THE KING INERTIAL NAVIGATION GYRO

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ABSTRACT

Development of the Kearfott Inertial Navigation Gyro, or KING, a miniature gyro whose design is based on state of the art principles, was initiated in December 1957. The objectives that governed in the design were high mass and restraint stability, low anisoelasticity, and high reliability over a long life. These objectives were implemented in the following philosophy: 1) reduction in the number of parts comprising the floated assembly; 2) matching of linear coefficients of thermal expansion; 3) reduction of thermal gradients in the floated assembly; 4) extensive use of beryllium as the structural material; and 5) choice of air core-rotor designs for the signal and torque generators. Performance objectives have been realized, as indicated by extensive testing. Day to day mass unbalance stability of 0.1 deg/hr/g has been achieved, including temperature cycling and vibration environments; anisoelasticity has been measured at 0.003 deg/hr/g^2; short term random drift is regularly less than 0.003 deg/hr with output axis vertical and less than 0.015/hr with input axis vertical; and a motor life test has exceeded 12,000 hr.

INTRODUCTION

The KING is a miniature, single degree of freedom floated rate integrating gyro. Its spin motor has an angular momentum of 510,000 gm-cm^2/sec in a package basically 2 in. in diam by 3 in. long, weighing only 0.8 lb.

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In considering first the design philosophy and its implementation, the unique features and the advantages realized by their use will be pointed out. Next the history of the unit will be considered briefly, and then the test methods in use and the results that have been obtained on a sample of units will be discussed.

DESIGN PHILOSOPHY

The design considerations that have governed in the development of the KING gyro have been high mass and restraint stability, low anisoelasticity, and high reliability over a long life. In order to achieve these goals, a conservative philosophy was followed.

Differential expansion was minimized to avoid the mechanical shifting between parts which inevitably follows with the net result of poor mass stability (1).[2] The number of parts comprising the floated assembly was first reduced to an absolute minimum. The fewer the joints between parts at which shifts may occur, the more rugged the design of the parts themselves; the more stable the materials chosen, the closer the attainment of perfect stability. The temperature coefficients of linear expansion of those parts comprising the floated assembly were then matched in order to avoid the mass shifts that would result from differential expansion between unmatched parts during temperature cycling under storage or operating conditions. Even with coefficients of expansion closely matched, if temperature gradients were allowed in the design, differential expansion would result. Therefore, temperature gradients throughout the floated structure were reduced to a minimum.

After careful consideration, beryllium was chosen as the major structural material in the floated assembly. The first advantage, of course, is its low density (2); extensive use of beryllium permitted applying a much greater percentage of the floated weight to the inertia rim of the gyro wheel. The rotating wheel actually comprises 65% of the gross weight of the floated element. The philosophy governing here was to increase the angular momentum to floated mass ratio - greater than 4000

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

$(gm\text{-}cm^2/sec)/gm$ - to improve performance. Second, the modulus of elasticity is high (3), more than 400% greater than that of the aluminum alloy commonly used in floated gyros. Beryllium parts of a given cross section are correspondingly stiffer, more rugged, and more stable. Beryllium is also an excellent thermal conductor (4), which serves to reduce the temperature gradients in the floated assembly, especially in the motor. It has a temperature coefficient of expansion (5) very close to that of the steel alloy used in the spin axis bearing, thus eliminating a major source of unreliability and instability. Beryllium is also one of the most dimensionally stable materials currently used in precision floated gyros. Finally, when beryllium was applied as a structural material in the design of the floated element, the effect of these advantageous characteristics was compounded, e.g., lower density and greater stiffness in the same material.

The design of the signal and torque generators was predicated on the reduction to a bare minimum of fixed torque (nongravity sensitive torque) instability. The signal generator was designed as a differential transformer (6), and the torque generator, a permanent magnet device, on the d'Arsonval principle (7). Since iron is completely absent from the rotors of both devices, the rotors exhibit unmeasurably small reaction torque; consequently, day to day changes in the reaction torque level are also unmeasurable.

IMPLEMENTATION

Besides the advantages obvious from the stated philosophy, others accrue in the implementation of the design. At the heart of the spin motor is a rugged beryllium shaft on to which are shrunk inner race blanks that are finish-ground in place to eliminate race distortion. A single motor stator is pressure cast into place on the shaft with a thermally stable epoxy resin. The net result is a well matched symmetrical assembly whose main member is an excellent thermal bus bar that cannot sustain a gradient of more than a couple of degrees centigrade, rather than the 15° to 20°C, as in older designs. The spin bearings themselves are, for a miniature gyro, a relatively large R-3 size. The contact stresses are correspondingly lower, which results in a significant increase in gyro life. The complete motor consists of four parts plus the balls and retainers; this compares with the 15 to 20 parts plus balls and retainers that are used in the old industry standard BuOrd Mark 24 motor design. Upon assembly, the contact angle is varied in order to produce low levels of anisoelasticity. The resultant motor assembly consists of very few rugged, stable, high conductivity parts, thus obtaining good dimensional stability, reliability, and long life.

The float itself, consisting of only two parts, is a short cylinder with conical ends, thus incorporating a large flotation volume in a minimal space; such a structure has proved very stable. The motor assembly is mounted into one of the float ends by means of an interference fit in order to minimize mass shifts along the spin axis. The two float ends are pressed together and sealed by means of a single firth joint, which is soldered in order to avoid seal failures over a temperature range from -80° to well over 200°F. Only solder joints are used on the float assembly, to the exclusion of less reliable cemented seals. After the float is hermetically sealed and the signal-torque generator rotor mounted, the floated assembly is temperature cycled from -80° to 212°F several times prior to final leak check to assure a reliable hermetic seal. The float assembly, with the addition of the end-for-end, radial, and buoyancy balance weights, is now complete and consists of relatively few rugged, symmetrical, and stable parts. Buoyancy balancing reduces the gyro mass unbalance temperature sensitivity.

The pigtails, which pass power to and from the floated assembly, are very small in size; their spring torques are not needed to balance out the signal and torque generator reaction torques that, in this design, are unmeasurably small. Though the design of the signal and torque generators used in the KING requires a greater number of pigtails (seven), the spring rate due to all the pigtails acting together has been experimentally verified to be approximately 0.1 deg/hr/deg of rotation about the precession axis. Variations in the pigtails' torque level at null are unmeasurably small even when the floated assembly is slewed through varying angles from null. It is felt that reliability gains significantly in this tradeoff of pigtails for reaction-torque-free signal- and torque-generator design.

Signal and torque generators, which incorporate iron rotors, are subject to large torque changes with angular position (spring rate) (8) as well as radial and axial position (reaction torque shifts) due to the changing length of the flux lines in the gap. By eliminating iron from the rotating secondary of the KING, the spring rate and positional torque changes are largely reduced to those of the pigtails already mentioned. The additional complexity of a requirement for electromagnetic centering is also eliminated. Reliability is further served by having the signal generator primary lamination poles completely buried in the epoxy resin potting compound. No ground edges, with many small interstices between laminations and epoxy, are exposed to the fluid system. Thus the efflux of dirt and bubbles during the life of the gyro is eliminated from this source.

The KING has been successfully applied in systems that supply digital pulse torquing inputs.

Proper design of elements already mentioned to further minimize dirt and bubble problems has greatly increased reliability. (Associated uncertainty torques have been greatly reduced.) The float shape lends itself to good fill characteristics; bubble traps are all but eliminated in the design of the stationary gimbal as well. The fluid gap is a relatively large 0.015 in. The torque generator permanent magnet assembly is mounted external to the fluid system so that any particles adhering to the surfaces of the poles cannot come in contact with the float to cause stiction torques.

Reliability is also largely improved by the design of the stops that limit angular freedom about the precession axis. Dual stops are used; that is, stops located diametrically opposite one another are contacted by the float simultaneously so that the pivots and jewels experience no forces at the stops. The stops themselves do not consist of spring members, but a unique design yields an inexpensive assembly without requiring extremely tight machining tolerances. Excessive input rates, whether due to equipment malfunction or human error, cannot cause any damage to the pivots and jewels.

Continuing with the design, a bellows assembly, one side of which is vented to the ambient, was incorporated to compensate for fluid expansion and contraction with temperature changes. In order to obtain the optimum in mass stability of the float assembly, it was important to minimize the pressure cycling that the float would experience as the temperature varied over the storage or operating temperature range. The lower spring rate of the vented bellows produces a much smaller pressure variation over a large temperature range than does the totally sealed bellows enclosed in a fluid system; the latter type of bellows has a larger spring rate that is the sum of the bellows intrinsic spring rate and that of the enclosed gas. All subassemblies are so designed that they can be checked and inspected individually. Final assembly is a relatively simple operation.

The gyro is filled with a dense flotation fluid. Its pour point is near the lower end of the temperature storage range; as a result, no failures are experienced due to pigtail breakage or any cracking phenomenon in the fluid. An indication of the freedom of this design from the problem of bubbles and degassing is indicated by the fact that the pump down prior to fill takes only 15 hrs at an elevated temperature. After fill, the gyro assembly is sealed off with a positive pressure on the fluid; this positive pressure is not relieved down to the lowest storage temperature. The viscosity of the flotation fluid is chosen so as to yield a gyro gain between 10 and 15. Gyros are regularly delivered, however, with gains as low as 6 and as high as 500. The KING is a relatively high gain gyro - purposely so - in order to obtain the advantages to reliability of a fluid that can traverse the entire storage temperature range with no damage to gyro performance.

The outer diameter of the gyro is completely surrounded by a magnetic shield to minimize the effect of external magnetic fields on the gyro's performance. The KING is designed to be mounted on trunnions at each end of the gyro. From a thermal standpoint, this has allowed more effective magnetic shielding and simpler application of the unit to an end item. The location of the gyro mounting surfaces at the ends of the unit places its connection to the heat sink at as great a distance as possible from the small fluid diameters surrounding the outside diameter of the float. As a result, the unit is less sensitive to temperature gradients.

The gyro was designed to permit final adjustment of mass unbalance and restraint (gravity and nongravity sensitive torques) on final test. This permits the reduction of these parameters to a low value on test rather than during the assembly procedure.

To recapitulate, therefore, the design philosophy has been implemented to produce a gyro that is small, simple, rugged, stable, and reliable, that consists of relatively few parts, and that attains an unusually high momentum to mass ratio.

HISTORY AND APPLICATION

Design of the KING was started in December 1957. It has been incorporated by several companies into well-known missile systems, ground based systems where gyrocompassing is very important, and space systems such as the Mariner A.

A completely interchangeable motor with hydrodynamic gas lubricated spin axis bearings has been under development. This KING version is intended for those applications where such benefits as extremely long life are important. A performance summary is given in Table 1.

TEST METHODS AND RESULTS

There are many ways to determine gyro characteristics. Ideally of course, gyros should be tested under conditions as comparable to operational conditions as possible. However, any given gyro may be used in one of several different orientations in a particular system and may through its life see different orientations with respect to gravity forces and magnetic and electrical fields. If the gyro were positioned in all possible orientations with respect to these fields, gyro life prior to delivery could be severely compromised through extensive testing.

However, if each axis is oriented in more than one orthogonal position and in both headings in each position, the effects of magnetic and gravity force fields in any conceivable pattern can be determined. Experience has shown that the six position test satisfied the requirements. In addition, the six position test allows all required adjustments to be made during the calibration portion of testing. On the KING family of gyros, this six position testing is conducted in the rate mode, rather than in the servo mode commonly used in the industry. In the rate mode (9), the signal generator output is demodulated, amplified, and applied to the gyro's torque generator with such a polarity as to drive the error signal to null. The current fed into the torquer is therefore directly proportional to the sum of input rates plus all other torques about the precession axis.

Rate mode testing is not test equipment limited when testing gyros for drift rates of 0.003 deg/hr as is servo mode testing where time and angle measuring equipment of primary standard level of accuracy is required. In addition, rate mode testing provides on a strip chart recorder an instantaneous presentation of drift rate which enables the gyro engineer to take note of any short term peculiarities that would normally be obscured by the 6 to 18 min average that is taken on a servo table test. Slew pulses of current may also be applied to the gyro torquer which, for a 1 or 2 sec interval, will overpower the control amplifier and drive the gyro away from null. When the slew pulse ceases, the gyro, under the action of the control loop, returns towards null until the restoring torque is balanced out by the gyroscopic torque plus any friction torques about the precession axis. When the gyro is first slewed to one side of null and then to the other side of null, the hysteresis level (friction torque level) in that particular gyro can be determined from the separation of the returns from each side. Rate mode testing also allows the gyro to be aligned with its output axis parallel to the polar axis in order to tumble the gyro about this axis; this is performed as a diagnostic test to determine any peculiarities with respect to position and the effect of large transverse loads on pivots and jewels.

It is interesting to note from recent tests conducted on new servo equipment that short term randomness of the KING gyro in azimuth orientation, that is, IAV as determined from 15 runs over 1° in a cogging test, is generally equal to that determined in the rate mode test.

During the six position rate test the gyro is captured by torquer current in each of the following positions (see Figure 1) 1) output axis south, spin axis down, input axis east (OAS, SA down, IAE); 2) output axis south, spin axis up, input axis west (OAS, SA up, IAW); 3) output axis south, spin axis east, input axis up (OAS, SAE, IA up); 4) output axis south, spin axis west, input axis down (OAS, SAW, IA down); 5) output axis up, spin axis east, input axis north (OA up, SAE, IAN); and 6) output axis up, spin axis west, input axis south (OA up, SAW, IAS).

The relation between drift rate and torquer current depends on the relation between torque and precession rate of a gyro, $T = H\omega$, and between torque and electrical current in a permanent magnet field. The relation is measured by solving the simultaneous equations for positions.

The simultaneous equations for the six positions are

$$\omega_1 = -MU_{IA} + R_{SAV} \qquad [1]$$

$$\omega_2 = +MU_{IA} + R_{SAV} \qquad [2]$$

$$\omega_3 = -MU_{SA} + R_{IAV} + \omega_e \sin lat \qquad [3]$$

$$\omega_4 = +MU_{SA} + R_{IAV} - \omega_e \sin lat \qquad [4]$$

$$\omega_5 = +R_{OAV} + \omega_e \cos lat \qquad [5]$$

$$\omega_6 = +R_{OAV} - \omega_e \cos lat \qquad [6]$$

Combining Eqs. 5 and 6 yields Earth's rate as follows:

$$1/2\ (\omega_5 - \omega_6) = \omega_e \cos lat$$

From this equation, the relation between measured torquer current and known Earth's rate establishes the torquer scale factor. In addition, restraints in this position can be determined from Eqs. 5 and 6

$$1/2\ (\omega_5 + \omega_6) = R_{OAV}$$

Torquer current data from the other four positions then immediately establish drift rates for each position. The other simultaneous equations separate the gravity sensitive from the nongravity sensitive errors for other orientations as follows:

$$-1/2\ (\omega_1 + \omega_2) = MU_{IA}$$

$$+1/2\ (\omega_1 + \omega_2) = R_{SAV}$$

$$-1/2\ (\omega_3 + \omega_4) + \omega_e \sin lat = MU_{SA}$$

$$-1/2\ (\omega_3 + \omega_4) = R_{IAV}$$

The six position test data is reduced to plots. No retrimming or rebiasing is performed between final test runs. Between the last calibration run and the first final test run, the gyro is vibrated at 7 g from 55 to 2000 cps on each principal axis for a total of 45 min; any shift resulting can be read from the plot.

Each gyro is also run for 1 hr in one OAV position, and then in one IAV position, with slew pulses of alternate polarity introduced at the rate of 6/hr. The drift rate between the slew pulses is read from the recording; the average of these six readings for the hour is the average drift rate during the hour; the standard deviation of these readings about the average is referred to as the standard deviation of the short term drift in OAV or IAV.

It is important to note that all standard deviations quoted are derived by using the expression:

$$\sigma = \sqrt{\frac{\sum x^2}{N - 1}}$$

where x is the deviation from the average and N is the number of such deviations. N - 1 is used in the denominator instead of N since the samples are not completely random; the resultant standard deviation figure is more conservative.

Gyros are also run for periods of 15 or 40 hr to obtain data on long term single run drift. Data for vertical (OAV) and azimuth (IAV) gyros exhibit long term drift rates of the same order of magnitude as short term.

A cross section of final test data is displayed in Table 2 in the form of a frequency distribution for a sample of 130 recent gyros; the number of gyros in each drift rate interval is shown, with each group represented by a bar. The peak to peak variation in mass unbalance and restraints during the five final test runs are shown, as well as the short term values already mentioned. In addition, for 26 of the gyros the total inertial drift rate for each of the five final test runs was available; the standard deviation of each set of five runs was determined and also plotted. The maximum nongravity and gravity sensitive levels are not shown since the requirement has varied on different contracts because of varying system requirements. However, the maximum gravity sensitive drift level, for example, can be adjusted to approximately 0.02 deg/hr greater than half the maximum day to day spread, if necessary.

Mass unbalance was found to vary a total of 0.25 to 0.75 deg/hr/g over the temperature range from 75° to 180°F on a sampling of gyros.

Gyros have been subjected to temperature of -60°F without their drift rates deviating from the day to day envelope resulting from room temperature cooldowns. Gyros have been stored at -80°F without damage.

Warmup time (drift stabilization time) is largely a function of how the gyro is applied but has averaged 5 to 10 min in lab tests from temperatures as low as -80°F.

A ball bearing motor assembly has been operated for 12,600 hr under operating ambient conditions with no visible damage or significant change in running characteristics. The motor was started and stopped an average of three times per week in order to measure the run-up and run-down characteristics.

CONCLUSION

The KING gyro was designed to meet high mass and restraint stability goals; data has been presented to indicate the extent to which these goals have been realized reliably. Extensive tests have been run on KING gyros which have realized rejection rates significantly lower than were anticipated in view of tight specs and high long term stability; e.g., one unit recently returned for comparison tests exhibited gravity and nongravity sensitive drift levels within 0.1 deg/hr of the values when shipped a year earlier. Significant strides have been made in improving reliability through reducing complexity and through sound design to minimize the effects of human, material, and process imperfections.

NOMENCLATURE

IA = Input Axis

OA = Output Axis

SA = Spin Axis

MU_{IA} = mass unbalance along the input axis (SAV); positive when positive input axis is heavy

MU_{SA} = mass unbalance along the spin axis (IAV); positive when positive spin reference axis is heavy

R_{IAV}
R_{SAV} = restraint (nongravity sensitive) drift as determined from data in position indicated
R_{OAV}

ω_i = inertial drift rate for gyro in position i

ω_e sin lat or ω_e cos lat = Earth's rate component along gyro input axis

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Table 1 Performance summary

Short Term Random Drift	
Output axis vertical (OAV)	0.003 deg/hr, standard deviation
Input axis vertical (IAV)	0.015 deg/hr, standard deviation
Nongravity Sensitive Drift	0.5 deg/hr max
Gravity Sensitive Drift	0.2 (deg/hr)/g max along IA or SA
Gravity Squared Sensitive Drift	0.010 (deg/hr)/g^2 max under linear vibration
Day to Day Variation	
Gravity sensitive	0.2 (deg/hr)/g max spread
Nongravity sensitive	0.2 deg/hr max spread
Temperature Sensitivity	0.011 (deg/hr)/g°F max

Table 2 Frequency distribution of gyro drift rate of a sample of 130 gyros

		deg/hr	Number of Gyros
Short Term Random Drift Standard Deviation of a One Hour Run	**OAV (49 gyros only)**	0.006 & up	4
		0.004 to 0.005	2
		0.002 to 0.003	10
		0.000 to 0.001	33
	IAV	0.021 & up	15
		0.015 to 0.020	16
		0.011 to 0.015	29
		0.006 to 0.010	33
		0.000 to 0.005	37
Day to Day Maximum Spread Between Runs: Cold Shutdown, No Retrimming, No Rebiasing	Mass Unbalance Along IA (SAV)	0.21 & up	2
		0.16 to 0.20	3
		0.11 to 0.15	11
		0.06 to 0.10	25
		0.00 to 0.05	89
	Mass Unbalance Along SA (IAV)	0.21 & up	2
		0.16 to 0.20	11
		0.11 to 0.15	20
		0.06 to 0.10	44
		0.00 to 0.05	53
	Restraints	0.21 & up	6
		0.16 to 0.20	15
		0.11 to 0.15	21
		0.06 to 0.10	40
		0.00 to 0.05	48
Day to Day Standard Deviation* Between Runs: Cold Shutdown, No retrimming, No Rebiasing *(116 gyros only)	IAV	0.101 & up	10
		0.076 to 0.100	13
		0.051 to 0.075	25
		0.026 to 0.050	37
		0.000 to 0.025	31
	OAV	0.101 & up	3
		0.076 to 0.100	7
		0.051 to 0.075	22
		0.026 to 0.050	39
		0.000 to 0.025	45

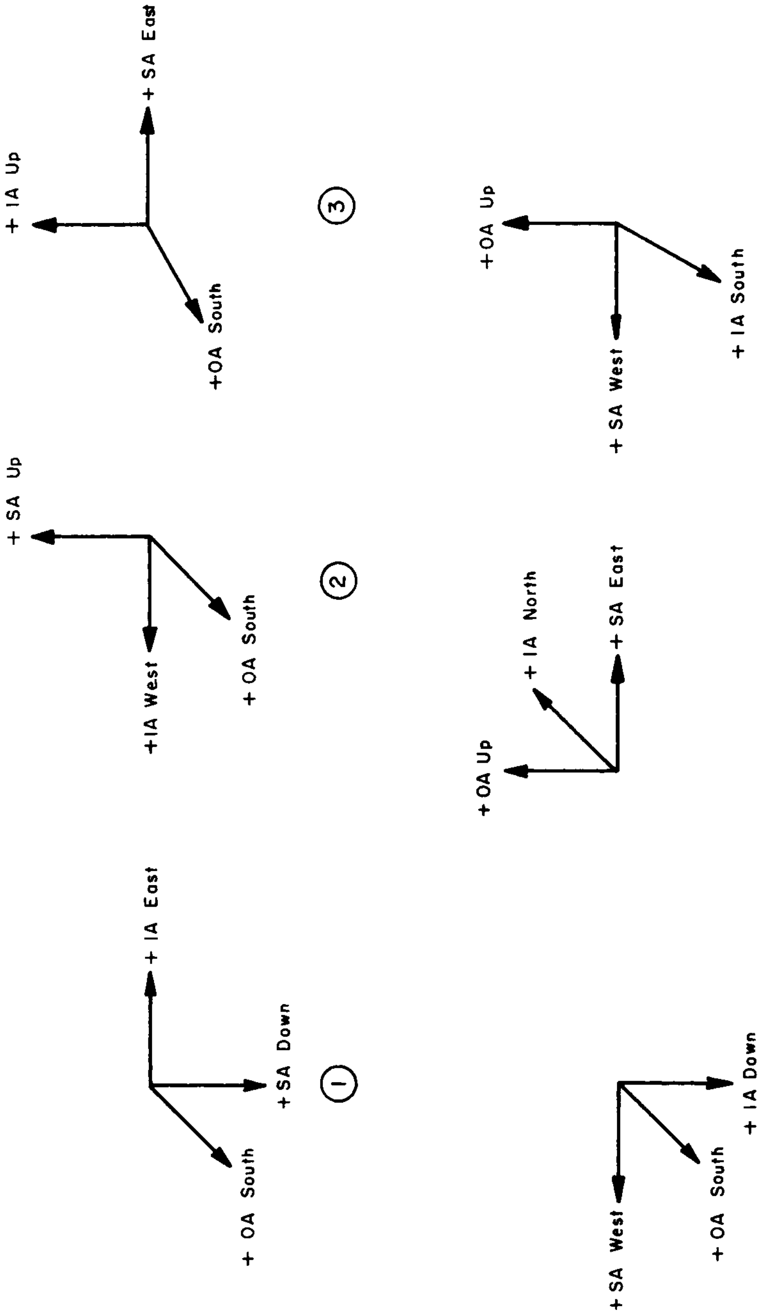

Fig. 1 Vector orientations for six position testing