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UNCONVENTIONAL INERTIAL SENSORS

ELECTRONICS RESEARCH CENTER
CAMBRIDGE, MA

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1. AERODYNAMICS, AIRCRAFT
2. AERODYNAMICS, MISSILES AND SPACE VEHICLES
3. AIRCRAFT: all manned atmospheric classes or specific types; components.
4. AIRCRAFT SAFETY AND NOISE
5. ATMOSPHERIC ENTRY: drag devices and forces; reentry maneuvers.
6. ASTRONOMY
7. ASTROPHYSICS
8. BEHAVIORAL STUDIES: psychology; personnel selection and training; human engineering.
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10. BIOCHEMISTRY
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14. CHEMISTRY, ORGANIC
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24. LAUNCHING DYNAMICS
25. MATERIALS, ENGINEERING: construction materials; properties.
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27. MATHEMATICS: abstract studies.
28. MISSILES AND SATELLITE CARRIERS: weapons; sounding rockets; satellite launchers.
29. NAVIGATION AND NAVIGATION EQUIPMENT
30. PHYSICS, ATOMIC AND MOLECULAR: structures; spectroscopy; periodic system.
31. PHYSICS, NUCLEAR AND PARTICLE: radiation; nuclear reactions; structures; force fields.
32. PHYSICS, SOLID STATE: cryogenics; crystallography; semiconductors; theories of elasticity, plasticity.
33. PHYSICS, THEORETICAL: classical mechanics other than fluid mechanics; magnetism; optics; acoustics; wave and quantum mechanics.
34. PILOTING: preflight and flight routines; rescue operations.
35. POWER SOURCES, SUPPLEMENTARY: auxiliary sources; batteries; solar and nuclear generators.
36. PROPELLANTS: characteristics; handling.
37. PROPULSION SYSTEM ELEMENTS: injectors; nozzles; heat exchangers; pumps.
38. PROPULSION SYSTEMS, AIR-JET: turbojets; ramjets; propeller systems. Includes these types using nuclear heat sources.
39. PROPULSION SYSTEMS, LIQUID-FUEL ROCKETS
40. PROPULSION SYSTEMS, SOLID-FUEL ROCKETS
41. PROPULSION SYSTEMS, ELECTRIC: ion jets; plasma jets.
42. PROPULSION SYSTEMS, NUCLEAR: fission or fusion systems using non-ambient working fluids.
43. PROPULSION SYSTEMS, OTHER: systems not assignable to other categories, e. g. solar radiation.
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47. SATELLITES: orbital.
48. SPACE VEHICLES: non-orbital.
49. SIMULATORS AND COMPUTERS: mathematical and physical.
50. STABILITY AND CONTROL: aircraft, missiles, and spacecraft.
51. STRESSES AND LOADS: calculation methods; structural tests; fatigue; vibration and flutter; aeroelasticity; stress analysis.
52. STRUCTURES: design criteria; component selection.
53. VEHICLE PERFORMANCE: specific flights; observed performance; history.

(Numbers above 53 not assigned.)

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UNCONVENTIONAL INERTIAL SENSORS

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SUMMARY

This paper surveys methods of operation, present state of development, and performance of inertial sensors not using principles of angular (or vibrational) momentum of rigid bodies. Fluid Sphere technology, using a rotating body of fluid, has made possible a gyroscope with two degrees of freedom. Ring Lasers, with their lack of moving parts, have achieved drift rates of a few tenths of a degree per hour. In Electrostatic Gyroscopes, where high voltage breakdown sets a limit to levitation forces, present design projections offer promise of 100 g operation for small balls. Magnetic Resonance Gyroscopes and Superconductive Gyroscopes are discussed, and an introduction given to newer concepts using Relativistic Sensors, Rotating Tensor Sensors, Vortex Rate Sensors, and Quantum Mechanical effects.

(0) INTRODUCTION

The context of the term Unconventional Sensors used in this paper covers concepts and devices not using angular (or vibrational) momentum of rigid bodies. Such concepts have been regularly examined at conferences such as that sponsored by the Bureau of Naval Weapons, Air Force Systems Command, and Republic Aviation Corporation at Farmingdale, Long Island, New York. Tables 0-1 and 0-2 give lists of the concepts covered in the unconventional field. Discussion of these concepts has been and indeed, still remains difficult, due to consideration of security and proprietary rights.

After considerable discussion with specialists in many aspects of the field, five devices and four classes of concepts covering phenomenology that may influence future devices emerge as leading candidates for examination. Duncan, in his 1964 State of the Art Review, [0-1,0-2] pointed out that only three laboratory concepts of angular sensors appeared that did not use the concept of angular momentum of spinning rigid bodies:

(a) those using vibratory momentum,

(b) nucleons (which exhibit spin momentum but can hardly be classed as rigid bodies),

(c) transit time difference of two beams of radiation propagating in opposite directions around the same closed path.

It is the second or concept part of the paper that lists some new ideas that have emerged since.

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(1) RING LASER SENSORS

The basic principle of operation of the ring laser gyroscope depends on a laser being a light amplifier. Once the working material is in an excited state, it will emit light as a result of the passage of a stimulating beam of light. The emitted light will be found to have the identical frequency, phase, and direction as the stimulating light. One of the requirements for this to happen is that the stimulating light have a frequency which is in one of the several rather narrow bands in which the excited material can emit radiation.

As is true of any amplifier, the laser can become an oscillator if it is coupled to a resonant device and if there is feedback of some of the output energy. The usual laser device consists of a suitable material (solid or gas) placed between two parallel mirror surfaces. The space between the mirrors forms a resonant cavity (resonant at each frequency at which they are separated by an integral number of half wave lengths) and feedback is inherent in the placement of the lasing material in the cavity. This device will, if the lasing material can be kept in an excited state, oscillate continuously at a frequency which is within the emission band of the material and at which there are an integral number of wavelengths of light in the round trip between the mirrors. The frequency can be discontinuously changed in these integral jumps over a narrow band by changing the separation of the mirrors.

The ring laser differs from the conventional laser in having three or more mirrors so placed as to cause the light to travel around a closed path (triangular, square or other); the lasing material (presently a He-Ne mixture for CW operation) is placed in one or more of the legs between mirrors as in Figure 1-1. In principle the ring laser is not different from the parallel mirror form and the possible oscillation frequencies are determined by having an integral number of wavelengths around the entire path. Because of the closed nature of the path, however, there can be two distinct light beams involved, one traveling clockwise and the other counterclockwise. Put another way, there can be two simultaneous oscillations for the two opposed directions of light travel.

For rotation sensing, the pertinent characteristic of the ring laser is that the effective distance around the closed path changes when rotation of the assembly occurs, the length increases for light traveling in the same sense as the rotation while the length decreases for light traveling in the opposite sense. Because of this the resonant frequencies for the cavity change, going up for one direction of light travel and down for the opposite. We thus find that under the influence of rotation the device will have two simultaneous oscillations at different frequencies with the difference being almost exactly proportional to the input angular rate. It should be noted that aside from the effects of rotation, the two paths are identical so that small path variations cancel. To make use of this interesting property, it is necessary to mix samples of the clockwise and counterclockwise beams and apply to a photocell detector. The total light intensity as seen by the cell will vary at the difference frequency and its electrical output will have this same frequency.

Certain of the points which make this an attractive approach to rotation sensing can be stated as follows:

1. The device should, theoretically, be unaffected by acceleration.
2. The device has no moving parts.
3. Its output is inherently digital (frequency is proportional to rate; hence, each count is a small angular increment).
4. The scale factor is a function of a relatively long path which can be very stable in percentage terms.

5. Because the speed of light is so great, the effective path length changes are very small for practical rates; for this reason, saturation rate is very high and second order effects are small.

There also are some problems:

1. There are many different cavity oscillation modes possible within the exciting line width, and operating conditions must be carefully selected and controlled to secure and maintain the particular mode desired.

2. There is always some coupling between the CW and CCW beams (backscattering from various optical surfaces, for instance), which tends to lock the frequencies together. This effect closely resembles the locking of oscillators in superheterodyning. The result is that the frequencies become distinct only above some effective path length difference or threshold; furthermore, in the region just above this threshold, the frequency difference is a non-linear function of the path length difference as seen in Figure 1-2.

3. There is no sense of rotation direction in the detected signal.

Experience has shown that practical devices can be expected to have a threshold too high to be useful (20 to 100 degrees per hour) due to the frequency locking. The introduction of an offset bias, however, reduces this considerably and additionally has the added virtue of giving rotation sense. A bias can take any form which causes an unbalance in the effective path lengths in the CW and CCW directions; it causes the oscillation frequencies to differ when no input rate is present and pushes the troublesome locking frequency away from zero rate. The bias must, of course, be great enough to place the locking frequency completely out of the range of rates which is of interest. It must be stable enough not to degrade the accuracy of measurement of the frequency difference. Bias also permits easy discrimination between CW and CCW inputs although it is not the only possibility for this.

There are a number of possible forms of bias (including an actual mechanical input), but most promising results have been obtained using a Faraday cell. This cell depends on the fact that the velocity of light in a dense medium is different for light rraveling with a magnetic field than for light traveling counter to the magnetic field as in Figure 1-3. Such a cell can thus be used to create the desired path length unbalance.

Use of a Faraday cell for bias has been found to eliminate the locking problem but it uncovers two new problems. The new problems are bias stability (related to magnetic field strength stability and characteristics of the material used in the cell) and oscillation mode stability. Bias stability is a relatively straightforward engineering problem and is being attacked as such. Oscillation mode stability is a somewhat different kind of problem and requires further discussion.

As has been stated, the ring laser can oscillate at any frequency which is within the narrow bands determined by the width of the exciting line, by characteristics of the lasing material, and in providing an integral number of wavelengths around the closed path. Since there may well be 10^6 to 10^7 wavelengths around the path, it is possible to have oscillation at any of several frequencies as in Figure 1-4. As first order effects, these oscillations are the same for CW and CCW beams and in general cancel; however, this is not true for second order effects. Any random switching of frequencies can be a source of randomness in the output frequency. Because, however, bias is assumed constant, it will be removed as a constant and the net result is a random drift.

Experience has shown that when using a Faraday bias cell in a moderately well-controlled temperature environment, but with no temperature compensation, the major randomness to be expected is due to the above-discussed mode changes. Results have been of the order of 5- to 10-degree per hour variations. (These would probably average out to a substantial degree over a long time period, but results of better than one degree per hour would be doubtful.)

The most recent work has been in the direction of frequency locking reduction of the ring by small motions of one of the rings (done piezo-electrically).

There are several possible techniques for a reference against which to do this. The particular approach used by Wing, Macek, and co-workers at Sperry has reduced the randomness in the output to an equivalent rate in the order of one degree per hour. Present indications are that the major source of randomness is now stability (thermal) in the Faraday cell. Studies are being actively pursued in mode enhancement of a single frequency and mode rejection of other frequencies in the cavity that are capable of being excited by the line width.

In terms of size, the ring laser is still relatively large. The recent results have been achieved in a triangular device in a solid homogenous block, sharply reducing scattering and permitting single moding in the cavity.

The status of the ring laser can be summarized as follows:

Present results are approaching conventional gyro performance but are not yet there.

Quantum jumps in performance improvement are still being made.

Present size is not competitive, but the enclosed area has been reduced by a factor of roughly eight in the past year while performance has been improved by a factor of around thirty; thus, it is difficult to predict the future.

Because the output is inherently digital, and because very high input rates can be accommodated, the device appears well suited for future use in strapdown applications.

Simultaneous attacks on frequency locking and biasing concepts are yielding substantial improvement.

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(2) ELECTROSTATIC GYROSCOPES

The electric vacuum gyro is a two-axis free gyroscope having long-term high precison for inertial navigation. It employs a spherical metal rotor shielded from stray magnetic fields and supported or levitated without physical contact in ultra-high vacuum by servo-controlled high-voltage electric fields. The rotor, initially accelerated by induction motor techniques, spins freely with virtually no friction during gyro operation. Fundamental advantages result from the simple geometry, the absence of internal heat dissipation and the elimination of high stress concentrations and wear associated with conventional gyro bearings.

Although the present work has been primarily for nautical applications, the gyro promises high efficiency for spacecraft and satellite applications where low acceleration environments permit the use of low voltage, low power consumption rotor support circuitry.

The electric vacuum gyro was invented in 1952 by Dr. Arnold Nordsieck[2-1] while studying the problems of inertial guidance of atomic submarines for accurate launching of Polaris missiles. Realizing that spin-axis bearings were a major source of gyro error, he undertook the study of field-supported rotors. Although magnetic fields easily provide the necessary large forces, troublesome torques result from eddy current losses, hysteresis losses, and rotor magnetic moment. Theoretical consideration of high-voltage breakdown in vacuum indicated that large forces could also be applied electrostatically without electrical breakdown. Furthermore, lightweight hollow rotors could be supported using the existing state of the art. Since electrostatic forces always act perpendicular to an equipotential surface, torque due to these forces can be minimized by using an accurate spherical metallic rotor for which all forces act through a common center which, by balancing, is made coincident with the mass center.

Spurious torques, due to electric fields interacting with an inaccurate spherical rotor, constitute the only important limitation to gyro performance.

Stray magnetic fields cause both precession and rotor slowdown torques. The earth's magnetic field, if not eliminated by shielding, typically results in a slowdown time constant of seven days. To achieve a drift rate of .0001 deg/hour requires a shielding ratio of about 60 and results by itself in a coasting rundown time constant of 24,000 days. This degree of shielding is readily achieved.

Residual gas causes principally a slowdown torque. The maximum permissible pressure (10^{-5} torr) for high voltage breakdown with properly conditioned electrodes results in a rundown time constant of 15 days. A pressure of 10^{-8} or 10^{-9} torr, which is needed to properly condition the electrodes, accounts for a rundown time constant of 15,000 to 150,000 days. Pressures of 10^{-9} torr have been achieved in the gyro, without benefit of bakeout, using a titanium ion pump developed at the laboratory.

Torques can result from a potential gradient along the rotor surface. For this reason, insulating materials, such as an anodized layer which can trap stray charge, must be avoided. Displacement charge flowing over a resistive rotor surface can also produce a gradient resulting in torque. However, this effect is completely negligible for a clean metallic rotor surface.

Early experimental work employing a hollow spherical rotor which had a "saturn ring" flange for capacitive angle data pickoff was conducted by the Instrument Development and Manufacturing Corporation,[2-2] General Electric Company,[2-3] and Minneapolis-Honeywell Company[2-4] under Navy contracts. The first tests in 1957 showed large spurious torque because of unexpectedly large unbalanced forces acting on the "saturn ring" caused by stray electric fields resulting from unpredictable charge (up to several hundred volts) accumulated on the isolated rotor. At that time, the University of Illinois, Coordinated Science Laboratory, began experimental work using completely spherical rotors, optical data readout techniques, and a simple resonant circuit, passive element rotor support or levitation serve circuit.[(2-5)] General Electric and Minneapolis-Honeywell followed with completely spherical rotor gyro designs under both Navy and Air Force contracts.[(2-6)] Significant improvements in the areas of high vacuum and high voltage vacuum breakdown made at the Coordinated Science Laboratory led to demonstrations of completely reliable electric vacuum gyro operation of both Minneapolis-Honeywell and the University of Illinois in 1959. The encouraging gyro test results stimulated a current Navy requirement for inclusion of electric vacuum gyros as monitors in the existing Ship's Inertial Navigation System (SINS).[(2-7)] Active electric vacuum gyro development is currently being supported at General Electric, Honeywell, Inc., and the University of Illinois.

Gimballed vs. Gimballess Electric Vacuum Gyro

The torque resulting from the action of electric fields on an imperfectly shaped spherical gyro rotor has led to the development of two basic forms of the electric vacuum gyro.

In the gimballess form, the gyro case is fixed with respect to the vehicle or stable platform and the rotor axis is allowed to assume any direction with respect to the case and levitation electrodes. Optical data readout is obtained by fixed photoelectric microscopes viewing coded patterns which cover a large proportion of the rotor surface and give a measurement of the rotor spin-axis angle, relative to the case. This form of gyro is subject to changing torques as changing regions of the imperfectly shaped spherical rotor come under and are acted upon by various electrodes. A compensating computer of considerable complexity is necessary to correct for these torques when highly accurate performance is required.

In the gimballed form of the gyro, the case is mounted in gimbals and servo driven so that the electrodes are always symmetrically located with respect to the rotor spin axis. Since the relative position of rotor and electrodes does not change, torque due to imperfect rotor sphericity interacting with any electrode can be maintained at a null value which is initially achieved by individual fine adjustments of the electrode geometries. The gimbal technique also enables the use of a null-balance type of optical data readout which generally affords greater accuracy. Added complexity is the only apparent disadvantage of the gimballed gyro.

The Gyro Assembly

The University of Illinois gyro is a gimballed type employing six orthogonally spaced electrodes for levitation, illustrated schematically in Figure 2-1.

The rotor is accurately centered within the electrodes by servo-controlled high voltage. An acceleration of 4 G on a 25 gram rotor is supported by 3800 volts RMS with an electrode gap of 0.025 cm. This gives a field intensity of 150,000 volts per centimeter and a field emission current of 0.5 micro amperes. For a given field intensity, smaller field emission currents result for narrower gaps. Field intensities of 1,000,000 volts/centimeter have been achieved without high voltage breakdown. Two pairs of photoelectric microscopes reading a zig-zag pattern around the rotor provide error signals for the gimbal servos which maintain the housing (electrodes and microscopes) in constant alignment with the rotor spin axis. The four induction coils in Figure 2-1 form a poly-phase motor for initial acceleration of the gyro rotor.

Present rotors have sphericities of 75-250 nanometer and are balanced to produce a pendulosity period of about three minutes of time. An air bearing support is used for preliminary balancing. Final measurements require the use of an evacuated electrostatic bearing, typically an actual gyro assembly.

Research in high voltage vacuum breakdown has indicated the necessity for clean vacuum systems free of organic vapors. Since precision parts prohibit bakeout of the gyro, vapor pumps are not used. A flask filled with activated charcoal and immersed in liquid nitrogen is used to reduce the system pressure from atmospheric to 10^{-2} torr in about one hour. The flask is then valved or sealed off and a Varian Vacion or similar titanium sputtering pump is employed to reduce the pressure to 10^{-7} or 10^{-8} torr. This pressure is usually maintained for several days before sealing off the gyro. After sealoff, the gyro pressure may rise as high as 10^{-5} torr. This drops quickly to 10^{-8} torr upon activation of the permanently attached combination titanium ion pump and Bayard-Alpert vacuum gauge. Pressures of 10^{-9} torr have been reached in the gyro.

The coils are excited by two phase power at a frequency of 2 or 3 kHz. A typical operating speed of 200 revolutions per second is reached in about 15 minutes. However, it takes about a day to dissipate the heat generated in the rotor during runup and achieve stable gyro operation. Figure 2-2 shows also the two Helmholtz coils which are excited by D.C. to damp the wobble which results when the rotor is initially accelerated about other than its intended spin axis and to torque the gyro into initial alignment. A uniform magnetic field creates a torque which tends to bring the rotor spin axis into alignment with the magnetic flux lines and thus the axis of the coils. Angular momentum is lost during torquing and must be made up by additional operation of the spin motor coils. During gyro operation all coils are de-energized.

Electric Torques

Simple gyro calculations, for a drift of .0001 degrees per hour using a 5.08 cm diameter hollow sphere rotating at 500 revolutions per second, show that the line of action of 1 G supporting force must pass within 6.6×10^{-9} cm of the mass center. Since electric fields act perpendicular to an equipotential surface, a good gyro would inherently result from the use of a rotor so accurate that the centers of curvature for all regions of the surface fall within 6.6×10^{-9} cm of each other. Since this accuracy is three orders of magnitude beyond realizability, special techniques are employed in the gimballed gyro for nulling the torques due to imperfect rotor sphericity. Centrifugal deformation causes additional elliptical distortion (2.5×10^{-4} cm),which is large compared to machining errors.

For a typical gyro design having 2.5×10^{-4} cm rotor distortion and drift rate of .0001 degrees per hour, the translational tolerance must be 2.5×10^{-7} cm, which corresponds to a levitation servo capacitance bridge balance of one part in 100,000. This is a difficult requirement which will probably be relaxed by making use of more spherical rotors specially machined to compensate for centrifugal deformation.

Status

The gimballed electrically supported gyroscope for Naval use is being successfully operated in the Fleet. Such gyros manufactured by Honeywell have been undergoing tests aboard the USS Compass Island for several years with very gratifying results. Performance specifications have been exceeded. Some results have been limited by the accuracy of the reference navigation systems. ESG data led to the discovery of otherwise undetected errors in the SINS timing system; i.e., a scalar counting down from the basic 60 cps master time reference would occasionally gain a count because of extraneous noise.[2-8]

The above gyroscope uses a 7.5 cm diameter spherical beryllium rotor preshaped to allow for centrifugal deformation. End axis optical readout ("D" pattern) for gimbal followup is employed. The rotor speed decays during operation with a several hundred day 1/e time constant. Rotor speed, since it determines sphericity, is used in computer compensation of the gyro. This gyro is designed for only 2 G and has a relatively high ratio of rotor-mass to electrode-area.

Although the specification life is exceeded, ultimate burnout of the filament in the combination vacuum gauge and titanium getter ion pump results in vacuum failure typically after 5,000 hours.

Since the existing conventional SINS systems are providing the required performance, ESG's are not currently being installed in new submarines.

A miniaturized version of the gimballed ESG developed for the Air Force by Honeywell has been laboratory-tested.

NASA is interested in a non-gimballed gyro capable of 100 G.[2-9] High voltage breakdown research indicates that with present materials, whisker growth (and ultimate breakdown) takes place at electric fields[2-10] greater than $0.5 \frac{\text{megavolts}}{\text{cm}}$. This provides a levitation force of 11,000 newtons/sq. meter of area and would accommodate 100 G using an as yet undeveloped 5 cm diameter rotor which weighs less than 11 grams.

The problems of low drift in a non-gimballed gyro subject to acceleration forces are many. However, short periods of acceleration followed by longer drift-free periods of zero $\tilde{g}$ space flight are feasible; and NASA is supporting the development of all-attitude, non-gimballed gyros with two-scale (high g and very low g) levitation systems. General Motors Research Laboratories under the direction of Arnold Nordsieck has developed and tested a novel all-attitude readout scheme using a repetitive pattern which covers a large portion of the rotor surface. They also have developed a technique for accurately figuring the spherical surface while the rotor is levitated and spinning at operating speed in vacuum.

There naturally is interest in a combined ESG and electrostatic accelerometer. Honeywell proposes nuclear magnetic resonance as a technique for accurately converting rectified AC levitation current of an existing gyro into frequency for use by the guidance computer.[2-11] Bell Aerosystems has developed an electrostatic accelerometer using variable frequency quantized voltage pulses for the input axis levitation.

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(3) FLUID SPHERE

The fluid sphere as pioneered by Sperry is illustrated in its most elementary form in Figure 3-1. It is seen to consist of a rotating member containing a spherical cavity which is completely filled with a liquid. Because of the rotation of the cavity the liquid body is also in rotation (at the same speed) and possesses angular momentum; for this reason, the liquid body attempts to maintain a constant spin axis direction in space. The liquid body, being spherical, is free to spin about an axis other than the cavity spin axis; for small space rotations of the direction of the cavity spin axis the fluid body spin axis will, therefore, continue to point its original direction in space.

The above describes a free gyroscope and, in the absence of viscous shear torques, the operation would be completely as described. Because there are viscous shear torques produced whenever there is a rotation of the cavity spin axis away from the direction of the liquid body spin axis, the liquid body spin axis is precessed back into alignment with the cavity spin axis. This is essentially an exponential response and the time constant is given, with reasonable accuracy in a boundary layer derivation by:

$$\tau = \frac{R}{5}\sqrt{\frac{2}{\Omega \nu}}$$

A more exact result is: $$\tau = \frac{R}{3.72}\sqrt{\frac{2}{\Omega \nu}} \qquad (3\text{-}1)$$

where	R	is the cavity radius in cm.
	Ω	is spin rate in radians per second.
	ν	is kinematic viscosity in stokes.
	τ	is time in seconds.

The fluid sphere is thus seen to be a rate gyroscope, having the above time constant in its response. It may also be considered a displacement gyroscope in which the displacement angle decays.

The relative shear between the cavity walls and the liquid body can be shown to take place in a relatively thin boundary layer that permits consideration of the liquid body moving as a unit.

Thus the liquid rotor acts much like a solid ball having a diameter slightly smaller than that of the cavity. This ball is separated from the cavity walls by a thin lubricating layer of the liquid. To make use of the gyroscopic properties of this "free rotor" some means must be provided to sense the displacement angle between the spin axes.

Figure 3-1 indicates ports through the cavity wall at points about 45° removed from the spin axis of the cavity. It will be seen from this figure that, if an angle, (δ) exists between the spin axes, the ports are at unlike radii with respect to the spin axis of the liquid body; for this reason, the centrifugally induced pressures at the two ports are unequal. One half revolution after the indicated condition, the two ports will have switched positions so that the differential pressure will have reversed sign. An alternating pressure, therefore, exists between the ports, and a differential microphone placed in a connecting passage will sense a pressure varying a spin frequency. The pressure is given by:

$$P = \rho \Omega^2 R^2 \delta \sin (\Omega t + \Phi) \text{ dynes/cm}^2 \qquad (3\text{-}2)$$

where ρ is liquid density in grams per cc.

Ω is spin rate in radians per second

R is cavity radius in cm.

δ is angular deflection in radians.

Φ is a phase angle and a direct measure of the direction in space of the axis about which the rotation, δ , has occurred.

It may be seen that the output of the microphone will go to zero when the angle δ goes to zero, and that a pair of phase sensitive demodulators, using as references the outputs of a two phase alternator coupled to the spin axis, will produce voltages proportional to rotations about two orthogonal axes lying in the plane normal to the cavity spin axis.

The above discussion has indicated, in broad terms, the theory of the gyroscope. Some added detailed statements are in order.

The center of gravity of the liquid ball is inherently coincident with the effective point of support, whether or not the cavity is an accurate sphere; this assumes that the liquid is uniform in temperature. Only axial thermal gradients are important; obtaining good mass balance (low g sensitive drift) is thus reduced to control of axial thermal gradients.

The liquid body is inherently isoeleastic. Even though the liquid is compressible and some CG shift results from acceleration, this shift is always along the acceleration vector.

The sensitive element is completely non-magnetic so no drift results from close proximity to strong magnetic poles.

Because the spin motor is external, no delicate power leads are required to introduce power. The motor can be large, is easily cooled, and does not dissipate heat in the sensitive element.

The differential pressure transduced by the microphone goes to zero when the displacement angle goes to zero. Because the pressure of interest is alternating it is easily sensed and a static shift of diaphragm position produces no output signal. For this reason there is no hysteresis error or time dependent bias error. It should also be noted that the null of the alternating pressure coincides with the zero displacement between the spin axes even if the sensing ports are at unequal angles with respect to the cavity spin axis.

Because the spin bearings are external to the sensitive element, position shifts in these bearings are not important. Furthermore, they can be large and well lubricated; this leads to long life and permits bearing selection to withstand high accelerations.

Because the density of the liquid is of secondary importance, accurate temperature control is not required. Variations in temperature do affect the viscosity of the liquid and, hence, the scale value; even this is relatively small, however, because the viscosity appears under the radical and because a low temperature viscosity index liquid can be used (about 1percent per degree F).

Pressure transducers can be used in pairs, as shown in Figure 3-2. Used in this way external vibration effects tend to cancel. In addition, the diaphragms can be made to have reasonably the same density as the liquid, thereby almost totally eliminating sensitivity to external vibration.

The optimum spin speed is low, leading to good life and rapid reaction.

Only simple moderate tolerance parts are required and no special assembly or adjustments are needed, so the construction costs are very low.

The device is inherently two degrees of freedom and it is only necessary to demodulate the signal in demodulators using as their references the outputs of a two phase alternator coupled to the gyroscope shaft to obtain the two signal components.

The status of the fluid sphere gyro work at Sperry as of March 1965 can be summarized as follows:

A design for a practical, usable device exists. See Figure 3-3. This gyro is about 11.5 cm long, 6 cm in diameter and weighs about 0.9 kg.

Results of tests show fluid sphere:

Acceleration sensitive drift $<$ 1° /hour/g.

Random drift .1° per hour

Bias $<$ 1° /hour

Has been subjected to 30 g centrifuge test. Tests after centrifuging showed no change of g sensitivity, bias or random drift.

Has been subjected to vibration from 10 to 3000 hz (10 g above 56 hz).

No anomolous behavior during vibration, no change of characteristics after.

Has been subjected to 35 g shock test, no change of characteristics.

Work is continuing toward further refinement with present emphasis on low cost tactical missile guidance applications. Unit is less than half the previous size.

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(4) MAGNETIC RESONANCE GYROSCOPES

Magnetic resonance gyroscopes refer to the class of gyroscopic devices which obtain their space reference information from a collection of atomic or nuclear magnetic moments. This type of gyro is also called a nuclear gyroscope. The basic principles of operation have been reviewed and various approaches to their instrumentation described.[4-1] Within the past year there has been an increase in the interest and activities in this area as shown by the new approaches that have been suggested. Each of the approaches makes use of the common sensing element which has no moving parts and thus eliminates problems directly associated with the manufacture, suspension, and powering of the rotating mechanical mass in a conventional gyroscope. The objectives of the various approaches include development of low cost gyros of modest accuracy, of gyros capable of function in very high g environment, of gyros with high reliability and very long life, and of gyros with extremely high sensitivity.

All of the approaches which have been suggested can be described starting from the equation of motion for a net nuclear magnetization $\vec{M}$ in a magnetic field $\vec{H}$

$$d\vec{M}/dt = -\gamma \vec{H} \times \vec{M} \qquad (4\text{-}1)$$

where γ is the gyromagnetic ratio.[4-2] The net magnetization $\vec{M}$ may result from the thermal equilibrium distribution of the nuclear magnetic dipole moments or from some non-equilibrium distribution that results from a process such as optical orientation. In Equation (4-1) all relaxation terms have been ignored. In practical instrumentation of an NMR gyro, these relaxation effects play an important role in determining the limits of operation and sensitivity. In a rotating frame of reference, the usual transformation gives

$$\left.\frac{dM}{dt}\right)_{rot} = - (\gamma\vec{H} + \vec{\omega}) \times \vec{M}, \text{ where } \vec{\omega} \text{ is angular velocity} \quad (4\text{-}2)$$

From observations in $\vec{M}$ and $\vec{H}$, the angular velocity $\vec{\omega}$ or its time integral may be obtained.

Discussion of Approaches

The induction gyro in Figure 4-1 is a rate gyro with a two axis response. The device as first conceived detects $\vec{\omega}$ as an equivalent field in a direction perpendicular to the $\vec{H}$ which is composed of two colinear fields H_0, a dc field, and H_1, an oscillatory field of peak value the same order of magnitude as H_0 and angular frequency $\omega_{RF} = \gamma H_0$. When rotation takes place, i.e. $\omega \neq 0$, the exact alignment of the dc and ac fields no longer exists. The nuclear magnetization is then caused to precess. The nuclear signal is received in pickup coils tuned to $2\gamma H_0$ and oriented to detect transverse oscillation of the magnetization. The nuclear sample is a proton water sample doped with paramagnetic ions. It has also been pointed out that the RF drive frequency may be a subharmonic of γH_0 and the fundamental frequency γH_0 picked up.(4-3) Several models have been constructed to test various aspects of the theory. Rotation rates of the order of 100 RPM have been detected. A more advanced model of the induction gyro has been designed and is currently under construction. This model will be shielded against the earth's magnetic fields. The output noise level will be equivalent to an angular velocity of the order of several earth-rate units. The object of this program is a unit with moderately low drift rates and modest cost. In addition to this approach, newer concepts are being explored which employ maser operation. In this instrumentation, two nuclei are also used to eliminate problems associated with magnetic field fluctuations.(4-4)

The optically pumped NMR gyro in Figure 4-2 is a device which obtains rotation information from simultaneous observation of steady state NMR signals from Hg^{199} and Hg^{201}. The rotation is detected as a phase shift between the two signals which are the outputs of an NMR controlled oscillator. This instrument is a single degree of freedom, rate integrating gyroscope, which is well suited for strapdown application due to its inherent insensitivity to rotation about any axis except the sensitive axis defined by the magnetic field.(4-5) The use of two nuclear species in the same magnetic field eliminates the need for exact control or knowledge of the magnetic field. Referring to the basic NMR gyro equation (4-2), the $\vec{H}$ field has two components: H_0 a dc field of moderate homogeneity, and H_1, an oscillatory field at the frequency γH_0, directed orthogonal to H_0. The rotation ω which is sensed is that component parallel to H_0. Several models have been constructed and tested. A rather complete theory has been developed. Experimental operation and theory are in agreement.

Typical test operation of the experimental gyro model of the gyro in laboratory has shown an uncertainty in the drift rate of 0.03°/hr. These were the results of static runs in which the uncertainty is taken as the rms deviation of the slope as calculated by least mean square methods.(4-6)

Recent developments in methods for producing regions with dimishingly small magnetic fields have now made appear possible a nuclear gyroscope in which the net nuclear magnetization is simply isolated from its surroundings. Referring again to the fundamental equation (4-2), when the magnetic field H is made equal, to zero, any apparent motion or change in direction of the net nuclear moment would be determined only by the rotation of the observation apparatus in inertial space.

An experiment has been proposed to test the Lense Thirring effect through observation on an He^3 gyro in a satellite.[(4-7)] This is further referenced in Section 6. The general theory of relativity predicts a small perturbation on the motion of satellites about an astronomical body which is rotating.[(4-8)] A gyro carried in polar orbit would yield the greatest effect. The long NMR relaxation times observed in liquid He^3 would give a gyro with sufficiently long life and sensitivity to test the existence of this effect.

Each of the proposed approaches to the instrumentation of an NMR gyroscope has required development of experimental techniques for solution of problems posed essentially by the approach taken. One problem common to all approaches to construction of an NMR gyro is that of magnetic field stability. In fact rotation and magnetic field have the same apparent effect on the dynamics of the nuclear magnetization; this necessitates the control or knowledge of the magnetic field to the equivalent of the desired error in measurement of rate of rotation in most approaches. In the induction gyro, this is done by means of shielding against stray fields and control of current in the coils which generate the field. In the optically pumped NMR gyro, the question of field control is answered through the use of two kinds of nuclei in the sample. In this case, the magnetic field is treated as an unknown equivalent to the rotation and eliminated through the appropriate instrumentation for this solution of the equations. In the He^3-gyro, the problem of the magnetic field control is to be solved by reducing the magnitude of the field to such a small value that any fluctuations in its value will not influence the accuracy of the measurements.

Conclusion

The feasibility of constructing instruments of useful sensitivity has been demonstrated by using experimental laboratory techniques. Several models of gyros have been operated under laboratory conditions. Future efforts will be concerned with the development of practical instrumentation of the proven techniques and to search for new materials and methods.

In order to see what sensitivities such devices may have, Culver has extended his analysis of the theory of NMR gyros to those in which the nuclei must be reoriented once every relaxation time.[4-9] Using presently observed relaxation times, an ultimate sensitivity of better than .001°/hr is indicated.

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(5) SUPERCONDUCTIVE GYROSCOPES

The superconducting gyro has offered promise of obtaining excellent constancy since it operates at a temperature approaching absolute zero where materials are chemically inactive, expansion coefficients approach zero and creep tendency of materials is reduced. Superconducting bearings are used to suspend the gyro rotor on a thin film of magnetic flux which permits high speed rotation in vacuum using a bearing which is free of wear and friction. The rotor is accelerated to operating speed with a superconducting motor which is practically lossless. Rotor alignment is maintained during spin-up by superconducting coils of a torquer assembly. During gyro operation these coils are used to apply error compensating torques. Such devices offer great hope of using effectively the intrinsic characteristics of outer space, i.e., zero "g" and low temperature.

The diamagnetic property of a superconductor is used to obtain bearing action and to produce rotational torques to the rotor. Magnetic flux lines do not penetrate the superconductor and are compelled to flow parallel to its surface, resulting in a force perpendicular to this surface which is proportional to the second power of the flux density. Somewhat unexpectedly, small hysteresis losses occurred in superconductors when a varying field was impressed on the surface even though the critical magnetic field was not exceeded. Such surface losses were found to be produced in the rotating rotor during every revolution due to changes in flux density resulting from acceleration forces. Since the rotor operates in a high vacuum these losses must be minimized to avoid overheating.

In earlier work, Harding[5-1] reported the rather compelling evidence of their existence when niobium spheres absorbed enough energy whilst rotating in the magnetic field to cause the thermally isolated rotors to exceed this superconductive critical temperature in a matter of minutes and thus lose support. Critical magnetic field and surface losses are influenced by impurities, surface strain, geometry and other factors. Figure 5-1 shows typical loss properties of vacuum-annealed niobium measured with a-c magnetic fields at a frequency of 290 hz.

The tendency of niobium to trap magnetic flux requires that the gyro be shielded from ambient magnetic fields during cooldown. In addition it is important that the critical magnetic field not be exceeded during gyro operation. Superconductors such as niobium-zirconium and niobium-tin, which remain superconducting at extremely high fields, have the property of permitting flux penetration at low density values and are therefore not useful for the gyro bearing.

Harding[5-2] has published an analytical solution to the problem of support field configuration leading to simple but useful coil systems shown in Figure 5-2. These coils carrying opposing currents create a constant gradient field.

$$B \propto \text{gradient } r^2 (3 \cos^2 \varphi - 1) \qquad (5\text{-}1)$$

in spherical coordinates which gives stability in all dimensions. By adjusting the strength of the gradient it has been found possible to eliminate magnetic torque in a rapidly spinning ellipsoidally deformed rotor with respect to degree of eccentricity or orientation of its axes relative to the coils.

The application of the superconducting bearing to support the spherical gyro rotor in an early General Electric model gyro is shown in Figure 5-3. Two bearing coils cause a magnetic flux to flow into the clearance gap around the rotor formed by the superconducting surfaces of the bearing assembly. This flux is required to flow through a fixed gap near the equator which is provided to improve bearing stiffness. Both vertical and lateral support is provided by these bearing coils which are wound around the outside of an evacuated cylindrical housing in which the gyro is mounted.

A superconductive motor used to spin the gyro rotor to a speed of 12,000 rpm is located within a thin non-magnetic enclosure which permits the rotor to operate in vacuum while the stator windings are immersed in liquid helium. Since a rotating magnetic field will not spin a smooth superconducting cylinder, a series of elongated slots is provided in the center of the rotor against which the rotating field can react. As illustrated in Figure 5-4 stator flux which enters the slots is distorted along one edge of the superconducting wall and results in a force which produces a torque. A two-phase stator winding is used to produce a rotating flux needed to spin the rotor. The motor is energized with frequency control obtained from an optical pickoff which views a slotted mirror machined in the rotor surface. Rotor synchronism is thereby automatically maintained until operating speed is reached and the motor de-energized. The time constant of rotor speed decay has been measured to be five months and should increase as rotor balance and surface properties are improved.

Torquers are used to maintain rotor erection during acceleration to operating speed and to provide error torque compensation during operation. Two torquer assemblies are located in the center of the rotor; one above and one below the motor, each containing four small superconducting coils interconnected to produce torques about two orthogonal axes normal to the spin axis. An optical pickoff used in an early gyro model was located outside of the cryogenic environment of the cryostat to permit use of conventional optical components. The rotor was viewed through a port provided with several vacuum-sealed thermal radiation absorbing windows.

In General Electric's current unit of the gimballed cryogenic gyro, major improvements relate to the bearing configuration and to the use of an optical readout system in which all parts operate at liquid helium temperature. Design features of this new gyro are shown in Figure 5-5. The bearing permits separate control of rotor stiffness along each of three orthogonal axes to give improved "g" capability and better accuracy, since the rotor will be maintained closer to the geometric center of the bearing than was possible in the earlier version.

The new cryogenic optical system follows recent development of small, high efficiency light-emitting diodes which, together with suitable semiconducting sensors, have permitted design of an extremely sensitive spin axis position sensing system using a reflecting flat surface formed on the rotor, tilted approximately one-half degree from the rotational axis. This results in the reflected image moving in a conical path which passes through a circular aperture to a germanium sensor. The amount of light received by the sensor varies with the misalignment of the rotor spin axis and the optical axis. With perfect alignment a constant amount of light passes through the aperture and no a-c signal output results. As the rotor tilts, an a-c signal is produced which has a magnitude proportional to the tilt angle. Information obtained from a rotor position reference slot used as part of the rotor optical system is used to obtain phase relationship of the spin axis signal to determine direction of rotor tilt.

Considerable progress, under AF and NASA sponsorship, by Harding, Buchhold, Schock, etc., has been made on gimballed and a bodybound version of this type of gyro. A gimballed cryogenic gyro has shown a constancy of drift at least as low as 0.005 degrees per hour during several test runs using different rotors.

Throughout development of superconducting gyroscopes it has been necessary to conduct special investigations of superconducting properties in order to define design limits and to evaluate the effects of manufacturing processes upon these characteristics.

Future improvement in gyro performance is seen by the use of niobium-coated ceramic rotors rather than the all-niobium rotors now available. The ceramic rotor will have higher dimensional stability and be lighter in weight. Acceleration force capability up to approximately twenty-five "g's" is predicted with the ceramic rotor. Excellent superconducting properties have already been obtained with niobium coatings on ceramic.

The gimballed cryogenic gyro has been shown to offer high accuracy potential, and no fundamental barriers to eventual future application have been uncovered. As advances are made in cryogenic technology, the low temperature environment becomes less of a challenge. Growing interest and research in the metallurgy of superconductors also will contribute to this program.

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(6) RELATIVISTIC SENSORS

At Stanford University a program to produce a special purpose gyro of unusual accuracy has led to some contribution to the state of the art. The special purpose is to check certain aspects of the General Theory of Relativity;[6-1] and the requisite drift rate is .01 sec/year.

Hope for achieving the low drift is based first on operation in a zero g satellite,[6-2, 6-3] which will track the spherical gyro rotor without touching it, thus eliminating the need for rotor support. The satellite will also shield the rotor environmentally; thus, it is hoped, drift-producing moments will be lower by 10^{10} than for an earth-bound gyro. At this point three contributions are reported.

1. To test the satellite translation control system, a two-dimensional translation-motion simulator--an air-cushion vehicle riding over a granite gauge block surface (1.2 m by 1.5 m) is now in operation at Stanford. This facility is the translational analogy of the rotary air bearing tables used for simulation of space vehicle attitude control. The granite block is servo-leveled to a few tenths of an arc second, and the friction level of the 10^{-2} cm air film corresponds to less than 10^{-7} g. Deliberate tilt of the table corresponds directly to aerodynamic drag in orbit, and the table angle can be programmed to simulate drag variation due to orbit ellipticity, atmospheric non-uniformity, etc. Operation at 200 nautical miles altitude is now being simulated with accuracy.

2. A major problem in conducting the relativity experiment will be readout of the gyro spin vector--particularly since the spherical rotor must be nearly iso-inertial (to one part in 10^6) to reduce gravity-gradient torque to

a level compatible with the desired drift rate. To solve this problem Professor Fairbank, of the Stanford Physics Department, has invented a technique of possible general interest. Exploiting his own discovery that magnetic flux in a superconductor is quantized, he will use a superconducting unmarked iso-inertial spherical rotor, and sense the London magnetic moment, which is aligned precisely with the spin axis. A special readout circuit (also superconducting) will automatically give a digital readout in flux quanta corresponding to .001 arc sec. The London moment has been detected with the special circuit in Professor Fairbank's laboratory using a very small cylindrical test rotor.

3. An "active damping" technique[6-4] for forcing a chosen axis of a free-rotor spherical gyro to align itself with the gyro spin axis automatically during spinup is being developed by Professor Lange. A rotor, iso-inertial to one part in 10^6, can be aligned in the same amount of time that it requires to accomplish spinup, while conventional passive damping could require months. This technique is useful because any rotor-fixed readout method, such as an optical flat for the unsupported gyroscope or rotor markings for an EVG, requires that the rotor spin about a known preferred axis. Air bearing laboratory models are being tested.

Principal investigators for the program are Professor Cannon, Professor Fairbank, and Professor Lange. Project Manager is Dr. D. B. DeBra.

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(7) ROTATING TENSOR SENSORS

It has been widely assumed that it is impossible to distinguish between gravitational and inertial effects. (Einstein's Principle of Equivalence) This is true for a point; however, for a finite sized body, Roberson, Diesel, and Forward have found that these effects possess different detectable tensor differences.

Inertial Fields

The linear acceleration, Figure 7-1, of a mass creates a uniform inertial field in the frame of reference of the vehicle which has purely vector properties and no spatial gradients. If the mass is rotating, Figure 7-2, the rotation sets up a symmetrically cylindrical inertial field. This not only has a radial gradient resulting from the change in the magnitude of the acceleration vector with a change in radius, but also a tangential gradient due to the change in direction of the acceleration vector with a change in angle. The resultant acceleration gradient field is a tensor of value zero in the direction of the rotation axis and value Ω^2 in the directions at right angles to the rotation axis. The gradient is constant and has no higher order gradients.

Gravitational Fields

The gravitational force field is equivalent to a gravitational acceleration field

$$a_k = \frac{1}{m} \nabla_k \varphi \approx -\frac{GM}{R^2} \qquad (7\text{-}1)$$

This can be detected, provided that the center of mass of the sensor and the object being sensed are not in free fall. If the object is in free fall with respect to the sensor the only measurable components of the gravitational field are the gravitational force gradients which comprise a symmetric tensor.

$$\Gamma_{ij} = \nabla_i \nabla_j \frac{\varphi}{m} \quad \frac{GM}{R^3} \qquad (7\text{-}2)$$

The spatial pattern of the gravitational force gradient fields can be seen in a simplified form in Figure 7-3.

If a differential force sensor or gradiometer is rotated through this spatial pattern, the output of the sensor will go through a maximum twice each revolution, while any residual unbalanced acceleration forces will cause excitation of the sensor only once per revolution. This double frequency effect and the more general properties of tensors can be used to separate the effects of acceleration, rotation and gravitation by frequency filtering techniques.

In Diesel's gravitational gradient detector, see Figure 7-4, an accelerometer mounted to a freely rotating double bob pendulum will not sense disturbance of the pivot axis since angular acceleration of the pendulum exactly concel the component along the accelerometer sensitive axis. The gravity gradient signal is not similarly cancelled since the mass of the bob is concentrated as two points 90° apart in space, and thus 180° apart with respect to the double frequency sinusoidal signal.

Forward's gravitational mass sensor, Figure 7-5, consists of a mass spring system with one or more vibrational modes which is rotated at some subharmonic of the vibrational mode. The presence of a non-uniform gravitational field excites the vibrational modes of the structure at twice the rotational frequency.

The readout of the very small vibrations ($2.5\ 10^{-11}$ to $2.5\ 10^{-14}$ m.) is achieved by the use of piezoelectric strain transducers mounted on the sensor arms. These transducers have been used in previous work to measure ac motions down to 2.5×10^{-16} m.

Present Status

Forward's cruciform mass sensor is under experimental investigation on NASA Contract NASw-1035. The sensor, when stationary, has already detected ac gravitational gradient signals as small as 10^{-8} sec^{-2} or about one percent of the earth's gradient. The major effort at present is the reduction of noise introduced during rotation. The noise level in the rotating sensor at present is about 15 times the signal expected from the earth's gradient and is due to turbulence in the vacuum chamber at 0.010 Torr as the sensor "windmills" through the residual air. A better vacuum system and a co-rotating vacuum chamber are being added to eliminate this source of noise.

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(8) VORTEX RATE SENSOR

Primary interest in this device is due more to the fact that the output of the vortex sensor may be used directly with fluid amplifier type elements, rather than using the sensor to obtain superior performance over conventional gyroscopic devices. This, no doubt, accounts for the fact that development of the vortex sensor is being performed by workers active in fluid systems work rather than gyro instrument engineers.

Simplified Operating Principles

The exact solution of the three dimensional equations of motion for a real, viscous, compressible fluid (Navier-Stokes equations) is not known except for a limited number of cases. Normally, a number of simplifying assumptions are made, which reduce the complexity of these equations. In the case of the vortex sensor, it is possible to make a sufficient number of these assumptions to permit a basic understanding of the unit.

Figure 8-1 shows the general configuration of the "pancake area" in the vortex rate sensor. Fluid (liquid or gas) is supplied under pressure to a plenum chamber surrounding the coupling element. This coupling element is made from porous material and will impart any angular velocity (ω) of the sensor to the fluid passing through. If it is assumed that the flow is two dimensional and that the fluid is inviscid and incompressible, the following analysis can be made.

If the sensor is rotating with an angular velocity (ω) the tangential velocity of the fluid of the coupling element (V_o) is given by

$$V_o = \omega R_o \tag{8-1}$$

From the conservation of angular momentum, the tangential velocity of the fluid at any radius (R) is inversely proportional to the radius, or

$$VR = K \qquad (8\text{-}2)$$

If V_i is the tangential velocity of the fluid at the sink, then

$$V_i R_i = V_o R_o \qquad (8\text{-}3)$$

or

$$V_i = \frac{V_o R_o}{R_i} = \frac{\omega R_o^{2}}{R_i} \qquad (8\text{-}4)$$

It can be seen from Equation (8-4) that the vortex flow, in effect, amplifies the tangential velocity imparted to the fluid at the coupling element.

The velocity in the radial direction (U) can be determined by the conservation of mass,

$$UA = K \qquad (8\text{-}5)$$

or

$$2 \pi R_o h U_o = K \qquad (8\text{-}6)$$

where h is the height of the vortex chamber and Uo is the radial velocity of the fluid at the coupling element. If the chamber is of constant height

$$2 \pi R_i h U_i = 2 \pi R_o h U_o \qquad (8\text{-}7)$$

From this relationship, it is seen that the radial velocity increases as the fluid approaches the sink. This also presents a practical limitation which determines the minimum value that the radius of the sink may approach. The simple one dimensional, isentropic flow equation gives the following relation between velocity and area

$$\frac{dA}{A} = (1 - M^2)\left(-\frac{dU}{U}\right) \tag{8-8}$$

where M is the Mach number of the fluid. The velocity, therefore, in the converging passage cannot exceed the velocity of sound. A limit is established on the sensitivity of the vortex unit, which is now a function of Ro/Ri and Uo, the entrance velocity of the fluid.

Another significant parameter in the vortex rate sensor is the transport delay. Since rate information is generated at the coupling element and is sensed in the sink region, there is a delay associated in the output with respect to the input. The delay is equal to the time required for a fluid particle to travel from the coupling element to the sink. The ideal transfer function can be expressed as

$$\text{Output} = K(\text{input})\ e^{-\tau s} \tag{8-9}$$

where τ is the transport delay of the sensor. From Eq. (8-5), it is seen that the radial velocity (U) is inversely proportional to the radius for a constant height vortex chamber, i.e.,

$$U = \frac{K}{R} \tag{8-10}$$

The differential equation relating distance and time is:

$$-dR = U dt = \frac{K}{R}\, dt \qquad (8\text{-}11)$$

and

$$\tau = \int_{R_o}^{R_i} dt$$

from Eq. 8-11 $dt = -\frac{R\,dR}{K}$

Therefore

$$\tau = \frac{1}{K}\left(\frac{R_o^2 - R_i^2}{2}\right)$$

finally

$$\tau = \frac{R_o^2 - R_i^2}{2U_oR_o} \qquad (8\text{-}12)$$

It is evident from this equation that large values of R_o and small values of U_o which are required for high sensitivity will also produce large transport delays, degrading the dynamic performance of the unit.

Practical Considerations

The simplified analysis provides a basic understanding of the vortex rate sensor; however, as with most sensor elements, the performance depends on the sensitivity of the pickoff device. In this case, the fluid rotational velocity at the sink must be sensed in some manner and used to drive a fluid amplifier. In general, however, the relative merits of pickoffs can be measured with respect to sensitivity, inherent noise generation and output power. The weighting factors associated with each characteristic are a function of the application; therefore, no order of rank may be given.

Noise generation in the coupling element can also present a problem. Although the amplitude of the noise may be small, it will be amplified by the sensor in the same manner as the signal.

Present Status

The feasibility of the vortex rate sensor has already been demonstrated in providing rate damping signals in an aircraft control system,and has also been used in conjunction with a fluid integrator to provide an attitude reference on an experimental missile control system. In both cases, test flights were highly satisfactory.

The operation of the sensor has been demonstrated on both liquids and gases. The operation of the sensor with sea water as the fluid medium offers a wide potential for naval applications. Ram air or water can provide free power in many cases. Compensation techniques to reduce supply pressure and temperature sensitivity are proving successful, and should permit the vortex sensor to operate under environments prohibitive to conventional sensors. The sensor can be made insensitive to radiation, thus could be used on a nuclear-powered vehicle with no shielding. The low mass of the fluid minimizes acceleration sensitivity, making the vortex sensor an ideal instrument for high "G" environments.

The vortex rate sensor is rather unique among the "unconventional" sensors in that its eventual use will be determined primarily on the extent of the application of "fluid amplifier technology." Although operational experience is limited at this time, development tests have been encouraging. The dynamic performance of units presently under development covers control frequencies of 5 hz or less. The vortex sensor offers significant advantages over conventional gyros on the scores of cost and ruggedness; indeed, a unit flown in a test missile was recovered after impact in perfect operational condition, even though the conventional gyro used for telemetry was destroyed.

The ultimate performance potential of the vortex rate sensor has yet to be achieved. There is room for improvement in both the sensitivity and dynamic response of the sensor. Considering the limited research and development effort expended on vortex sensors, the progress to date has been gratifying. However, as the technology receives wider attention, new concepts offering significant improvements will come forth.

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(9) QUANTUM MECHANICS

It is perhaps no more than an intuitive feeling of the author that the best accomplishments in the unconventional sensors will come from examination through quantum mechanics and solid state theory of the fundamental properties of material structure. This type of approach probably optimizes the search for microminiaturized "electromechanical" type sensors compatible with electronic microcircuitry. This last section lists some of the very attractive ideas being studied by Jacobs and his co-workers at Autonetics.

Helicon Gyro

The helicon gyro concept can be described as a circularly polarized electromagnetic wave that propagates with extremely slow phase velocity along the magnetic field lines of a plasma. Helicon wave frequencies as low as a fraction of a cycle per second have been detected in a small sample of sodium. Since the frequency of the circularly polarized waves should be determined by the physical properties of the plasma alone, the measurement in inertial space of this frequency would be independent of the state of rotation of the solid. If, however, the measurements were made in a rotating frame of reference, the frequency would be shifted by the rotation rate. Hence, rotation rate might be measured as a shift in helicon frequency. Because helicon frequencies are low, and frequencies can be measured with great precision, a sensitive rate sensor should result. By choosing two helicon waves in two plasmas with opposite fields, the vehicle rotation could be produced as a direct output of the sensor. Such a device has no moving mechanical parts, and has the virtues of simple construction, and small volume. It would have no g sensitivity and, hence, have utility as a high g and rate device.

Diode Laser Accelerometer

An interesting acceleration sensing device has been designed taking advantage of the properties of solid state injection diode lasers. It has been shown at Autonetics that the lasing frequency of GaAs diodes can be tuned by hydrostatic pressure. Preliminary results indicate that the stress sensitivity is such as to yield a very sensitive device with a wide dynamic range. The instrument is mechanized by supporting a proof mass between two diodes which are caused to lase. The optical outputs of the two are combined and heterodyned. Under acceleration, the stress on one diode is increased, and decreased on the other, causing a respective increase and decrease in the optical frequency. By mixing these light beams in a photocell, a beat frequency proportional to acceleration is obtained. This instrument is similar in principle to the vibrating string accelerometer with diode quantum oscillator lasers replacing the vibrating strings.

Ferromagnetic and Solid-State Resonance Effects

The area of oscillatory effects in solids is one where new approaches may lead to stress-frequency transducers having high reliability and long lifetime. Such sensors could be small in size, and have no moving parts, and operate over a wide temperature range at about room temperature with no requirements for a cryogenic environment. Solid-state oscillatory effects can be conveniently divided into four areas:

1. Radio frequency ferromagnetic resonance in uniaxial magnetic thin films,
2. Magnetoacoustic resonance,
3. Current oscillations in semi-conductors,
4. Solid-state plasma.

Radio frequency ferromagnetic resonance (FMR) in uniaxial magnetic thin films may be applied to acceleration-sensing by utilizing the high magneto-elastic sensitivities of certain uniaxial films and by utilizing the high stress sensitivity of FMR to the angle between an applied field and the anisotropy self-field in the film. In terms of Q, the Q of FMR is already rather high, but coupled with the high angular sensitivity, the Q is enhanced by several orders of magnitude. A stress-sensor of high resolution is therefore anticipated.

Magnetoacoustic resonance is a phenomenon observed at microwave frequencies rather than radio frequencies in materials which have both high-Q magnetic modes and acoustic modes which are rather tightly coupled. The frequency range over which the effect has been observed is from 1 to 10 gHz. The sample size is about 0.25×10^{-6} m. For pump powers above a threshold of approximately 3 milliwatts both magnetostatic modes and acoustic modes can be excited. The strong effect of the stress-field upon the acoustic frequency will be communicated to the magnetic system through the electron spin-phonon interaction. The effect of stress may then be observed indirectly through its effect on FMR frequency, which can be determined with good precision.

Current oscillation in semiconductors is another area in which application may be made to a stress-sensor. Small size is again possible; the sensing material itself may be a cube 10^{-2} cm on a side. The high-Q oscillation, which exists after a threshold value of electric field (about 1000 volts/cm) is applied across the sample, depends on both sample dimensions and material properties. Both are expected to change sensitively with stress.

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