitivity. For purposes of demonstration and preliminary study, a less complicated system than that described in Ref. 10 is being built, and special emphasis has been placed on magnetic suspension system design.

Several reviews of magnetic suspension system designs exist14,15,16) and the electronic circuits used in this work have been previously described by the author10). The rotor height is photo-optically sensed using a current controlled LED and a photodiode. The control circuitry is all solid state and stabilized with an active operational amplifier differentiator. A Kepco Corp. Bipolar power supply/amplifier, model BOP36-5 (M), drives the servo coil which consists of about 700 turns of 22 AWG magnet wire wound on a plastic form in 9 layers. The coil core/pole piece is a 1 cm diameter rod of cold rolled steel rounded at the tip to properly shape the magnetic field. A permanent magnet is used to provide most of the lifting force and the servo system then trims the coil current in order to keep the rotor magnetically floating in space at some adjustable position below the coil pole piece. A wide range of rotors can be supported with this system, but 1 cm diameter steel ball bearings are typically used.

The feedback loop contains one summing amplifier which can be driven with the normal signal plus an externally supplied low frequency sine wave to make the rotor oscillate vertically. One might wish to do this in order to have the rotor »mechanically scan« some region of its chamber in order to sense temperature variations and, perhaps, average over them.

In practice the rotor height can be varied over a 1 cm range before the feedback loop becomes unstable, although with further effort, this could be increased at least a factor of 2.

One disadvantage of this rather simple system is that the coil dissipates about 15 W of heat in the vicinity of the rotor which sets up unacceptable thermal gradients that disturb the measurement, since at this point no chamber or insulation has been put around the rotor. As work progresses, the suspension system will be changed to a purely differential, split diode sensed arrangement such as that developed by Koldewyn17) or Cheung et al.4). In such systems coil dissipation can be kept below 100 mW providing that the rotor is carefully positioned such that the lifting force provided by the permanent magnet almost exactly offsets the gravitational force of the earth on the rotor.

The rotor can be supported indefinitely with this system. In fact, stable rotor support with similar systems for periods of up to 0.1 year have been reported10) with no indication that it could not stay in support longer.

The system used to measure rotor angular speed depends on the speed range of interest. One system used by the author8) at low rotational speeds incorporated sensitive Jones optical levers and a digital counter which recorder the rotational periods of the rotors under study. At high speeds (100 Hz and above), most workers choose to bounce laser light off the rotor surface and monitor the reflected light from a rotor scratch pattern with a photomultiplier tube or a sensitive photodiode. Either system involves the interaction of the rotor with a light beam and this may be a source of unwanted rotor heating, depending on the level of sensitivity one is interested in. At the highest levels of sensitivity, one could magnetically sense the rotor angular speed by monitoring, perhaps with a SQUID, the motion of the unavoidable off axis component of the rotor magnetization vector as it spins.

The other constants of the rotor, such as its thermal expansion coefficient, specific heat, etc., should not vary appreciably over the course of a data taking run, providing that the angular speed is kept below the plastic flow limit above which the rotor material creeps and changes its properties. It would, however, seem wise to avoid contamination of the rotor surface with vacuum pump oils, greases, etc.; otherwise the validity of Eq. (5) might be questioned due to unwanted mass transfer. Further the rotor absorptivity, a, might change during the course of a pumpdown thereby confusing the results.

Recent data on isothermal rotor decay ratios[10)] shows that as expected, the decay ratio at atmospheric pressure depends on the rotor speed. For a plastic cylinder with a small steel suspension slug spinning at 1 rotation per second ($I = 1.1 \times 10^{-4}$ kg · m^2), decay ratios of about 6.6×10^{-4} are expected and found. For an isothermal rotor in vacuum (still gas fraction limited), the same rotor spinning in air at approximately 0.1 Pa should have a decay ratio of about 10^{-6}, independent of its angular speed, and again, this was found to be the case experimentally.

The most important design parameters for such a system have been discussed in the paragraphs above, but an additional one is the rotor's angular speed. Small rotors spinning at low speeds (100 radians/s or less) can be driven up with relatively little power; but at high speeds, the design of the drive coils becomes somewhat more complicated. This is because their reactive impedance becomes very large at high frequencies. For instance, a 1 mH coil carrying a 10 MHz signal presents an equivalent impedance of 10,000 Ω to its current source, even though it may be only a few ohms at dc. One solution to this type of problem is to use power amplifiers that have a high output impedance.

The working conditions in which such experiments must operate are discussed next. As mentioned above, one of the largest disturbance mechanisms encountered is ambient vibrations. The spectrum of typical laboratory floor vibrations shows sizeable peaks at many frequencies. These include low frequency natural earth microseisms at $\sim$10 mHz, mechanical hum from motors and transformers at power line frequencies, transient shocks from door closings, and so on. Such vibrations can couple into the rotor's spin and cause angular speed fluctuations which might mask the signal of interest. To counteract this problem, we have built vibration isolation stations on which our magnetic suspension systems are mounted. They consist of massive stones mounted on damped pneumatic springs such that the resulting structure acts as a mechanical filter with a low frequency cut-off at 1 Hz. A second problem is securing a fail-safe source of electrical power. Clearly, any interruption in electrical power will cause the rotor to drop. Even switching elsewhere on the power line mains can send out high frequency transients which disturb the suspension. Therefore, it is necessary to use a battery backup system with a fast automatic switch that can transfer the load whenever necessary. Several types of commercially available instruments accomplish this in 5—10 ms or less. Detailed considerations of other working conditions for these types of magnetic suspension systems have been published elsewhere[10,13)].

The measurement procedure itself is straightforward. The task, of course, is essentially one of monitoring the angular speed of the rotor. To start with, though the rotor must be placed in suspension and driven up to its optimum operating speed. Measurements of its angular speed are made photo-optically. Using standard techniques[10], it is possible to make such measurements at the 10^{-7} level. Digital frequency counters are used to quantify the decelerations during spindown. Data collection and reduction is done in the standard way[10].

Under routine laboratory conditions, the values of the most important operating parameters are as follows. The residual vibrational amplitudes at the experimental station are < 5 μm. The long term drift in the rotor's vertical position is $< 3 \times 10^{-3}$ mm/hour. The natural frequency of the magnetic suspension is ~ 25 Hz. The error of the rotor timing system should be < 0.1 μs. The ambient temperature of the laboratory room should vary no more than 0.5 C. Under these conditions, the sensitivity of the rotational pyrometer will be limited only by the long term drifts which would otherwise be responsible for the rotor's angular speed decay ratio in the absence of temperature fluctuations.

The recent completion of the magnetic suspension hardware built for this work, though, has not allowed time for data collection on the decay ratios of non-isothermal rotors as would be of interest here. Therefore, when such data is available, it will be published elsewhere.

4. *Conclusions*

A rotational pyrometer has been proposed and is currently under development. The system uses a magnetically suspended rotor as a test mass whose rotational speed is dependent upon its thermal expansion coefficient. As the rotor expands, its angular speed decreases because of the conservation of angular momentum. Competing effects also operating on the rotor speed decay ratio are discussed, and the behaviour of the rotor decay ratio in response to conduction and radiation at both low and high gas pressures is analyzed.

A magnetic suspension system for preliminary studies has been developed, and the results of isothermal rotor spindowns from a previous experiment are presented as a prelude to the more interesting rotational pyrometry now in progress.

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PRIJEDLOG ROTACIJSKOG PIROMETRA ZA PRECIZNA MJERENJA TEMPERATURE

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Originalni znanstveni rad

Predlaže se rotacijski pirometar za vrlo točna mjerenja relativnih promjena temperature. Uređaj primjenjuje magnetski ovješenu feromagnetsku kuglicu kao rotor kojemu se određuje relativno smanjivanje kutne brzine kao funkcije temperature rotora. Raspravljaju se drugi utjecajni činioci i izračunata je predviđena osjetljivost uređaja. Opisana su prethodna istraživanja s jednim uređajem s magnetskim ovješenjem, kao i podaci o izotermičkom relativnom smanjivanju kutne brzine od ranijeg mjerenja. Podaci o predloženoj metodi, tj. za neizotermički rotor, još nisu dobiveni i objavit će se kasnije.