PRINCIPLES OF THE ELECTRIC VACUUM GYROSCOPE

A. Nordsieck[1]

University of Illinois
Urbana, Illinois

ABSTRACT

The general conception and the design principles of a gyroscope with rotor supported only by electric fields and turning freely in high vacuum are outlined. A configuration is described in which the support is supplied by an a-c passive resonant servo system, and readout is accomplished by photoelectric observation of a pattern on the equator of the rotor, and the case is gimbaled and made to turn with the rotor angular momentum vector. This configuration is probably optimum in the present state of development; however, some future improvements are suggested that promise a simpler, better performing configuration.

INTRODUCTION

The electric vacuum gyroscope is a free (i.e., two-axis) undriven gyroscope in which the rotor is situated in high vacuum, free of all material contact, and is supported by electric stresses. The concept was arrived at by asking how best to decouple the rotational degrees of freedom of a rigid body to the ultimate possible extent from the external world. If there is high vacuum and no material contact and if the rotor is a figure of revolution about its axis of rotation, the torques due to residual gas are very small, typically causing the freely coasting rotor to have a slowdown time of several years and causing the angular momentum vector to turn at a rate several orders of magnitude less than even this very small rate. There remain, then, precisely three sources of torque: magnetic stresses, electric stresses, and gravity or acceleration stresses. The

Presented at ARS Guidance, Control, and Navigation Conference, Stanford, Calif., Aug. 7-9, 1961.

[1]Professor of Physics, University of Illinois

torque due to magnetic stresses is minimized by keeping the rotor as free of permanent magnetic moment as possible and by shielding out magnetic fields due to external causes. The torque due to electric stresses is minimized by making the rotor surface as nearly spherical as possible and by making it of a good electrical conductor. The electric stress is everywhere normal to the surface of a good conductor and so cannot produce any torque about the center of an ideal conducting sphere. The alternative approach of employing magnetic stresses to support a rotor of either ferromagnetic or completely diamagnetic (superconducting)material seems less promising to the author because the requirement that the stress be normal to the rotor surface is more reliably and precisely fulfilled by electric materials (conductors) than by magnetic materials. Ferromagnetic vacuum suspension methods were well developed for other purposes some time ago by Beams and collaborators (1)[2], and superconducting suspension has been demonstrated more recently (2).

If the center of mass of the rotor does not coincide accurately enough with the center of the spherical figure, then gravity or accelerations of the apparatus will cause torques that will generally be predictable so long as the mass unbalance does not change with time.

In the subsequent sections, the design principles of the electric vacuum gyro are discussed in more detail.

VACUUM SYSTEM

The two problems in connection with the vacuum are to produce high vacuum (10^{-7} to 10^{-8} mm Hg is desirable) about the rotor and the stress-supplying electrodes without heating the parts much above room temperature, since they are precision parts, and to maintain the vacuum with a compact pump rigidly attached to the gyro case and operable in any aspect relative to gravity. The latter is a requirement in the best performing present design, because this design requires the case to turn (in gimbals) so as to follow the rotor angular momentum vector.

Both the forementioned problems have been solved by strict cleanliness in the handling of the parts, initial charcoal trapping, and maintenace of vacuum by means of a compact combination titanium getter pump and ion pump sealed to the gyro case.

[2]Numbers in parentheses indicate References at end of paper.

SUPPORT SYSTEM

The support system involves three major problems. First, the electric stress on a surface is only $0.442\ E^2 \times 10^{-6}$ dynes per cm^2 where E is the voltage gradient at the surface in volts per cm, so that quite large voltage gradients are required to support rotors of reasonable weight, making flashover an important consideration. Second, the electric stress system is inherently unstable because of Earnshaw's theorem in electrostatics (3); consequently the voltage gradients must be controlled by servo amplifiers to provide static and rate stability. Third, there is a severe reliability problem, for if the support system fails while the rotor is turning, the whole instrument is irreparably damaged.

In regard to the flashover problem, one is able, at present, to work reliably with voltage gradients of several hundred thousand volts per cm, which is still only about 1/10 the theoretical cold-emission limit, and further research on the mechanism of electrical flashover in vacuum may make voltage gradients nearer the cold emission limit practically possible.

The direct approach to the support servo problem is to use d-c high voltages combined with high frequency capacitor bridges to measure translational displacements of the rotor and thus provide error signals for controlling the stress producing high voltages. Essentially three servo loops are required, each controlling the potentials of a pair of diametrically opposite electrodes facing the rotor surface, to handle the three translational degrees of freedom of the rotor.

A less direct approach to the support servo problem which has some considerable advantages over the above is to use a-c high voltages and a passive resonant circuit composed of the rotor to electrode capacitances resonating with external inductors; the circuit being driven by a constant voltage, constant frequency generator. The circuits are tuned off resonance in such a sense that when a rotor to electrode gap increases, there is a resonant increase of voltage across that same gap. A three-phase version of this system can be used with one phase for each of the three translational degrees of freedom, the rotor naturally becoming a floating neutral. This system does not have inherent rate stability, as it would have if the rotor were in a viscous medium; however, rate stability can be provided either by capacitors with oil-damped movable plates effectively parallel with the rotor or by nonlinear inductors properly coupled into the circuit. The advantages of the system are that it is less sensitive to the d-c rotor potential, which is difficult to control; that it tends to be more reliable because it contains few active elements; and that the generator voltage is amplified by resonance.

So long as the rotor is ideally spherical, there need be no special relationship between the electrodes and the spin axis of the rotor because of the above mentioned principle that for a spherical rotor the torque due to electric stresses vanishes. However, the electric torques are inherently the largest source of gyro drift, and in order to minimize them for a rotor that is somewhat centrifugally distorted, it is best to keep one electrode pair lined up with the spin axis and the other two pairs with equatorial diameters. Such a configuration nullifies the electric torques due to any departure from sphericity which is reflection symmetric with respect to the rotor equator; but it implies that the electrodes and the case to which they are affixed must turn with the spin vector of the rotor.

ROTOR DESIGN PRINCIPLES

The rotor should obviously be made of a nonmagnetic good conductor and of a material of high ratio of stiffness to mass, so that it can store the greatest angular momentum for a given centrifugal distortion. Beryllium is essentially the best material, and aluminum next best.

The mass distribution in the rotor is preferably such that the moment of inertia about the intended axis of rotation is appreciably larger than the moment about an equatorial diameter, for then internal friction will cause the spin to stabilize about the intended axis quickly, and any systematic pattern placed on the rotor for readout purposes will stay in its intended plane.

The voltage-gradient limitations mentioned above imply that a hollow rotor is required, for a solid one has too large a ratio of mass to surface area for reliable support at present.

Any joints involved in the fabrication of the rotor must be vacuum tight and symmetrical with respect to the axis and preferably located in minimum stress regions, and they must not involve any appreciable projections or indentations in the exterior surface.

READOUT SYSTEMS

The direction of the angular momentum vector of the rotor must be determined very accurately, not only because it is the essential intelligence supplied by the instrument, but also because the case must be made to follow this direction.

In early versions of the electric vacuum gyro, this readout was accomplished by having a metallic equatorial flange on the rotor and placing electrodes on both sides of this flange to form two high frequency capacitance bridges for reading out the two relevant orthogonal infinitesimal rotations. However, it was found that the flange caused unacceptably large electric torques. In general, it seems unwise to depart from the concept of a complete unmodified spherical rotor surface.

There is one very neat and economical optical readout system that requires some modification of the spherical surface, though only in a minor way. If a flat is machined near the pole of the rotor with its normal tipped slightly relative to the spin axis and this flat is illuminated with parallel light, the reflected beam will describe a cone at rotor angular velocity. The axis of such a cone can be determined very accurately by the same methods as are used in conical scan radar systems. The advantage of such a system is that it requires only one optical train and uses parallel light so that the source and detectors need not be close to the rotor surface. The spoiling of the spherical surface near the pole is a disadvantage.

Probably the most satisfactory readout system for use when the cage is made to follow the rotor spin vector is the following. A sinusoidal mark of small amplitude and with a large integral number of complete cycles fitting round the equator is placed on the rotor straddling the equator. The mark represents a reduced optical reflectivity of the rotor surface. Four optical systems are attached to the cage at 90° intervals around the equator, and each of these illuminates the equator with a focussed spot of light and detects the reflected light by means of a photomultiplier tube and amplifier. The time spacing of the successive pulses as the pattern on the rotor surface passes under the focal spot of the optical system reveals whether the spot is above or below or precisely on the equator. By properly combining and filtering the outputs from two diametrically opposite optical systems, a very accurate measure of the infinitesimal rotation of the rotor axis relative to the case may be obtained. The advantages of this system are that the integrity of the spherical rotor surface is left complete, there is some redundancy in the system, and the primary data rate is very high, so that considerable smoothing of the data can be done.

AREAS OF IMPROVEMENT AND ULTIMATE LIMITATIONS

Research on the mechanisms of electrical flashover in vacuum may be expected to enable the support of heavier and therefore simpler and stiffer rotors.

Another major simplification would result from developing means of turning the electric field configuration at the rotor surface without physically turning the electrode structure and the cage. This would involve electronic swivelling of the field pattern by methods analogous to electronic scanning, as distinct from mechanical scanning, of radar beams. The readout problem would have to be solved anew, since the detectors would wander over the surface of the rotor rather than staying near the equator or the pole. Some progress has been made in the practical solution of these problems.

The ultimate limitations of the electric vacuum gyro will probably be: 1) dimensional stability of the rotor material, which operates at normal temperature but under moderately high stress conditions; 2) dimensional stability of the electrode structure, which can probably be optimized by using ceramic structural materials; and 3) stability of the electrical parameters of the important elements in the support circuits (e.g., the inductors).

REFERENCES

1 Beams, Young and Moore., J. Appl. Phys. 17, 886 (1946).

2 Harding, John T., "The Cryogenic Gyroscope", Paper No.1949, American Rocket Society Meeting, Stanford, Calif., Aug. 7-9, 1961.

3 Stratton, Electromagnetic Theory (McGraw-Hill, 1941)p. 116.