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OF A MINIATURE ROLL STABILIZED GYRO PLATFORM

by

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PERFORMANCE AND APPLICATIONS OF A MINIATURE ROLL STABILIZED GYRO PLATFORM

By N. F. SINNOTT and R. O. RASMUSSEN

Summary.—The basic types of gyroscopic instruments that are available for telemetering attitude data from research test vehicles do not fulfil all requirements, and frequently a compromise in performance and data is necessary. This applies particularly to spin stabilized research rocket vehicles, wherein the high roll rate environment produces serious errors in gyroscopic devices, and frequently eliminates a gyro system from application in such vehicles.

A new gyroscopic attitude reference device, called a Roll Stabilized Gyro Platform or Miniature Attitude Reference System, has been developed for use on spin stabilized rocket vehicles. The construction and design of the system is described, followed by a discussion of error factors and over-all accuracy of the system. This new gyro system fills the void between low cost standard free gyro assemblies and the sophisticated but costly inertial platform systems. It offers additional performance features that are useful in telemetry applications which are described in this paper. Several examples are discussed, of how the roll stabilized gyro platform functioned in typical flight tests of spinning rocket vehicles.

Introduction.—The applications of gyroscopic attitude reference systems generally can be classified into two major groups:

1. As an integral part of a guidance, autopilot, stabilization, indication, or control system that is acknowledged to be fundamentally essential to the operation of a missile, rocket, aircraft, vehicle or mobile equipment.
2. As accessory instrumentation for telemetry of vehicle performance in flight test, or for stabilization and control functions of a specialized nature in research and development programs, plus some special applications as an indicating instrument.

Both groups encompass an extremely wide variety of applications. In the first group the gyro system is usually designed specifically for the application, which is often justified by the high production quantities of the prime system and its sub-systems. The common characteristic of the second group, however, is that the gyro reference is of secondary importance in the operation of the vehicle or program. It is usually desirable, therefore, to obtain gyro systems from currently available designs with a minimum of modifications. The second category, the application of specific gyroscopic devices to instrumentation and control requirements of research and development test programs, is the principal area of interest considered in this paper.

Essentially there are three basic types of gyro reference systems, with numerous variations of each, from which to choose the gyros for an R. and D. or test program.

1. A rate gyroscope assembly. Three gyros are required for a 3-axis reference. The gyros are hardmounted to the vehicle frame, thus the reference frame is body-fixed. The output signals are proportional to input angular velocities about the body-fixed axes.
2. A 2-axis displacement gyroscope assembly. Two gyros are required for a 3-axis reference. The output signals are proportional to vehicle angular displacement and the reference axes are established when the gimbals are uncaged or erected.
3. A 3-axis inertial platform system. Output signals are proportional to vehicle angular displacement and the reference axes are fixed in inertial space, unless purposely slaved to an earth reference.

In telemetry applications or for instrumentation and control applications, it is common practice to draw upon one of the many variations of the first two basic gyro systems. These systems usually are of modest cost, and their size, weight, complexity and environmental capabilities are generally acceptable. However, there are weaknesses in accuracy and in the performance of these gyro systems. A 3-axis inertial platform system is inherently more accurate and flexible than the displacement gyro or rate gyro. It frequently receives attention whenever the requirements for an attitude reference system tend towards the unusual flight regime or require high accuracy. Unfortunately, the extremely

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high cost, complexity, size and weight usually preclude the use of an inertial platform for attitude measurements in a telemetry system on research and development vehicles.

The limited choice of available basic gyro systems is particularly exemplified in research rocket test programs, since there is an inclination among aerodynamicists and rocket vehicle design engineers to spin stabilize either the entire vehicle or various stages of it.

Spin stabilization is an extension of the technique of imparting a continuous roll motion to free fall vehicles for the purpose of minimizing dispersion errors. The roll rate is, of course, much greater in high velocity rocket vehicles, and can be induced by either aerodynamic configuration, spin rockets, or by spinning the vehicle on the launcher. Unfortunately, the continuous roll motion of the vehicle frame produces a significant error on a standard 2-axis displacement gyro. This error is a precession of the inner gimbal of the gyro caused by the torque being applied to the outer gimbal through the friction in the outer gimbal bearings, slip rings, pickoffs, etc. The precession rate increases with higher vehicle roll rates to such a degree that the accumulated inner gimbal error is intolerable for most applications in spin stabilized rocket vehicles. The condition is accentuated by the high vibration and acceleration environments that are prevalent with solid propellant spin stabilized rockets. Higher gyro bearing preloads necessary to survive the environment would increase outer gimbal friction torque thus increasing inner gimbal drifts during sustained roll motions.

A new gyro system was designed for use as a telemetry instrument for spin stabilized rocket vehicles. This system is known as a 'miniature telemetering roll stabilized free gyro platform' or 'miniature attitude reference system'. It is also apparent that it increases the selection of basic gyro systems available to the aerodynamicist or test project engineer for attitude measurements. It has numerous applications using various configurations based upon the fundamental roll stabilized system concept.

Description.—Ordinarily the name 'stable platform' implies complete stabilization in inertial space as achieved by a 3- or 4-gimbal stable platform, using single-degree-of-freedom rate integrating gyros or floated free gyros for the purpose of providing a space fixed reference for guidance and control functions. The miniature roll-stabilized gyro platform, however, is servo-stabilized around the roll axis only. Fig. 1 is a functional schematic of the system. It contains two, two-degree-of-freedom free gyros mounted on the roll stabilized platform, with the roll gyro mounted so that its outer gimbal axis senses disturbing roll motions of the platform, thus providing an error signal to the roll servo to stabilize the platform. The second gyro thus is isolated from the spinning motion of the rocket vehicle and can be oriented to sense pitch motions around its outer gimbal. The inner gimbals of both the roll and pitch sensing gyros can be used to sense yaw and/or azimuth attitude. For telemetry applications yaw data is derived from the inner gimbal of the roll sensing gyro. The spinning motion of the vehicle induces torques that are coupled through the support bearings of the platform, tending to disturb its position. The motions of the platform about the outer gimbal of the roll-yaw gyro are sensed by an inductive pick-off. This inductive pick-off supplies a signal to a demodulator-equalization network through the d.c. servo amplifier to a d.c. servo motor mounted on the platform frame. The induced torques to the platform are thus cancelled by equal and opposite d.c. servo motor torques. This servo loop is a classic type 1 servo with r.c. lag-lead compensation.

The miniature attitude reference system is an extension of a predecessor system. A detailed description of this system is available in an earlier paper¹. The rather large weight and size of the earlier platform rendered it unsuitable as a telemetering attitude transducer for most applications, and instigated the development of a miniaturized and more versatile unit.

The performance characteristics of the miniature attitude reference system are shown in Table 1.

Table 1

PERFORMANCE CHARACTERISTICS

Gyro Motors

Type—Induction.

Excitation—400 cps single phase square wave (from integrally contained d.c. to a.c. inverter).

Pickoff

Multisegmented potentiometers—1 000 ohms impedance.

Linearity 1%, and resolution 0.5% of each segment. Contact resistance 50 ohms maximum under vibration environment.

Yaw Potentiometer—3 segments connected in parallel, each segment 3 000 ohms. Angular length 180°.

Pitch Potentiometer—8 segments connected in parallel, each segment 8 000 ohms. Angular length 360°.

Roll Potentiometer—4 segments connected in parallel, each segment 4 000 ohms. Angular length 360°.

Roll servo pickoff—Induction pickoff.

Caging System

Caging Input— 28 ± 3 volts d.c.

Caging Time—30 seconds maximum.

Uncaging Time—0.1 second maximum.

Uncaging—Apply 28 ± 3 volts d.c. to arm the uncaging system. Remove to uncage.

Caging Accuracy—0.25 degrees.

Operational Range

Yaw— $\pm 85^\circ$ Pitch— 360° Roll— 360°

Drift

0.5 degrees/minute maximum.

1.0 degrees/minute maximum under vibration.

Environmental Conditions

Temperature—minus 65°F to plus 165°F .

Vibration—7 G r.m.s. from 15 to 1000 cps.

Acceleration—50 G along the roll axis.*

Roll Spin Rate—720 r.p.m. nominal.*

Shock—50 G along the roll axis.

Angular Acceleration—100 rad/sec².

Power Requirement

28 ± 3 volts d.c.

Current drain—1.0 to 2.0 amps depending upon servo load.

Weight

8 pounds maximum.

*Simultaneously applied.

Fig. 2 illustrates the mechanical details of the system. A view of the completely assembled unit is shown, with an exploded view of the major subsections beneath.

The miniature platform is 5 in in diameter by 7.5 in in length and weighs 8 lb including the vibration isolators. The system is designed for mounting over vibration isolator trunnions. These trunnions are provided with indexing slots for correct system alignment. The platform supplies attitude data on three axes; roll, pitch, and yaw. The data is derived from the multi-segmented potentiometers mounted on the appropriate gyro gimbal and platform axes. The platform and all gyro gimbals are electrically cagable and uncagable. Microswitches are actuated from the caging arms of the platform and gyro caging levers, which provide continuity for circuits to indicate a caged or uncaged condition in external control panel equipment. The angular range about each axis is 360 degrees for the roll and pitch axes and ± 85 degrees for the yaw axis. The system contains its own integral d.c. to a.c. inverter, requiring 28 ± 3 V d.c. input power. A design feature of the system is the totally modular design for the two gyros, the caging mechanism, and the electronics chassis, plus the platform frame and roll gimbal.

The pitch and roll-yaw gyros are position-indexed and mounted on precision pads. The inverter module is built on a 0.125 in thick aluminium plate and is supported on a floating mount until it is drawn down against heat sink support bosses in the cap. The amplifier module is attached by heat sink blocks and posts to the inverter plate.

System Characteristics and Performance.—Characteristics of gyro systems must be evaluated in light of the intended use. Typical of the characteristics to be considered are power consumption, servo capability, size, weight, angular range, over-all accuracy, and cost. Of these, however, the principal measure of the merit of any gyro reference system is over-all accuracy. Error contributing sources are:

- (1) Drift in the gyros.
- (2) Misalignment of the system reference axes with the true vehicle launch attitude co-ordinate axes, nonorthogonality of gyro gimbals and spin axes.
- (3) Pick-off calibration errors, including linearity, resolution and zero offset.

In discussing the above three error contributing sources, we must split each into further subdivided categories. In the first category there are many drift contributing sources:

- (a) Random drifts, which are totally unpredictable.
- (b) Bias drifts, which are predictable and recurring.
- (c) Mass unbalance of gimbals or g -sensitive errors.
- (d) Anisoelastic or g^2 sensitive drift errors caused by intercardinal acceleration or vibration.
- (e) Gimbal coupling errors, which are not true errors but are often uncorrected effects due to the necessity for providing spin axis freedom through 'Hookes-joint' suspension.

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One method of evaluating gyro performance is to operate free gyros under what is called Scorsby motion. Scorsby motion consists of sinusoidal pitch-yaw motions and roll motions being simultaneously induced into the gyro system. During 10-min Scorsby test periods gyro drift is recorded. Although it is not a perfect method for evaluating gyro drift performance under missile applications, it is one of the most common and certainly quite useful laboratory methods of evaluating platform and gyro performance. Two plots of system drift characteristics under Scorsby motion are provided in Fig. 3 and 4. For a statistical sampling of seven units, data is recorded of the gyro drift rates in pitch, roll, and yaw as a function of the frequency of their occurrence. Any unit exceeding 0.5 degree/min drift rate is automatically rejected during acceptance test. The data shown is a statistical compilation of the final drift runs made on each system during its acceptance testing. The statistical distribution of drift in a free gyro system is not a normal distribution.

Fig. 4 portrays a different breakout of Scorsby drift rate in which random and bias drift terms have been separated from the mass unbalance drift term. This can be done by running the Scorsby tests in converse attitudes. When plotted, the mass unbalance drift appears as a sinusoidal term modulating a d.c. term. The d.c. drift term is due to random and bias torques. Though this method is not totally rigorous because of uncertainty of the random term, a fairly accurate evaluation can be made for mass unbalance. Repeated runs can be used to separate bias and random terms.

From a statistical sampling of seven units, the following average drift performance characteristics of the miniature attitude reference system have been compiled:

- (a) Random and bias term: .092 degrees/min.
 - (b) Mass unbalance term: approximately .111 degree/min/g.
 - (c) Anisoelastic term: approximately .05 degree/min/g² at 45 degrees intercardinal acceleration or vibration.
 - (d) Gimbal coupling errors are dependent upon vehicle rotational sequence. The configuration of this system minimizes the effect of gimbal coupling for most flight regimes. The worst condition would occur when a vehicle experiences a large angle of yaw followed by a large angle of pitch.
- If the roll axis coupling error due to yawing followed by pitching motions is significant in a particular flight, the data can be corrected by using the expression:

$$\sin R = \frac{\sin Y \tan P}{\sqrt{\tan^2 P + \cos^2 Y}}$$

This expression gives the error position of the roll gimbal (R) for a pitch angle change (P) following a yaw angle (Y). The measured yaw and pitch motions while the roll gimbal is in this error condition would be a function of the cosine of R , and for small angles of R the error in pitch and yaw measurements is minor.

It should be noted that under drift characteristic (c), drift can be introduced by on-axis vibrational excitation through various ball bearing effects. In order to minimize these errors for typical missile flights, coaxial vibration isolators were included as part of the total system. These isolators are particularly effective in isolating solid propellant burst frequencies in the range of 400 and 600 c/s and provide good isolation at all system gimbal resonant frequencies.

Gyro error analysis cannot be lightly made and gyro error is dependent upon the complete time history of the vehicle in which the system is to be used. Acceleration and vibration, including knowledge of its energy spectrum, as well as the vehicle attitude changes are essential factors in determining gyro drift.

During flight in which long free fall periods are prevalent, the relatively benign environment during free fall is favorable to low drift rates in the gyros.

In category 2, the misalignment errors of the system should also be subcategorized. Misalignment errors can occur from the following:

- (a) Machining tolerances.
- (b) Caging preset misalignment and uncaging misalignment due to precessing torques generated during uncaging.
- (c) Elastic characteristics, such as vibration isolator sag, etc.

The miniature attitude reference system maintains gimbal axis alignment of approximately 0.25°. Uncaging misalignments are less than 0.25°. Caging inaccuracy is held to less than 0.25°.

Category 3 includes errors in the area of pickoff calibration. These errors are well known and will not be extensively examined here. Typical wire-wound potentiometer limitations include wire-to-wire minimum resolution, non-linear resistance change, and wiper pressure. Contact resistance affects signal/noise ratio, and is generated by vibration and shock, causing wiper bounce. Measurements were made on the miniature attitude reference system through a 50 c/s low-pass filter. Contact resistance of the potentiometers on all axes was less than 25 ohms under 7 g vibrational inputs between 15 and 1 000 c/s, while maintaining the drift rates previously stated.

The roll axis servo system has a steady state torque capacity to provide platform stabilization under simultaneous 50 g's longitudinal acceleration and 12 r.p.s. spin rates with velocity constant errors not exceeding 0.1°. Though it is not a simple second order system, its measured damping ratio is approximately 0.5 times critical. Neglecting a.c. bandpass poles and demodulator poles, the open-loop servo transfer function is:

$$\frac{\theta_0}{E_1} = \frac{1.205 (-.255S + 1) (-.25S + 1)}{S (-.0075S + 1) (1.435S + 1) (-.0355S + 1)}$$

θ_0 = Platform Output Angle.

E_1 = Open Loop Error Input.

The servo design was directed toward the necessity of minimizing velocity constant errors and providing minimum dynamic errors by responding to high angular accelerations.

Applications.—The basic application for which the miniature roll stabilized free gyro platform was designed is to provide attitude data to be telemetered from a spin stabilized rocket vehicle. For most telemetering applications the reference axes are usually established when the gyro system is uncaged, while the vehicle is mounted on its launcher. The system could be programmed to uncage at some time during the flight. However, the reference axes would then be arbitrarily aligned to the vehicle axes at the instant of uncaging.

Due to the particular orientation of the gyros on the roll stabilized gimbal in this configuration of the system, there are additional features which are useful in field testing of research vehicles. These features are:

1. Unlimited range about the pitch axis.
2. Elimination of any inner gimbal precession error resulting from a sustained rotation about the roll axis.
3. Availability of useful attitude data after gimbal lock condition.
4. Minimized errors arising from gimbal coupling effects.
5. Compact packaging, resulting in small size and weight.

The type of attitude reference data that this system provides is identical to the data supplied by a pair of 2-axis displacement gyros (free gyro system), in which the pitch reference axis rotates with the vehicle about the yaw axis, and the yaw reference axis rotates with the vehicle about the pitch axis. The roll stabilized gyro platform, therefore, can serve as an attitude measuring device wherever a 2-axis displacement gyro system is used. This system will soon be replacing telemetering free gyro systems in all of Sandia's free-fall vehicles and rocket vehicles, wherever attitude data is required.

The unlimited pitch range is particularly useful in test programs that require the vehicle to be ejected, tossed or lobbed in a manner that precludes the use of a standard 2-axis gyro due to the limited range about the inner gimbal axis. The inner axis of each of the two gyros used in the roll stabilized gyro platform do, of course, have a restricted range of ± 90 degrees, at which point they reach the standard gimbal lock condition that is encountered in a 2-axis gyro.

Unlike the free gyro reference system, wherein the gimbal lock condition on either or both of the two separate gyros usually signifies a total loss of a useful reference, the roll stabilized gyro platform is able to provide useful data even after reaching gimbal lock on either or both gyros. The reason for this is that the pitch and yaw reference axes on their respective gyros are orthogonally aligned on the common roll gimbal and always remain orthogonal even after reaching the gimbal lock condition on either gyro.

For the purpose of telemetering attitude data, the significance of this feature is that a form of useful attitude data is always available. Prior to the gimbal lock condition the pitch-yaw reference axes are both aligned perpendicular to the vehicle longitudinal axis, with the yaw axis always contained in the plane of the trajectory and the pitch axis orthogonal to the yaw axis. This orientation will provide pitch and yaw data of the vehicle relative to the launch position. When the inner gimbal of

the roll-yaw gyro reaches its limit, the gyro will gimbal lock and the roll stabilizing gimbal will rotate until the inner gimbal of the gyro comes out of the gimbal lock condition. The pitch and yaw reference axes will then be oriented in an arbitrary position about the roll axis, and the data from the pitch and yaw gyros will have no meaningful relationship to the original reference axes. They will, however, remain orthogonal to each other and will make useful measurements of the aerodynamic behavior of the vehicle. The coning angle, coning frequency and roll rate is valuable data to an aerodynamicist, and is comparable to the type of measurements required from a rate gyro assembly in telemetry applications.

The roll stabilized gyro platform is currently being used on several different rocket vehicles for telemetered attitude measurements. The following is a tabulation of telemetered data from several typical rocket flights:

Sand Vehicle No. 1.—Two stage, solid fuel continuously rolling rocket, payload section 21 in dia.

Launch acceleration: 16 *g* average for 4.5 sec.

Second stage acceleration: 27 *g* average for 2.8 sec.

First stage peak roll rate: 1.04 r.p.s.

Second stage peak roll rate: 0.43 r.p.s.

Maximum pitch-yaw coupling motion: $\pm 2.5^\circ$ at 1.18 c/s.

After parachute deployment the vehicle pitched rapidly to maximum pitch of 267° at 132 sec then developed a large erratic conical motion with an average peak-to-peak angle of 100° and frequency of 0.294 c/s. At 295.35 sec one of the erratic oscillation peaks reached 87 degrees about the yaw axis. The roll stabilizing gyro tumbled and the roll gimbal rotated arbitrarily for 0.9 sec to a new position, and the two gyro axes formerly called pitch and yaw continued to measure angular dimensions of the conical motion. The vibration and acceleration environments did not cause any detectable effects on the performance of the gyro platform.

Sand Vehicle No. 2.—Same rocket, smaller payload. Similar vehicle performance until after parachute deployment, when it rapidly developed a large cone angle. Roll gyro tumbled at 139 sec and after the roll gimbal reached a new position the pitch-yaw channels again produced useful data.

In its ultimate operation it is intended to deploy collector blades from this vehicle and spin the entire assembly at 10 r.p.s.

Strypi Test Vehicle.—XM-33 powered, single stage spin stabilized vehicle, payload section 31 in dia., 131 in long.

Launch acceleration: 14 *g* for 1.46 sec.

Peak roll rate (sustained): 3.7 r.p.s.

Pitch and yaw oscillations: ± 1.5 deg. max.

At 434 sec the vehicle yawed to a peak of 76° while pitching over backwards to 260° , then on re-entry oscillating in a smooth conical motion, damping to zero by 464 sec.

Vibration was less than 3 *g* r.m.s. and did not affect the performance of the gyro platform. The gyro signals were monitored and used as range safety backup during launch.

Scout S-116.—(Snap-10A) multi-stage solid fuel vehicle. First three stages guided—fourth stage spin stabilized. The vehicle was programmed to a peak down pitch angle of 119.6° at 157.4 sec by the guidance system, monitored by the roll stabilized gyro platform. At 214.1 sec the pitch angle had tilted back up to 97.5° , at which point the spin rockets were fired and the vehicle spin stabilized at a roll rate of 2.38 r.p.s.

At 283 sec and a mean pitch attitude of 99.75° a large oscillation developed, measuring 19.2° peak-to-peak on the pitch axis and 17.82° on the yaw axis, at a frequency of 0.178 c/s. The oscillation had reduced slightly when telemetry blackout occurred at 320.0 sec. The vibration and acceleration environment did not have detectable effect on the performance of the roll stabilized gyro platform.

Slaved Attitude Stabilized Telemetry Instruments.—Some research test programs require instruments that are oriented toward a particular direction in space for relatively short periods of time. This need is accentuated when such instruments are to be carried on spin stabilized rockets. To meet this requirement for Sandia's field test activities, an instrument package will be mounted within a 3-axis gimballed assembly that is slaved to the reference axes of a roll stabilized gyro platform. The gyro system normally would be carried in the vehicles for telemetering attitude data on such programs and simultaneously would provide the signals for slaving the gimbals of the stabilized instruments. The slaved gimbal assembly will be caged so that the line of sight of the instrument package will be aligned

in the direction of interest at the specified time during the flight of the vehicle. Uncaging will be accomplished when the roll stabilized gyro platform is uncaged. The data from the attitude stabilized detection instruments will be connected through slip rings and flexwires to their voltage controlled oscillators and telemetry package.

Co-ordinate Converter.—The system could function as an Eulerian angle co-ordinate converter for the purpose of obtaining telemetered data of vehicle motions about space-fixed reference axes. Eulerian angles are obtained from the inner and outer gimbals of the roll stabilizing gyro in the basic configuration of the system. To obtain the third Eulerian angle, the pitch gyro could be re-oriented on the roll stabilized platform with its inner axis parallel to the space-fixed spin axis of the roll gyro. The resultant data would be telemetered for computer analysis at the ground station.

Non-Telemetry Applications.—There are variations and modifications to the basic roll stabilized free gyro system under design that will enable it to be applied to various attitude control and short term guidance functions. It has been difficult to maintain a suitable attitude reference for such functions in spin stabilized vehicles.

Conclusion.—The roll-stabilized gyro platform is a useful, versatile instrument for attitude measurements, particularly in spinning rocket vehicles. It is capable of overcoming many of the defects of 2-axis displacement gyroscopes in telemetry applications. It can serve as an alternative to complex, costly, and large 3-axis stabilized platform systems wherever the accuracy and angular range do not warrant adoption of a more sophisticated system.

REFERENCE

Sandia Corporation Report Number 476, entitled "Attitude Measurements on Spin Stabilized Rocket Vehicles."

FUNCTIONAL SCHEMATIC - ROLL STABILIZED FREE GYRO

Fig. 1

Fig. 2

ROLL, PITCH AND YAW DRIFT VERSUS FREQUENCY OF OCCURRENCE

10 MINUTE, 7.5° SCORSBY DRIFT TEST, 7 SYSTEM SAMPLING

Fig. 3

AVG DRIFT RATE RANDOM + BIAS AND MASS UNBALANCE
10 MINUTE, 7.5° SCORSBY DRIFT TEST, 7 SYSTEM SAMPLING

Fig. 4

Fig. 5. Roll Stabilized Gyro Platform (Exploded View)