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PRESENT-DAY GYROSCOPIC INSTRUMENTS AND PROSPECTS FOR THEIR FUTURE DEVELOPMENT

(Based on Information in the Foreign Literature)

S. I. Antonov

ABSTRACT

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Current trends in the development of gyroscopic instruments are surveyed. Structural modifications imposed in gyroscopic instruments in response to new operating conditions are considered. The suppression of drift through the use of new types of gyroscopic suspensions is discussed in some detail, with the present stage of development of each type indicated in a table.

The growth of rocket and aviation engineering has advanced many problems /128* in connection with raising the accuracy and reliability of gyroscopic instruments.

The most important parameter of the gyroscope is the drift rate of the rotor axis under the influence of perturbing moments; this parameter is adopted as a criterion of the level of achievement in gyroscopic technology. At the end of World War II, gyroscopic instruments were rated in terms of drifts of approximately 10 deg/h. In the last ten years, gyroscopes have been developed with drift velocities on the order of 0.1 to 0.01 deg/h. The improvement in quality by 1955-1956, therefore, is measured in the ratio 10^2:1.

Typical of the present state-of-the-art in the manufacture of gyroscopic instruments are the wide variety of type and broad range of admissible drift

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*Numbers in the margin indicate pagination in the original foreign text.

errors. This is governed largely by the diversity of purposes for which the gyroscopes are intended.

The construction of gyroscopes and the admissible drift errors are most significantly affected by the following:

1) designation of the vehicle, as defined by the permissible target accuracy or error in arrival at a destination, the flight time, and the overhall physical dimensions;

2) dynamics of the vehicle;

3) control system warmup time;

4) conditions anent operation of the control system as a part of the vehicle.

The accuracy of gyroscopic instruments is illustrated in table 1 as a function of the type of vehicle. The requirements imposed by keeping ballistic rockets in a state of constant readiness and by prolonged continuous functioning of the control systems in satellites and submarines have motivated the development of gyroscopic instruments with an almost unlimited serviceable lifetime, gyros with electrical, electromagnetic, and aerodynamic suspensions, the molecular gyro, etc.

The gyros used in modern technology may be classified according to their /129 accuracy into two categories, depending on the admissible drift error:

1) low-accuracy instruments, to be used under rigorous external conditions; these instruments have low stability;

2) high-accuracy instruments, also to be used under rigorous external conditions; these instruments have high stability.

As a result of the modernization of low-accuracy instruments and simplification of high-accuracy instruments for special purposes, an intermediate, medium-accuracy class has emerged (see table 2).

TABLE 1 /130

ACCURACY OF GYROSCOPIC INSTRUMENTS

Vehicle	Flight time	Admissible drift rate deg/h	Equipment
Short-range tactical rockets (anti-tank, air-to-air, etc.)	to 1 min	30 to 60	Autonomous gyros
	to 5 min	10	Stabilized platform
1. Medium- and long-range tactical rockets	few min. to hours	5 to 0.1	Autonomous gyros and autopilot systems
2. Transport planes			Stabilized platform
			Inertial platform
1. Strategic rockets	few min. to hours	0.1 to 0.001	Inertial platform
2. Fighter planes, bombers			Autonomous gyros in guidance and control systems
3. Rocket planes	Few hrs. to days, months		
4. Submarines			
5. Satellites			

TABLE 2

CLASSES OF ACCURACY			
Characteristics	Low accuracy	Medium accuracy	High accuracy
1. Drift rate, deg/h	60 to 5	5 to 0.1	0.1 to 0.001
2. Type of suspension:			
a) rotor	Ball bearings	Ball bearings	Ball bearings, gas bearings
b) gimbal			Hydrostatic suspension
3. Operating conditions (common to all classes)	Vibration, accel. 15 g, freq. 5 to 2000 cps Presence of radiation conditions	Impulses, accel. to 60 g Presence of dust, moisture, conditions for growth of fungus, etc.	Temperature to 200 deg C
4. Relative cost (assuming the price of the simplest gyro instrument as unity)	1:12.5	12.5:30	30:100

1. OPERATING CONDITIONS AND MODERNIZATION OF GYROSCOPES

The external conditions under which gyroscopes must operate are specified by the following parameters:

1) vibrations with 15 g acceleration at frequencies from 5 to 2000 cps;

2) impulses with accelerations to 60 g;

3) temperature to 200°C;

4) radiation;

5) the presence of dust, moisture, conditions for the growth of fungus, etc.

The present requirements serve as the starting point for the design of low- and high-accuracy gyroscopic instruments.

In special instances, the specification of these norms is more stringent. For example, some gyroscopic instruments are designed to operate under conditions involving impulse accelerations up to 100g. Work is being done on the development of miniature gyros designed to operate at temperatures up to 370°C.

In a number of cases, the ability of the gyro to withstand large impulsive shock-type loads, as well as vibrational and linear accelerations without any appreciable alteration of the drift rate is more important than the assurance of small drifts. One of the main reasons for the onset of drift under the influence of accelerations is nonuniformity in the rigidity of construction in the direction of the principal axes. Very often the structural elements determining the distribution of rigidity introduce irregularities in stiffness (for example, the gimbals). Design measures are therefore aimed primarily at increasing the stiffness of the overall structure of the gyro.

Certain grades of steel, for example stainless, have begun to find application as the material for the inner and outer gimbals, while beryllium is being used for very precise gyros (by the Litton firm in particular, for a three-axis gyroscope).

The configuration of some of the parts has undergone a change; the inner gimbal is made in the shape that will impart the maximum stiffness, namely spherical. It has been found that the least stiffness in the chain of elements governing the equivalent stiffness in a given direction is possessed by the /131 bearings. Many firms have updated the bearing assembly; the outer ring of the bearing is made more massive. The rotor axis and gimbal are made to function simultaneously as the outer ring of the bearing, permitting an increase in their diameter.

In certain types of instruments, a very high stiffness is acquired. The Kearfott firm has developed a free gyro with drifts of less than 0.5 deg/min under conditions of vibration at accelerations of 28g.

For rockets with a very short flight time (less than one minute), gyros with a simple configuration have been built. The gyro rotor is accelerated up to about 20 000 r.p.m. from the pressure of gas in storage tanks or from a coil spring. The runup time is 100 msec. The gyro operates in the free-rotor mode. The drift rates in this mode do not exceed 30 deg/h. Instruments of this type transmit large mechanical overloads and are distinguished by high reliability.

2. MAIN TRENDS IN THE DEVELOPMENT OF PRECISION GYROSCOPES

The drift rate is decreased by one to several orders of magnitude primarily as the result of new techniques in the suspension of the gyro.

Ball Bearing Suspension

The range of drift in gyroscopic instruments with ball bearing suspensions falls between the limits 60 to 0.1 deg/h, where drift rates of 1 to 0.1 deg/h are observed when friction effects are averaged out by the application of injection in the bearings. Considerable difficulties are encountered in attempting higher accuracy on the part of ball bearings, but efforts to improve them are continuing.

The use of ball bearings in the gyro rotor and in the suspension of the gimbals has the following shortcomings:

1) Appreciable perturbing torques, which increase with time, are imposed on the gyro.

2) Due to variation of the friction torque in the ball bearings, in the spin motor there are variations in the thermal conditions of the gyro and load on the power source.

3) The center of mass of the spin motor assembly shifts due to wear in the ball bearings.

Hydrostatic (Floated) Suspension

Gyros with hydrostatic (floated) suspensions are being developed by a laboratory at the Massachusettes Institute of Technology, where in about 1947 a two-axis integrating gyroscope was built with drift rates of 6 deg/h.

The first report of a three-axis gyro using hydrostatic suspension, with /132 drift rates of 0.1 deg/h appeared in 1956 (firm of Bosch Arma). Somewhat later, there were reports of integrating gyros being manufactured, and in 1961 a free gyro was manufactured with hydrostatic suspension, having drift rates of 0.01 deg/h.

The residual pressure on the bearings of a hydrostatic suspension in a gyro assembly amounts to 1% of its weight for instruments with standard dimensions and 80-90% for miniature and ultraminiature gyros.

The volume of feed fluid is minimized in present-day gyroscopic instruments in order to reduce the harmful effects of convective currents due to heating of this fluid.

In the first stage of development of instruments with hydrostatic suspensions, the rotor of the gyro was rotated on ball bearings, while more recently ceramic bearings with gas lubrication have been used for this purpose.

Hydrostatic suspensions have the following shortcomings:

1) the need for maintaining the temperature of the fluid supply at some fixed level throughout the guaranteed service life (thermostatic control);

2) the onset of dangerous torques due to convective currents in the fluid supply during operation of the spin motor and heating elements;

3) considerable warmup time required for arrival at the nominal thermal regime;

4) precession of the gyro gimbals due to damping torques;

5) technological problems in the removal of air bubbles from the fluid supply.

Gyros with hydrostatic suspensions are used in the guidance and control systems of many rockets (Atlas, Titan, Thor, and others).

Gas Bearings

An important trend in the development of gyroscope technology is the design of instruments with gas bearings.

Gas bearings are distinguished by the following characteristics:

1) There are no surfaces with very high loads; the supportive surface or load surface is one hundred times the same surface of ball bearings.

2) There is no physical contact between the bearing surfaces during movement of the rotor, so that the bearings do not wear out in service.

3) Mechanical noise is reduced; considerable vibration is induced in ball bearings by minute roughnesses. /133

4) With the large contact surface, the heat conduction through bearings with gas lubrication is many times greater than through an equivalent ball bearing.

5) No problems arise in connection with chemical decomposition of the lubricants or radiation effects.

A distinction is made between two types of gas bearings: aerodynamic and aerostatic.

Aerodynamic suspension. - Aerodynamic suspensions are used in two modifications:

1) In a ceramic gyro, the required supportive pressure is created by the relative motion of the pivot and bearing of the spin motor; the other degrees of freedom are generated kinematically by the spin motor bracket in the gimbal (one or two).

2) In a gyro with a spherical rotor turning in a housing, the film supporting the sphere is also created as the result of relative motion, but the housing is capable of moving relative to the geometric axes of the sphere's equatorial plane (which act as the axes of the inner and outer gimbals).

In the latter case, we have a gyro with an aerodynamic suspension. The American firm Autonetics has developed and fabricated a free gyro whose rotor is in the form of a spherical aerodynamic bearing. The instrument has three degrees of freedom, one unconstrained with respect to the axis of rotation and two constrained with respect to two mutually perpendicular axes. The latter two are the output axes.

The instruments may be used in guidance and control systems of intercontinental missiles, for which readiness to instant alert is a requirement.

In the fabrication of gyros with aerodynamic bearings, one comes up against considerable technological difficulties engendered by the use of special materials (ceramic, beryllium, etc.), which are difficult to work and machine. Moreover, it is essential to observe micron tolerances, calling for precision machining of the spherical surface and the observance of strict sphericity.

In small integrating gyros, the rotor of the ceramic gyromotor is suspended on a gas film less than 1.3μ. The noise generated in an integrating gyro with a rotor supported on ball bearings is reduced thirtyfold in the case of a ceramic gyro (equivalent type).

Aerostatic suspension. - The aerostatic suspension is used, like the fluid in a hydrostatic suspension, to support the gyro assembly. Aerostatic bearings require an external source of pressure, usually a small compressor. /134

The aerostatic suspension is less susceptible to harmful temperature effects than the hydrostatic version. Its drawback is contamination of the air delivered from the compressor. The clearances in an aerostatic bearing are somewhat greater than in the aerodynamic type, but very rigorous demands are imposed on guaranteeing a symmetrical flow of gas inside the bearing.

Electrostatic Suspension

A gyro with an electrostatic suspension comprises a sphere rotating in an electric field, the sphere being invested with three degrees of freedom.

The electrostatic field for supporting the sphere is produced inside a ceramic housing by electrodes carrying a high d.c. voltage.

The vertical and horizontal coils inside the ceramic housing create a rotating magnetic field around the rotor, turning the rotor at a rate of 24 000 r.p.m.

In the operational state, a clearance of 0.64 mm is established between the rotor and vertical walls of the housing. The sphere (rotor) is made of beryllium and, in the case of the first prototypes, has a diameter of 76 mm. The overall dimensions of the ceramic housing are 120 mm in height and 89 mm in diameter. A small-scale version will bear 1.8 kg and utilize a power of about 4 W. A high vacuum is created inside the ceramic housing, comparable to that used in vacuum-tube technology (10^{-5} to 10^{-6} mm Hg).

The principal difficulties encountered in the design of gyros with electrostatic suspensions are considered to be the following:

1) the production of spheres with very small deviations from sphericity (with precision better than 0.13 μ);

2) the design of the ceramic housing with a high hermetic seal.

The main reasons for drift in the electrostatic gyro are imbalance of the sphere mass, the effect of magnetic fields, and spurious electrostatic fields.

It is assumed that in spacecraft under conditions of weightlessness, the drift in gyros with an electrostatic suspension will not exceed one degree in one year of continuous operation. Under these conditions, the problem of creating the vacuum is simplified. It is postulated that a gyro with electrostatic suspension should not be any more expensive than gyros with a high-quality hydrostatic suspension.

Manufacturers are also engaged in the development of gyros in application to the problems of space rocket control. In 1959, American firms built some experimental prototypes of gyros with an electrostatic suspension to be used /135 as tracking sensors for the Polaris rocket.

Electromagnetic Suspension

The rotating sphere of the gyro is suspended in a vacuum by electromagnetic fields and, as in the case of the cryogenic gyroscope, the sphere is maintained under conditions of near-absolute zero temperature.

Due to the fact that superconductors, being diamagnetic, are repulsed by magnetic field sources, it is possible in principle to obtain stable support, by contrast with the electrostatic type, which requires a feedback system in order to hold the sphere in a stable suspended state.

In a superconducting circuit, the dc current required to create the supportive magnetic field is retained therein for a long period of time after disconnection from the power supply.

The instability of the gyroscope dimensions, as one of the most important causes of deterioration of the performance characteristics, actually vanishes for materials at low temperatures due to the coefficient of linear expansion approaching zero.

In experimental prototypes, magnetic fields have been used to support spherical rotors of solid niobium 42.5 mm in diameter and weighing about 300 g under the conditions of a $2 \cdot 10^{-6}$ mm Hg vacuum and a temperature of 4.2°K.

Gyros with an electromagnetic suspension have been proposed for use in precision navigation systems in outer space flights.

Hydrostatic Suspension of the Gyro Assembly and Aerodynamic Bearings for the Rotor

A composite type of suspension has gained rather widespread acceptance. The firms of Kearfott and Minneapolis-Honeywell have developed two-axis gyros whose rotor is turned on aerodynamic bearings, while the weight of the spin motor is floated hydrostatically. Ceramic gyros are included among these instruments.

Some firms are manufacturing almost wholly ceramic bearings, others are limited to the use of ceramic bearings in the gyro rotor. In the latter case, it is possible to obtain large kinetic moments for all physical sizes.

In 1961, a free gyro was turned out with aerodynamic bearings for the rotor and hydrostatic suspension of the gyro assembly, with the float and gimbal made of beryllium in order to minimize the influence of uneven stiffness distribution and to diminish displacement of the center of mass under the action of the accelerations of the gyro rotor.

Molecular Gyroscope /137

Many firms are engaged in the development of gyroscopic sensors utilizing the gyroscopic properties of molecules and atoms.

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TABLE 3

STATE-OF-THE-ART IN THE DEVELOPMENT OF GYROSCOPIC INSTRUMENTS BY NON-SOVIET MANUFACTURERS

Type of instrument and suspension	Expected drift deg/h	Stage of development	Remarks
1. Hydrostatic suspension: a) Rotor on ball bearings; 3-axis with elastic filaments in place of gimbals	10^{-1}	Manufactured since 1957	Bosch Arma; used as course instrument
b) Rotor on ball bearings; 2-axis integrators	10^{-2}	Manufactured since 1957	Minneapolis-Honeywell, Sperry, and others
3-axis free rotor	10^{-2}	Manufactured since 1960	Litton (for inertial guidance systems of fighters and interceptors)
c) Rotor on gas bearings; 2-axis ceramic	$(1-5) \cdot 10^{-3}$	Manufactured since 1960	Minneapolis-Honeywell
3-axis	10^{-3}	Prototypes in 1961	For control systems
2. Electromagnetic suspension (cryogenic gyros)	--	Exptl. prototype in 1960	For spacecraft control systems
3-axis gyro	10^{-4}	Work continuing on new versions	
3. Electrostatic suspension	--		
3-axis gyro	10^{-4}	Prototypes in 1961	Minneapolis-Honeywell, General Electric; for submarine with Polaris missile.

TABLE 3 (Cont'd.)

Type of instrument and suspension	Expected drift deg/h	Stage of development	Remarks
4. Aerostatic suspension 3-axis gyro	--	Conceptual design plan published in 1961	--
5. Aerodynamic suspension 3-axis gyro	--	Tentatively, production begins 1960-1961	Autonetics has fabricated 3-axis gyro for control system of Minuteman intercontinental missile.
6. Molecular gyroscope	10^{-6}	Project development of prototype for control systems by 1966-1970	Leading manufacturers

The principal difficulty in the realization of a molecular gyro is the complexity of electronic detection of the output signal, although the actual sensor is regarded as rather simple.

Anticipated Accuracy and State-of-the-Art

The anticipated accuracies of gyroscopes in terms of their drift rates are shown in table 3 for various types of suspension, as well as their stage of development. It is important to note that the choice of suspension does not resolve all of the problems associated with increasing the accuracy of the gyroscope. Stabilization of the center of mass is the next most important problem relating to the minimization of drift. Only an improved technology in the fabrication of the components, superior materials, symmetrical constructions, and other factors can solve the second problem in achieving accuracy.

Other factors strongly affecting the reliability and accuracy of every type of gyroscopic instrument are the quality of seal against leakages, flexible current leads for the power supply, the problem of angle measurement and transmission, the linearity of the moment sensors, etc.

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