Ultra-Low-Friction, Zero-Power Magnetic Suspension System of the Spinning Rotor Vacuum Gauge

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Summary

Magnetic suspension systems have been developed at the University of Virginia (Holmes and Beams 1937) for the special purpose of spinning small bodies up to ultimate speed. The frictional torque acting on a rotating body when being suspended in a magnetic field with a highly symmetric flux distribution around the vertical axis was found to be many orders of magnitude lower than the torque exerted by gas friction at atmospheric pressure. Consequently, that type of suspension system was proposed and used lateron for pressure determination in rarefied gases. Drag torques down to 10^{-17} Nm have been resolved under optimum laboratory conditions. The present paper describes the magnetic suspension system of the "Spinning Rotor Vacuum Gauge" (SRG) which as a commercial unit resolves about 10^{-14} Nm under regular laboratory conditions. This figure corresponds to a pressure resolution of about 10^{-7} mbar, nitrogen equivalent, of the gauge. The SRG was introduced as a transfer standard in 1979 by BIPM and is commercially available since 1981. The gauge head functions will be discussed with special emphasis on minimization of the residual drag.

Introduction

The achievement of low bearing friction is a general aim in mechanical engineering. Ultra-low friction is demanded if rotational drag is to be determined for metrological purposes. The most advanced practiced system of this kind is the spinning rotor gauge (SRG), which allows pressure determination in rarefied gases by evaluation of the gaseous drag on a freely spinning rotor [1,2]. In a high vacuum, i.e. at pressures below about 10^{-2} mbar, reasonable pressure resolution can be achieved only in the absence of mechanical bearing friction. The development of a non-contacting magnetic rotor suspension by Holmes [3] in 1937 is to be regarded as the starting point of high-resolution friction metrology. The residual bearing friction in a magnetic rotor suspension results from eddy current losses in the rotor due to asymmetries of the magnetic field with respect to the rotor spin axis, as well as from eddy currents in conducting material in the vicinity of the rotor due to a non-uniform rotor magnetization. The inner losses (inside the rotor) are minimized by providing a highly symmetric suspension field while outer losses can be widely reduced by making the rotor from homogenious material and giving it a highly symmetric shape. The above conditions have been realized to a high degree by the type of permanent magnet suspension described in the present paper. Torque resolutions of the order 10^{-17} Nm have been achieved in laboratory units especially designed for basic research in the field of gravitational dynamics [4,5]. The above resolution corresponds to a deceleration time constant of several hundred years as observed on a 2.5 mm steel ball spinning at 200 Hz. Time constants of still several years can be resolved by the present commercial spinning rotor gauges.

Gauge head functions

A schematic of the gauge head is shown in Figure 1. The design of the stator package was guided by the need for a most symmetric arrangement of all suspension and operation components around the vertical spin axis of the rotor. The rotor is typically a 4.5 mm diam ball bearing. The ball is stabilized between two mutually attracting rear-earth-cobalt magnets supported and centered inside a mild steel case. The case provides magnetic flux return and effective shielding of the stator package against outer magnetic fields. The field symmetry in the center of the 35-mm magnetic gap is enhanced by circular pole discs made of Armco iron. The axial field strength is tuned by the number and location of the discs so that the magnetic forces acting on the ball just balance the gravitational forces when the ball is in the center of the stator package. At this position the ball is unstable along the vertical axis and natural stability is given in the horizontal plane, where the ball favours the location of highest field strength right on the symmetry axis of the system.

Only minimum active axial control is necessary for keeping the ball to the central equilibrium position. This is done by two coils coaxial with the magnets and equidistant above, respectively below the ball. The coils serve for sensing of the vertical rotor position (inductive pickup) and simulta-

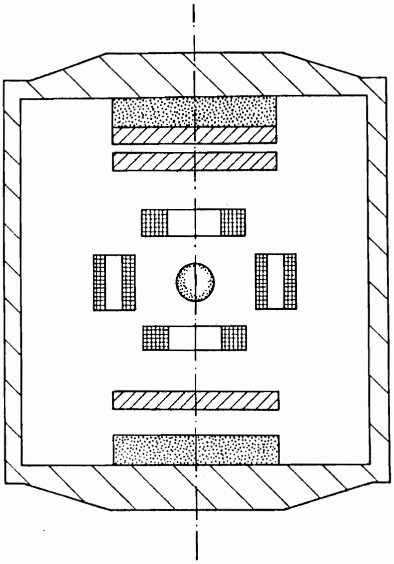

Figure 1. Single-axis permanent magnet suspension

neously for magnetically restoring and damping of the rotor along the vertical.

When the ball is at the magnetic equilibrium position the sensor output voltage and the control current become zero. A special section of the axial stabilization electronics serves for automatic tuning of the sensing-and-control amplifier to the zero-power condition. Thus, heat generation within the coils is reduced to a negligible amount associated with the inductive pickup.

In order to suppress or damp out lateral oscillations of the ball which would lead to disturbancies of the rotational field symmetry, the ball is surrounded by additional four coils in 90-deg separated, off-axis positions. In Figure 1 two of these coils are shown. The magnetized ball rotor induces a voltage proportional to its lateral velocity in one of these coils which is used for pickup while the opposite coil serves as the corresponding damping actuator.

The arrangement of further coils which are necessary for operation of a spinning rotor gauge are shown in the perspective view of the complete gauge head in Figure 2. Four drive coils with horizontal axes in connection with a two-phase generator drive the ball up to the operation frequency of about 410 Hz. After spin-up, the frequency of the freely rotating ball is picked up by two coils next to the rotor. An a.c. voltage is generated in these coils due to the horizontal component of the rotor magnetization. This rotating component mainly results from the asphericity of the ball. In view of a useful pickup amplitude, high-grade production ball bearings are too spherical, even though desirable for lowest eddy current drag. Low eddy currents and distortions of the magnetic field symmetry by the vacuum encapsulation is achieved by making this from an amagnetic steel (1.3952) tubing providing high electric resistivity and low permeability.

Vertical line-up (±0.5 deg) of the stator package is required for the rotor to be matched with the field symmetry axis.

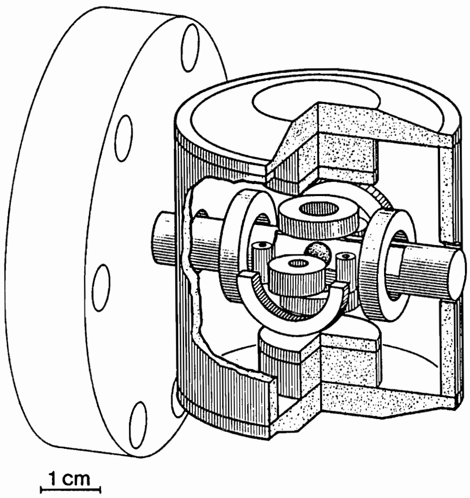

Figure 2. Spinning rotor vacuum gauge (SRG) head

Performance

The attributes of the ultra-low friction magnetic bearing structure with respect to resolution of low drag effects is visualized by Figure 3. The rotor frequency was monitored at a background gas pressure below 10^{-9} mbar over a period of three days.

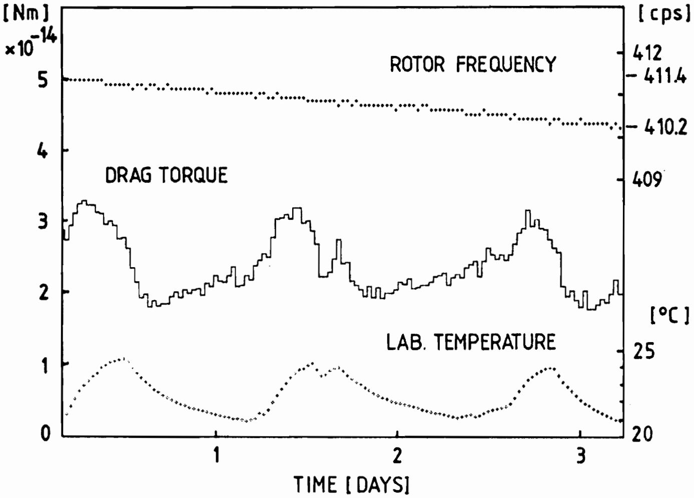

Figure 3. Frequency decay of SRG rotor and equivalent drag torque in correlation with laboratory temperature

The absolute frequency decay during this time was 1.2 cps. With a mean spin frequency of 410.8 cps this gives a decay ratio of $1.5\text{x}10^{-8}$ sec^{-1}, or a decay time constant of about two years.

With the gas friction eliminated, the decay is due to the eddy current drag. The mean value of the drag torque as obtained from the frequency decay is about 2×10^{-14} Nm and the resolution is of the order 10^{-15} Nm. In terms of gas pressures this resolution is of the order $\pm1\text{x}10^{-8}$ mbar.

The obvious fluctuations of the drag torque, which amount to about 1/3 of the overall drag are correlated with the drift of the laboratory temperature. The fluctuations are caused by the change of the rotor size with temperature and corresponding changes of the rotor inertia. Due to conservation of the angular momentum of the freely spinning rotor fluctuations of the rotational speed come into appearance. The example was chosen in order to demonstrate that no longer the bearing friction of the SRG suspension, but other effects determine the limit of torque resolution [6].

The temperature effect underlines the importance of a zero-power stabilization, which became feasible with the permanent magnet bearing concept.

A natural limitation of the residual drag torque acting on the ball is given by the Corriolis effect [7]. This is caused by the tendency of the ball to keep its spin axis fixed in space, while the support field turns with the earth. For central European latitudes the resulting drag torque is of the order 10^{-15} Nm. Thus, the drag actually observed in a commercial SRG is not far from the Corriolis limit.

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