NAS 12-642

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R-645

INERTIAL GYROSCOPE SYSTEM APPLICATION CONSIDERATIONS

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ACKNOWLEDGEMENT

This report was prepared under DSR Project 55-31600, sponsored by the Electronics Research Center of the National Aeronautics and Space Administration through Contract NAS 12-642 with the Instrumentation Laboratory, Massachusetts Institute of Technology, Cambridge, Mass.

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FOREWORD

NASA experience has indicated the need for uniform criteria for the design of space vehicles. Accordingly, criteria are being developed for the following areas of spacecraft technology:

Environment
Structure
Guidance and Control
Chemical Propulsion

Individual components of this work will be issued as separate monographs as soon as they are completed. This document, Inertial Gyroscope System Application considerations, is one such monograph. Others to follow under the Guidance and Control category will treat topics associated with gyroscopes, accelerometers, inertial systems, computers, and optical equipment.

These monographs are to be regarded as guides to design rather then NASA requirements, except as they may be included in formal project specifications. It is expected, however, that the criteria sections of these monographs, revised as experience may dictate, eventually will dictate the uniform design practices for NASA space vehicles.

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A_{IA} - The misalignment angle between the gyro float and the case, about the input axis.

A_{SA} - The misalignment between the gyro float and the case, about the spin axis.

A_{OA} - The float-to-case angle about the output axis with respect to its null position.

$\dot{A}_{OA}$ - The first time derivative of the output axis float angle with respect to the case.

$\ddot{A}_{OA}$ - The second time derivative of the output axis float angle with respect to the case.

a_S - Acceleration along the gyro spin axis.

a_I - Acceleration along the gyro input axis.

a_O - Acceleration along the gyro output axis.

ADIA - Acceleration-dependent gyro drift due to acceleration along the input axis.

ADSRA - Acceleration-dependent gyro drift due to acceleration along the spin reference axis.

ADOA - Acceleration-dependent gyro drift due to acceleration along the output axis.

BD - Acceleration-independent gyro drift (bias drift).

Breakaway Voltage - The minimum voltage level needed to initiate gyro-wheel-rotor angular rotation.

Case - The structure that gives support for the internal working parts of the gyro unit, encloses the parts, and carries provisions for external connections of all kinds.

C_{OA} - The gyro output-axis float-to-case damping coefficient.

C_{SA} - Gyro float-to-case damping coefficient for rotational motion about the spin axis.

C_{IA} - Input-axis float-to-case rotational damping coefficient.

C_r - Float-to-case translational damping coefficient for motion along the input or spin axis.

C_z - Float-to-case translational damping coefficient for motion along the output axis.

Corner Pocket - A term associated with magnetic suspension which describes a non-self-centering float characteristic that arises when an undesirable combination of float endshake, suspension tuning, and extreme float position in the case occurs.

Damping - For angular velocity of the float with respect to the case a retarding torque acting on the float with a magnitude proportional to the magnitude of the angular velocity of the float with respect to the case.

Dropout Voltage
- The wheel voltage level at which a synchronized wheel slips out of synchronization.

Ducosyns - "Dual coplaner microsyns", literally; an electromagnetic float support in which the signal-generator and torque-generator windings are separate from the suspension windings.

Endshake - The maximum translational output-axis float motion permitted by mechanical limits.

Float - The sealed gimbal which contains the gyro wheel and drive-motor assembly and which is supported by appropriate suspension devices within the case of the gyro.

Gyro Gain
- The static ratio of gyro-output precessional rate to input-axis rate; i.e., H_s/C_{OA}.

Gyro Transfer Constant
- The static ratio of gyro output-axis signal-generator voltage to the input-axis angle.

Gyro Transfer Function
- The ratio of gyro output to input, including the float dynamic effects.

H_s - Rotor spin-axis angular momentum.

IA - Input Axis. Fixed to float at right angles to the OA and the SA.

IRA - Input Reference Axis. Fixed to case, coincident with IA when OA and ORA are coincident and the SG is at null.

I_{OA} - Float moment of inertia about the gyro output axis.

I_{SA} - Float moment of inertia about the gyro spin axis.

I_{IA} - Float moment of inertia about the gyro input axis.

I_{SR} - The wheel-rotor moment of inertia about the spin axis.

Jewel - An output-axis mechanical stop which operates with the pivot for float-to-case motion limiting in the SDF gyro.

Jogs - A term applied to gyro nonmodel drift shifts which may or may not disappear with time (settling) and which may or may not be acceptable. In a quiet environment, the term usually can be interpreted as a wheel-torque characteristic, indicative of bearing-lubrication condition.

K_{IA} - Suspension rotational spring constant for float-to-case rotation about the input axis.

K_r - Suspension translational spring constant for motion along the input or spin axis.

K_z - Suspension translational spring constant for motion along the output axis.

K_{SA} - Suspension rotational spring constant for float-to-case rotation about the spin axis.

K_{SS} - Float structural compliance resulting in deflection along the spin axis due to acceleration along the spin axis.

K_{II} - Float structural compliance resulting in deflection along the input axis due to acceleration along the input axis.

K_{IS} - Float structural compliance resulting in deflection along the spin axis due to acceleration along the input axis.

K_{SI} - Float structural compliance resulting in deflection along the input axis due to acceleration along the spin axis.

K_{IO} - Float structural compliance resulting in deflection along the output axis due to acceleration along the input axis.

K_{SO} - Float structural compliance resulting in deflection along the output axis due to acceleration along the spin axis.

ΔM - Residual random torque.

M_{TG} - Command torque to the torque generator.

m - Wheel mass.

Minimum Synchronizing voltage
- The lowest level of wheel drive voltage which will drive the wheel rotor up to full speed (which is determined by frequency and number of poles).

NBD - The uncompensated bias drift in a gyro.

OA - The SDF gyro Output Axis, a float axis. The axis of freedom provided with a pickoff which generates an output signal as a function of output angle.

ORA - The SDF gyro Output Reference Axis, a case axis.

p - Differential operator.

Pivot - An output-axis stop which operates with the jewel for float-to-case motion limiting in the SDF gyro.

SA - The gyro rotor spin axis (a float axis).

SRA - The gyro rotor spin reference axis (a case axis).

SDF - Single-degree-of-freedom; in gyros, the term infers that float motion is intended to occur only about the output axis.

SG - Signal generator, or output-axis angle-to-voltage transducer.

SF - Scale Factor, here intended to be restricted to the torque-generator torque-to-current (or current-squared) ratio.

S_{SG} - Signal-Generator voltage-to-angle ratio.

t_f - Float time constant for motion about the output axis, I_{OA}/C_{OA}.

t_{TG} - Torque-generator electrical time constant, L/R.

TG - Torque Generator.

V - Vertical.

W_D - Gyro rate drift error.

W_{IRA} - Gyro rate input about the input reference axis.

W_{SRA} - Gyro rate input about the spin reference axis.

W_{IA} - Gyro rate input about the input axis.

W_{SA} - Gyro rate input about the spin axis.

W_{OA} - Gyro rate input about the output axis.

W_{ORA} - Gyro rate input about the output reference axis.

$\dot{W}_{OA}$ - First time derivative of gyro rate input about the output axis.

$\dot{W}_{ORA}$ - First time derivative of gyro rate input about the output reference axis.

SECTION 1

INTRODUCTION

The inertial guidance, navigation, and control subsystem is a major element of many space vehicle systems. The gyro is a critical component of inertial guidance, navigation, and control subsystems. An understanding of the close relationship between gyro performance and mission success, and the elements of system design that affect gyro reliability and performance, is required for successful subsystem integration.

Failure to evolve a gyro design consistent with system and mission requirements may at best incur the penalty of increased system complexity, or may at worst cause a mission failure.

Elements which must be reconciled in a successful gyro/system integration are:

1. Gyro performance
2. Wheel and bearing structure
3. Torquer characteristics
4. Signal-generator characteristics
5. Float-support characteristics
6. Thermal characteristics
7. Gyro testing
8. Reliability.

This monograph discusses problems and solutions related to the above elements in order to help the system designer negotiate the specification for a gyro which will reflect concern for both the system-imposed requirements and the realities of gyro construction. Although most of the discussion deals with inertial grade, single-degree-of-freedom floated instruments, much of the material applies to any type of gyro that uses a spinning wheel. Excluded from the scope of the monograph is the discussion of design elements which are functions of the independent judgment of the gyro designer — such as joint design, material selection, mechanical arrangement, and assembly techniques.

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SECTION 2

STATE OF THE ART

The gyroscope as a classical instrument has been thoroughly described in the literature (Ref. 1,2,55). Developments during the past twenty years have resulted in the availability of gyroscopes suitable for the inertial guidance of space vehicles. Without major exception, these instruments are based on the use of a rotating mass and may be classified as either single-degree-of-freedom gyros or two-degree-of-freedom gyros.

In single-degree-of-freedom gyros the rotating mass is mounted in a gimbal that permits freedom of motion about one axis relative to the case. The gimbal may be floated by immersion in a fluid which supplies both flotation and damping, or it may be suspended hydrostatically (Ref. 3) with damping provided electronically.

The two-degree-of-freedom gyro senses angular motion by measuring the displacement of the rotor spin axis relative to the case in two orthogonal planes. The rotating mass may be mounted in mechanical gimbals or may be supported by electric or magnetic fields as in the electrostatically-suspended vacuum gyro and the cryogenic gyro, respectively.

Application of a typical gyro (Fig. 2-1) to the inertial-navigation problem may be accomplished by using either a gimballed or strapdown configuration (Ref. 3,4,5).

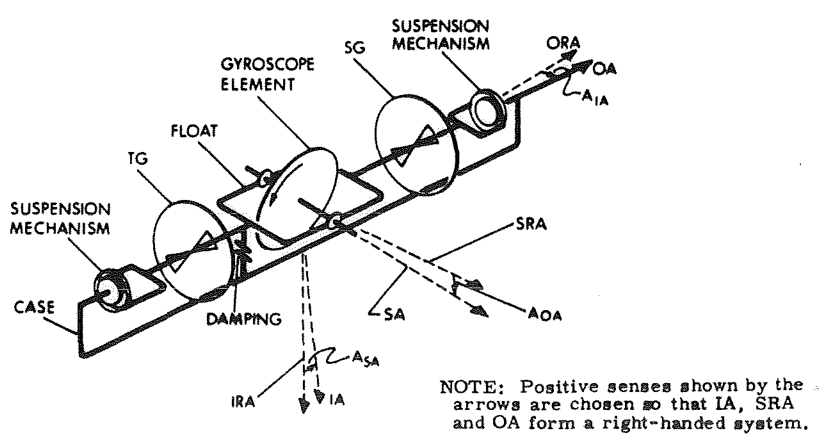


Fig. 2-1. Line schematic of SDF floated integrating gyro unit.

In gimballed-platform applications, the gyro float angle is continuously nulled by platform-gimbal torquer action which holds the platform referenced to the gyro nulls. In strapdown-system applications (Ref. 4,6,7) the gyro float angle is nulled by torque applied to the output axis (OA) of the gyroscope. In either case, the torquing current, which may be continuous (analog) or a series of pulses (digital), is derived from a measurement of the float output-axis angle. The servo loop, comprised of float dynamics, float-angle pickoff, torquing electronics, and the torquer, is called a rebalance loop. In the strapdown application the rebalance current becomes a measure of input rate (for continuously torqued gyros) or incremental input angle (for pulse-torqued gyros). The elemental considerations in the following paragraphs are applicable to both strapdown and stabilized-platform applications.

2.1 Gyro Performance

This section considers the gyro performance equation with supporting assumptions in sufficient detail for most applications. Discussions of gyro errors are presented with bounds (Tables 2-1 and 2-2). References are made to suggest the more complex error possibilities that are beyond the scope of this document (Ref. 1,7,8).

Table 2-1. Gyro Characteristic Time in Seconds (Ref. 4,9)

	Gimbal System	Strapdown System
Translational		
Spin Axis (C_r/K_r)	100–500	25–50
Input Axis (C_r/K_r)	100–500	25–50
Output Axis (C_z/K_z)	10^4	$10^3 - 1.5 \times 10^3$
Rotational		
Spin Axis (C_{SA}/K_{SA})	10–15	1–2
Input Axis (C_{IA}/K_{IA})	10–15	1–2
Output Axis (I_{OA}/C_{OA})	0.0005–0.001	$10^{-3} - 10^{-2}$

C_d = float damping coefficient (dyn-cm-s) — r(radial), z(axial)
K = suspension spring constant (dyn-cm/rad)

Table 2-2. Range of Gyro-parameter and Drift-coefficient Typical Values.

Parameter/Coefficient	Symbol	Units	Typical Range	
			Minimum	Maximum
Float Output-Axis Moment of Inertia	I_{OA}	gm-cm^2	1×10^2	2×10^3
Output-Axis Linear Damping Coefficient	C_{OA}	dyn-cm-s	6×10^4	1×10^6
Float Time Constant for OA Rotations	$t_f = I_{OA}/C_{OA}$	s	1×10^{-4}	33×10^{-3}
Output-Axis Spring Rate	K_{OA}	dyn-cm/rad	1×10^2	1×10^3
Rotor Angular Momentum	H_s	gm-cm^2/s	5×10^4	3×10^6
Torquer Scale Factor	SF	$^\circ$/hr/mA	75	1200
Float Commanded Torque (i = torquing current)	$M_{TG} = SF(i_{TG})$	dyn-cm	—	10^5
Torquer Time Constant	$\tau_{TG} = L/R$	s	25×10^{-6}	100×10^{-6}
Output-Axis Angle	A_{OA}	rad	—	$\pm 3.5 \quad 10^{-2}$
Rotor Spin-Axis Moment of Inertia	I_{SR}	gm-cm^2	40	2000
Signal-Generator Voltage-Angle Gradient	S_{SG}	V/rad	5	150
Gyro Transfer Constant	$H_s/C_{OA}(S_{SG})$	V/rad	5	40
Gimbal-to-Case Misalignment Angles	A_{IA}, A_{SA}	rad	5×10^{-6}	75×10^{-6}
Rotor-to-Gimbal Misalignment Angles	—	rad	5×10^{-6}	75×10^{-6}
Anisoinertia Error Coefficient	$(I_{SA} - I_{IA})/H_s$	$^\circ$/hr/(rad/s)^2	4	30
Acceleration-Squared (Anisoelastic) Error Coefficients for	$\frac{m^2}{H_s}(K_{SS} - K_{II})$	$^\circ$/hr/g^2	0.03	0.15
$\sum M[f(a^2)]$	$(m^2/H_s)K_{SO}$	$^\circ$/hr/g^2	0.004	0.015
	$(m^2/H_s)K_{SI}$	$^\circ$/hr/g^2	0.004	0.015
(m = wheel mass)	$(m^2/H_s)K_{IO}$	$^\circ$/hr/g^2	0.004	0.015
	$(m^2/H_s)K_{IS}$	$^\circ$/hr/g^2	0.004	0.015
Acceleration Error Coefficients for	ADSRA	$^\circ$/hr/g	0.075	1.5
$\sum M[f(a^1)]$	ADIA	$^\circ$/hr/g	0.075	1.5
	ADOA	$^\circ$/hr/g	0.05	0.15
Acceleration-Independent Error Coefficient for $\sum M[f(a^0)]$	BD	$^\circ$/hr	0.075	1.5
Uncertainty Coefficient for $\sum M_r$	ΔM	$^\circ$/hr/day	7×10^{-5}	2×10^{-2}

2.1.1 The Gyro Performance Equation

A reasonably complete gyro-performance torque equation for operation in a torque-rebalance loop is:

$$\underbrace{I_{OA}\ddot{A}_{OA} + C_{OA}\dot{A}_{OA}}_{\text{Output Axis Float Dynamic Torques}} + \underbrace{K_{OA}A_{OA}}_{\text{Output Axis Spring Restraint Torques}} = \underbrace{H_s W_{IRA}}_{\text{Desired Torque}} + \underbrace{M_{TG}}_{\text{Commanded Torque}} - \underbrace{I_{OA}\dot{W}_{ORA}}_{\text{Output Axis Coupling Torque}} - \underbrace{H_s W_{SRA} A_{OA}}_{\text{Cross-coupling Torque}}$$

$$+ \underbrace{(I_{SA} - I_{IA})\, W_{IRA} W_{SRA} + (W_{IRA}^2 - W_{SRA}^2) A_{OA}}_{\text{Anisoinertia Torque}} + \underbrace{M\, f(a^2)}_{\text{Torques due to acceleration squared sensitivity}}$$

$$+ \underbrace{M\, f(a^1)}_{\text{Torques due to acceleration sensitivities}} + \underbrace{M\, f(a^0)}_{\text{Acceleration insensitive Torques}} + \underbrace{M_r}_{\text{Residual Random Torques and Other Undefined Torque Errors}}$$

where

$\sum M[f(a^2)]$ = the sum of torques which are functions of acceleration squared, i.e., compliance torques.

$\sum M[f(a^2)] = m^2[a_S a_I(k_{SS} - k_{II}) - a_S^2 k_{IS} + a_I^2 k_{SI} - a_O a_I k_{IO} + a_O a_S k_{SO}]$

$\sum M[f(a^1)]$ = the sum of torques which are functions of acceleration, i.e., the sum of $H_s \times$ ADIA (torque error produced by acceleration along the spin axis), and $H_s \times$ ADOA (torque error produced by acceleration along the output axis).

$\sum M[f(a^0)]$ = the sum of torques that are acceleration-independent, i.e., $H_s \times$ BD (bias drift) whose primary contributors are flexlead restraints, and magnetic reaction torque.

$\sum M_r$ = the sum of all other torques, random and systematic (but assumed random within the scope of the equation) including both inaccuracies and uncertainties.

$I_{(\ )}$ = the moment of inertia of the float about each of its principal axes (SA, IA, OA).

C_{OA} = the viscous damping coefficient of the float about OA.

H_s = the spin angular momentum of the wheel.

A_{OA} = the angle of the float from null, with respect to the case, about OA.

$W_{(\ )}$ = the angular velocity of the gyro case about each of its respective reference axes (SRA, IRA, ORA).

m = wheel mass

$a_{(\ )}$ = the linear acceleration of the gyro along the float axes (S, I, O).

k_{ij} = the compliance of the wheel within the float along the i axis due to force along the j axis.

$\dot{W}_{ORA}$ = the first time derivative of the angular velocity about the ORA.

M_{TG} = the commanded torque to the torque generator.

$\dot{A}_{OA}$ = the first time derivative of the output-axis angle.

$\ddot{A}_{OA}$ = the second time derivative of the output-axis angle.

K_{OA} = the output-axis spring rate, or torque-to-angle gradient.

2.1.2 Performance Equation Assumptions

Assumptions inherent in the equation are:

1) the float output axis (OA) and the case output reference axis (ORA) are coincident,
2) no bearing friction exists between the float and case,
3) float products of inertia are negligible,
4) the wheel angular momentum (H_s) is time-invarient with respect to the gimbal,
5) no wheel rotor-to-gimbal misalignments exist,
6) no torque rebalance loop errors exist.

Gyro torque errors resulting from relaxation of these assumptions would appear in the ($\sum M_r$) term via redefinition and expansion. More complex models are developed in the literature (Ref. 7).

2.1.3 Discussion of Gyro Errors

The left side of the performance equation describes the gyro output-axis response (Ref. 4) which varies with the number of right-side terms that are "excited" (i.e., anisoinertia is effective only in the presence of spin-reference or input-reference axes rates) at a given time. It is useful to consider the effect of terms on the right side separately to achieve some insight to their effects, but it must be recognized that interactions can occur when assumptions are relaxed. Figure 2-2 graphically summarizes gyro-error sources for a strapdown application.

2.1.3.1 Spring-Restraint Torque Error

An important effect in some applications is residual output-axis angular spring rate. Its sources may be found among flexleads, magnetic-field gradients, viscous coupling (in 2-axis gyros), and input-angle-induced flow-field distortions associated

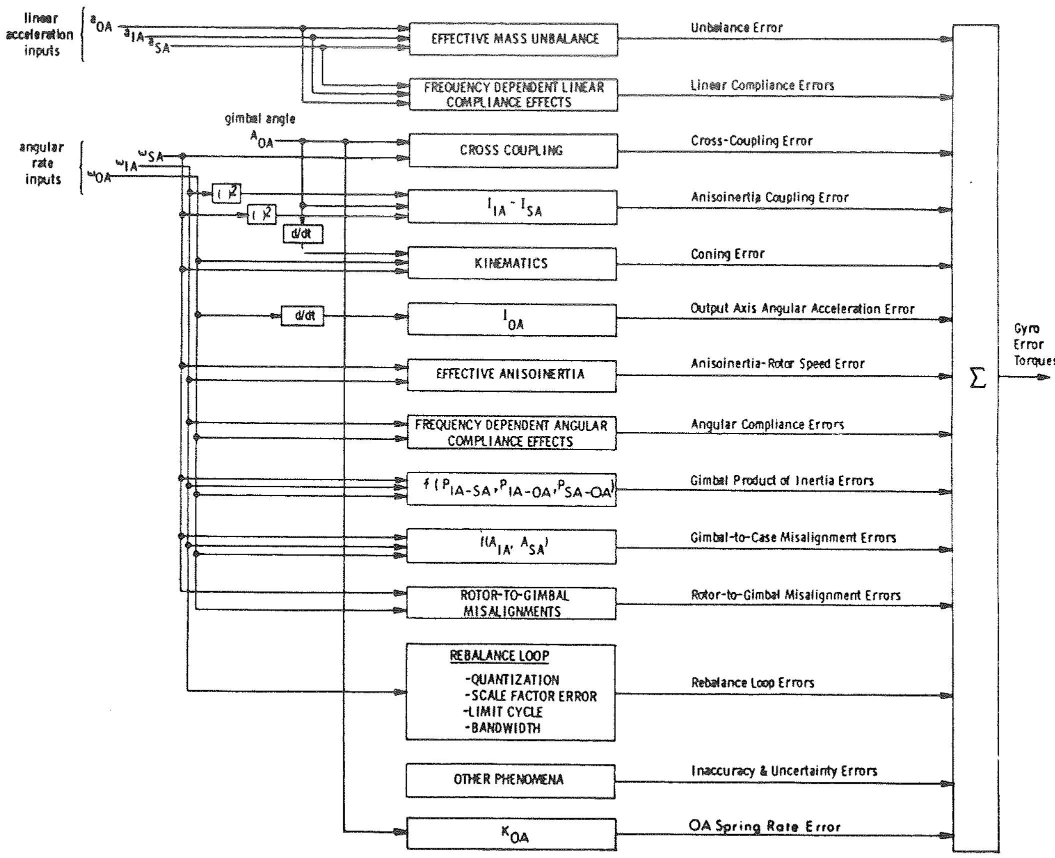


Fig. 2-2. Strapdown single-degree-of-freedom gyro error torques. (From Ref. 7)

with hydrostatic gas-bearing suspensions. Its significance as an error depends upon the size of precession angles and the physical environment.

2.1.3.2 Output-Axis Coupling

Principally introduced by the float output-axis inertia, output-axis coupling may be viewed as the tendency of the float to remain at rest when the case is accelerated about the output axis (Ref. 4).

2.1.3.3 Cross-Coupling Error

Cross-coupling error results from a portion of the case rate about the SRA being applied about the actual gimbal input axis (Ref. 4). Note from the complete performance equation that cross-coupling has the characteristics of a "desired torque" component, disappearing if $A_{OA} \to 0$.

2.1.3.4 Anisoinertia Error

Anisoinertia errors are caused by unequal input-axis and spin-axis float moments of inertia (Ref. 4).

2.1.3.5 Acceleration-Squared Errors

The torque sensitivities to the square of acceleration are called compliance errors or anisoelastic errors. Indicated in the performance equation as $\sum M[f(a^2)]$, they arise principally from the compliance of the wheel within the float (Ref. 4).

2.1.3.6 Acceleration Errors

Defined in the performance equation as $\sum M[f(a^1)]$, these errors result from acceleration components along the principal axes of the gyro. The equivalent rate-error contributions are defined as:

$$W_D = (ADIA + ADSRA + ADOA)$$

where IA, SRA, and OA are the axes along which acceleration is applied. Among the mechanisms for these torques are float asymmetries, eccentricities, ellipticities, nonhomogeneity, and thermal gradients.

2.1.3.7 Acceleration-Independent Error

The input-axis equivalent drift rate for this error is termed bias drift (BD), for which the equivalent torque about OA is listed in the performance equation as $\sum M[f(a^0)]$. The principal sources of this error are flexlead residual-torque fluid anomalies and reaction torque originating in the electromagnetic float suspensions and signal and torquer transducers. Compensation techniques may be employed to reduce the bias drift to required levels if such levels are not achievable by nonadjustable design.

2.1.3.8 Residual Torque Summation (M_r)

Beyond the range of identified systematic error sources, allowance is made by the addition of this term for all unaccounted-for errors. For this document, the term $\sum M_r$ represents residual random torque ΔM.

It should be recognized that implicit in the term $\sum M_r$ is the means to expand the performance equation to account for additional errors such as those resulting from float products of inertia; vibropendulous torques; anisoinertia rotor-speed error; rebalance-loop errors due to quantization, scale-factor error, limit cycle, and bandwidth; and others which are considered in the literature (Ref. 7).

Each of the considered error sources is susceptible to further modification from environmental forcing functions, the most influential being thermal, vibration, and noise. The systems designer must be made aware of the limitations and constraints imposed by the gyro he has selected.

2.1.4 Coning Error

Although not included in the model equation, coning error must be considered in the design of inertial guidance systems as well as in gyro testing.

Coning errors result from specific oscillatory input motions to the gyro. If phase-displaced oscillations of the same frequency appear about the output axis and the spin axis simultaneously, the input axis develops a kinematic drift rate represented by (Ref. 4):

$$W_D = AB\pi f \sin\delta$$

where

f = coning frequency in Hz.
A = magnitude of oscillatory rate input about SA.
B = magnitude of oscillatory rate input about OA.
δ = phase angle.

2.1.5 Representative Gyros

Figure(s) 2-3 illustrate a variety of single-degree-of-freedom gyros. These are typical, but not all-inclusive. Each gyro requires that essentially the same functions be provided internally in support of the completed gyro, but the mechanization of those functions may vary considerably as a result of the gyro-application tradeoffs and the particular design agency.

Irrespective of the hardware form, each element of the gyro (wheel motor, torquer, etc.) contributes to the gyro's performance characteristics. These elements are examined for gyro-performance influence in the following sections, starting with the wheel and progressing outward through the torquer, signal generator, and float support. Then thermal characteristics, followed by gyro testing and reliability, are discussed.

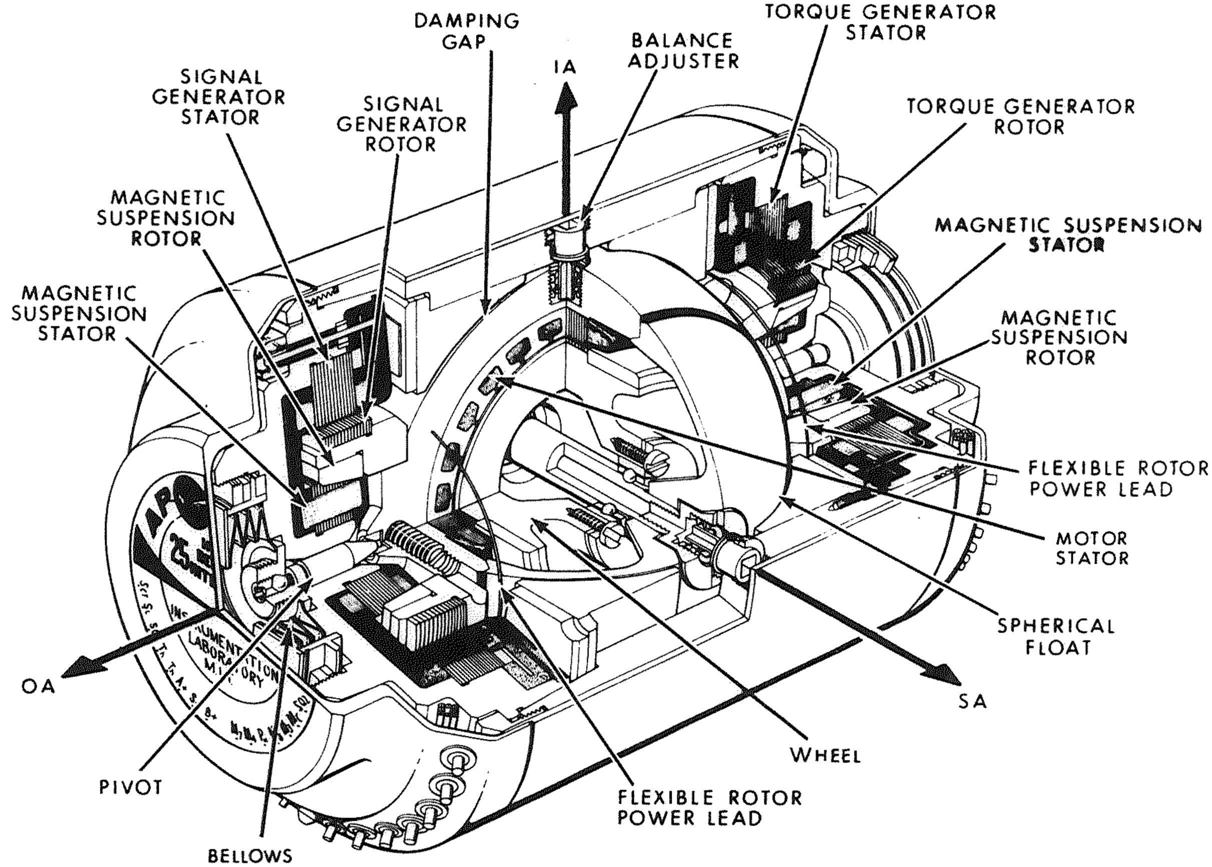


Fig. 2-3a. Cutaway view, Apollo II inertial reference integrating gyro.

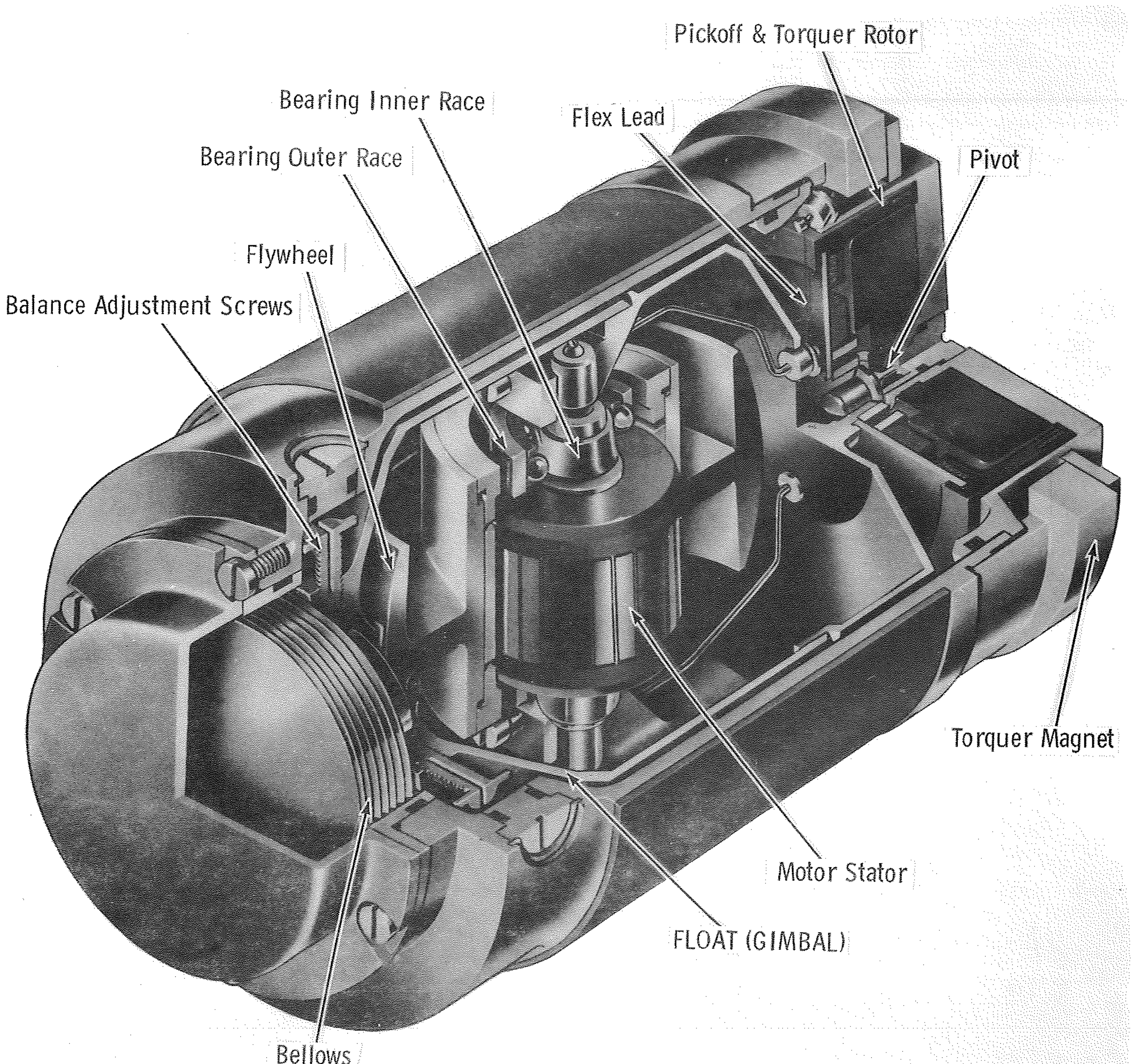
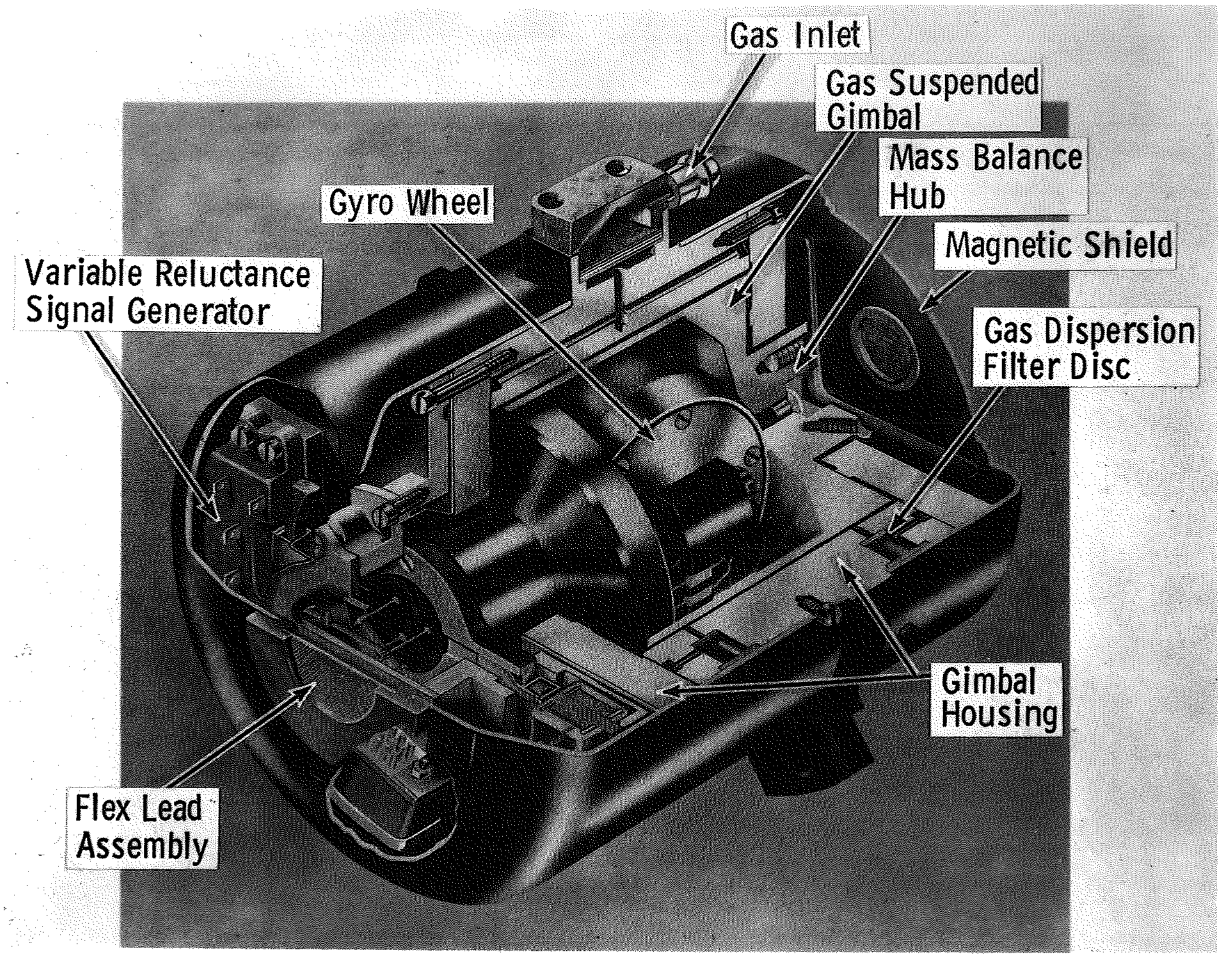


Fig. 2-3b. Kearfott King I gyroscope.



- $H = 2.5 \times 10^6$ cgs units
- No compensation
- Apollo Reliability
- Low Drift performance
- Beryllium Structure

Fig. 2-3c. Saturn AB-5-K8 gyro assembly.

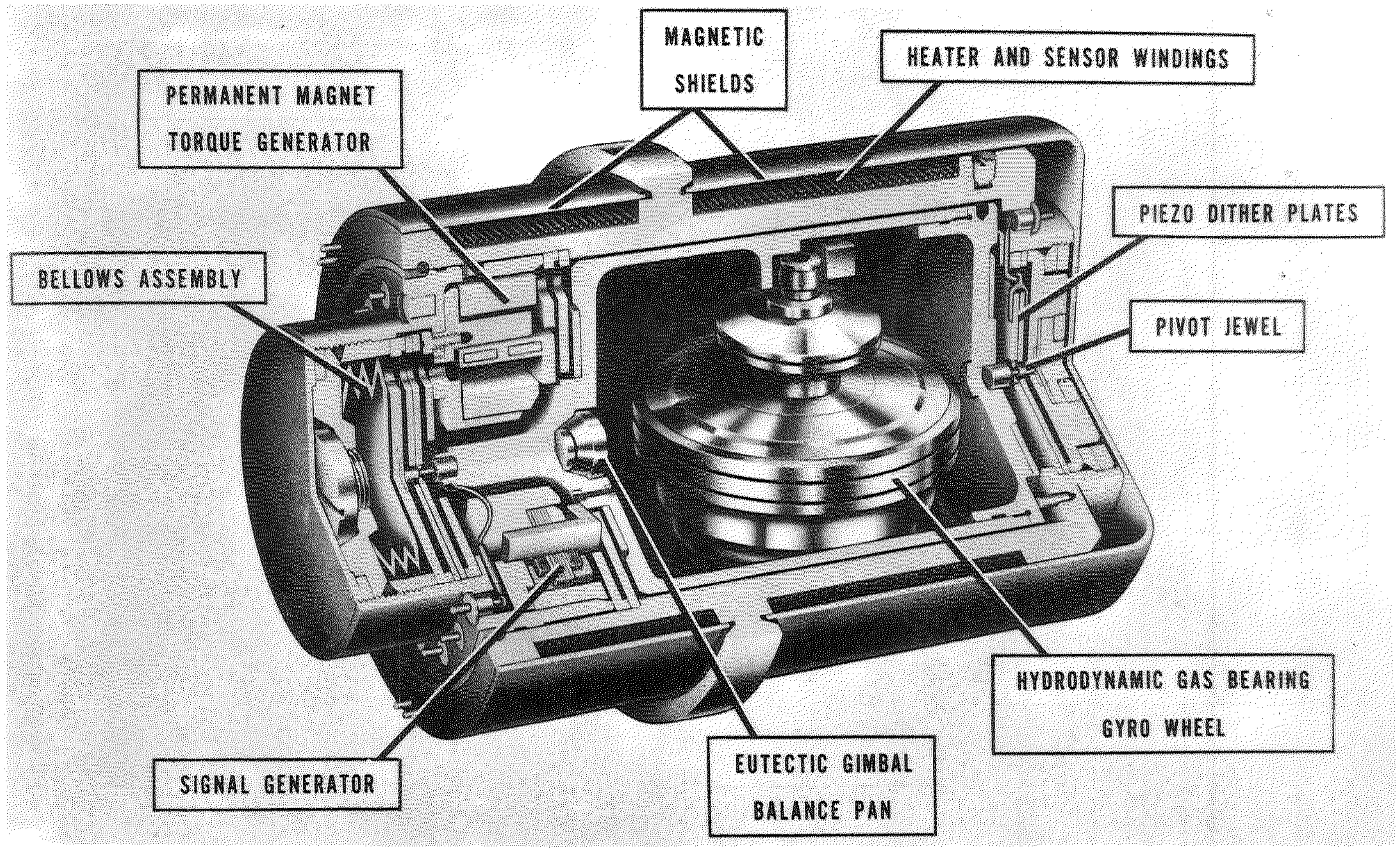


Fig. 2-3d. Honeywell GG334C gas-bearing strapdown gyro.

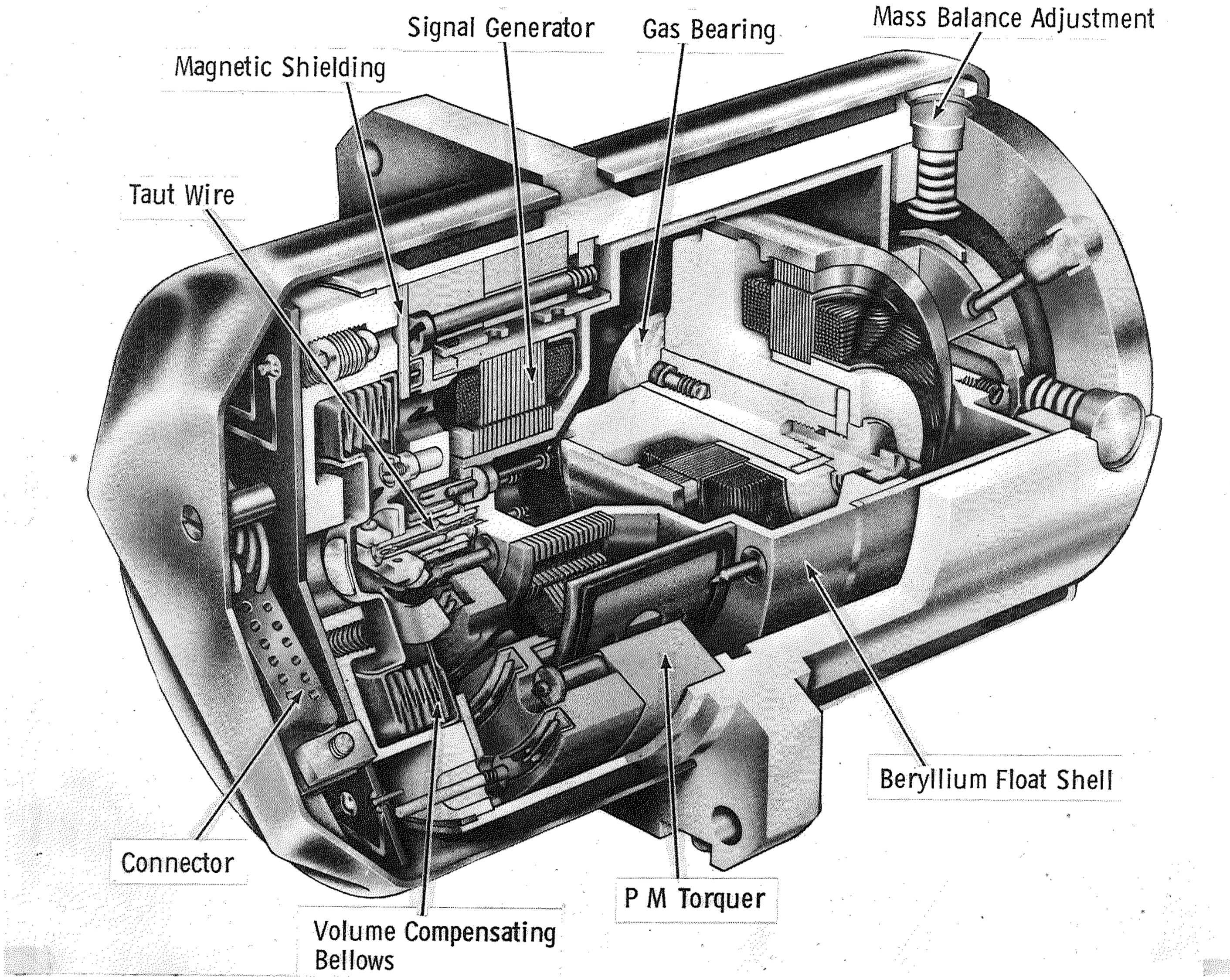


Fig. 2-3e. Precision product department (Northrup Corp.) GI K7G gyro.

2.2 Wheel and Bearing Structure

There are four major considerations directly associated with the operation and reliability of the gyro wheel:

1. Wheel mass stability.
2. Anisoelasticity.
3. Wheel drives.
4. Bearing life.

The system designer should understand these four elements in order to properly specify, incorporate, test, and monitor the gyros in his particular system. The following paragraphs describe the state-of-the-art, and problems and prospects for improvement for each of the areas.

2.2.1 Wheel-Mass Stability

Two methods are used to support the rotating wheel and to provide the required mass stability of the wheel assembly.

1. Ball-bearing (elastohydrodynamic) support.
2. Gas-bearing (hydrodynamic) support.

The stability of the center of mass of the wheel (and hence, to a large extent, the stability of ADIA) is determined by the thermal and mechanical characteristics of the individual parts and assemblies comprising these support elements.

In a ball-bearing support, required stiffness is obtained by varying a combination of ball-bearing assembly design elements. In a gas-bearing support required stiffness is obtained by varying the bearing-gap geometry or gas density. Both types of support are complex, with the limiting considerations being available motor torque, required stiffness, thermal gradients, bearing operating-temperature tolerance, lubricants, power requirements, and heat-removal mechanisms.

2.2.1.1 Bearing-Related Gyro Performance Stability

The principal gyro parameter affected by wheel instability is the drift rate due to mass shift along the spin axis (ADIA). Instability can result from a change in the elastic characteristics of the support bearing or by a shift in the relative positions of one or more of the wheel-assembly components, including the lubricating oil. In a well-designed and properly assembled high-grade inertial gyro, it is usually the change in a bearing's dynamic geometry that has the greatest effect on gyro performance.

Currently used indicators of bearing characteristics do not provide at each interrogation quantitative information which defines the gyroscopic performance capability of the wheel. A chronological tabulation of this information, however, is used to assess qualitatively the degree of performance-related bearing deterioration resulting from usage. The issue of attaching greater weight to differential wattmeter readings, run-up and run-down time measurements, frequency profiles, dynamometer records, ADIA stability, or reduced voltage start capability remains unsettled, but records of the changing characteristics of each provide some indication of wheel-performance potential. In each case, however, records suffer from the problem of interpretation. The typical lack of monitoring capabilities for these indicators in the system limits the information available for performance prediction.

The experience with gyros used on the Apollo guidance and navigation platform illustrates the preceding discussion. The two types of Apollo production gyros, designated Apollo I and Apollo II, used wheels of identical design. Analysis of a large volume of data from each version showed considerable differences in both performance and life. The drift repeatability of Apollo II was better than that of Apollo I by a factor of two to one. The failure rate attributable to wheels was three times as high for Apollo II as for Apollo I. The conclusion drawn was that improved drift stability did not necessarily correlate to wheel-life expectancy improvement (Ref. 10), implying that more records of a sufficient number of indicators with experienced interpretations could have more positive correlations.

2.2.1.2 Dynamic Wheel Effects on Gyro Performance

The dynamic characteristics of the spinning wheel are important for the effects that result from interaction between the wheel and the electrical sensing and torquing elements of the gyro. Wheel noise at sensitive frequencies may modulate the signal-generator output voltage and deteriorate the performance of the servo loop. Similarly, applied vibrations can generate spurious drift rates (Ref. 11,12). An example of this phenomenon is called synchronous vibration torque, defined as the torque produced about the gyro output axis as the result of vibration along the spin axis at the same frequency as the wheel angular rate.

Synchronous vibration torques were identified in actual practice during the early phase of the Centaur program (Ref. 13). The Honeywell guidance system used in the Centaur program employed Honeywell SDF fluid-floated, ball-bearing gyros Type DCG49D15. During the system test program, the gyros exhibited a drift-rate change as a function of platform-gimbal orientation. An exhaustive test and analysis program identified the cause as synchronous vibration torque. Each gyro wheel produced vibrations at the wheel angular rate and at an amplitude proportional to the mass unbalance of the wheel. The platform gimbal structure had a mechanical resonance at the wheel frequency. As the gimbals were reoriented with respect to each other, the transmissibility varied accordingly, resulting in varying magnitudes of coupling from one gyro to another.

A variation of this problem occurred in the Gemini program when modulation of the gyro-signal-generator 7.2-kHz carrier by the 400-Hz wheel voltage caused a platform oscillation whose period was a function of the beat frequency of the three gyros and whose amplitude was a function of spin-motor rotor unbalance. This problem was solved by the addition of a 400-Hz filter in the gyro-electronics summing amplifier. In both the Centaur and Gemini programs, a major reduction in the gyro-rotor unbalance was the indicated corrective action.

2.2.2 Anisoelasticity

Anisoelasticity — the difference in the elastic coefficients along, and at right angles to, the spin axis of the wheel — creates a variable drift-producing torque proportional to the square of the applied acceleration. The achievement of isoelasticity is a design goal involving, among other things, the geometry and materials of the wheel and gimbal; the results are verifiable by test. A reduction in anisoelasticity represents a tradeoff between the development effort required to optimize the design from the initial results and the system requirements affected by this parameter.

It is in the area of frequency-dependent dynamic effects that examples of system problems abound. In many cases the means of correction is simple but the effort expended to confirm and define the problem is very expensive.

An example of this situation occurred in the Apollo Lunar Module (LM) Abort Sensor Assembly (ASA) (Ref 14). This system utilizes three Norden model R1-1139B SDF floated gyros in a strapdown configuration. Tests performed at United Aircraft Corporation showed that exposure of the ASA to skew-axis vibration with sinusoidal inputs of 3 to 5 Hz resulted in large drift errors in the gyro loop. Rates in excess of 5 Hz created torques greater than the magnetic spring strength between the rotating field and the wheel hysteresis ring, causing the wheel to fall out of synchronism. In the 3- to 5-Hz region the wheel speed was irregular (wheel hunt), resulting in an observed drift error. Analysis showed that, if inputs of the same frequency were applied around both the gyro input and spin axes, a positive input rate would be indicated by the gyro in the absence of any applied rate. For this system the problem was only a theoretical possibility because the requirement that both inputs peak at the same frequency could not be met. The moments of inertia about the axes were unequal and resonance at a single frequency would not, therefore, occur.

2.2.3 Wheel Drive (Ref. 15)

A third element of wheel design that affects system operation is the driving device provided for the wheel (Ref. 16), including both the motor and the power supply.

Most precision gyroscopes use two- or three-phase synchronous motors to drive the wheel. A limiting factor, regardless of the type of input, is the total power supplied to the wheel. The operating voltage must provide an excess of torque so that an increase in load or a supply variation will not throw the wheel out of synchronization. An operating voltage higher than the minimum required to synchronize the wheel results in decreased efficiency. The spin-motor supply must be designed to provide this power capability reliably and stably under the worst-system conditions expected.

Overexcitation (Ref. 16) can be used to improve the efficiency of the driving motor at the expense of using a more complex power supply. Such a supply provides pulses of excess drive voltage at periodic intervals to maintain a stable level of magnetization.

2.2.4 Bearing Life

Wheel bearing life is dependent on the stability characteristics of the bearing and its lubricant, and is affected by the failure definition chosen. Life is properly defined as the operating hours during which the mass instability caused by the wheel remains within the system specification. Ultimate failure, however, occurs functionally when the gyro for any reason will not satisfactorily perform its system function.

2.2.4.1 Ball Bearings (Ref. 17)

For ball bearings, deterioration consists of one or more of the following:

1) Wear of metal parts.
2) Wear of retainer.
3) Breakdown of lubricant.

Experience on several programs large enough to produce reliable statistics shows clearly that a small percentage of selected ball bearings produced wheels that had a very long life (i.e., 30,000 hours or more). A larger percentage produced wheels which had a moderate life (i.e., 3,000 to 6,000 hours). A substantial percentage (more than 50%) did not produce good wheels. The population of gyros on these large programs contained a proportion of long-life and moderate-life bearings. The vast difference in life expectancy between the two groups explains why examination of the running characteristics of a gyro population during the first few hundred hours as practiced on these programs did not necessarily correlate with the eventual failure rates. Some gyro programs at MIT/IL OAO suggest that very long life and high bearing yield can be achieved through the use of adequate screening techniques. Many techniques are available for screening bearings, retainers, and completed wheels to eliminate assemblies with short life. This screening can be done with high efficiency. However, much work remains to determine the proper corrective action in the event that wheels and subassemblies fail to pass the required criteria.

Bearing life may be improved by changes in operating temperature. Results from the Lunar Orbiter program in which both Sperry SYG1000 and Kearfott Alpha gyros were employed, suggest that a $20^{\circ}F$ reduction in operating temperature (to $145^{\circ}F$) resulted in doubled operating life. This can be attributed to the principle that the speed of chemical reactions decreases with decreasing temperature. Assuming no change in the lubricant, the improvement might also be attributed to the increased elastohydrodynamic film thickness resulting from the increased oil viscosity at the lower temperature.

2.2.4.2 Gas Bearings (Refs. 18, 19, 20)

For gas bearings, deterioration may consist of one or more of the following:

1) Deposit of contaminants on working surfaces.
2) Loss of lubrication film.
3) Wear of operating surfaces.

The performance of gas-bearing wheels, by virtue of their simple geometry and dimensional precision, should be much more predictable than ball-bearing wheels. Experience indicates that failure eventually results from progressive deterioration of the surfaces caused by the stop-start cycle, possible contaminants, and aging which is probably chemical in nature. As the surfaces deteriorate, the starting-torque level increases until the system voltage will no longer start the wheel. In the absence of high-speed touch-downs (as from excessive slew rates) which could result in catastrophic failure, the expected system failure mode is a non-start. With cleanliness assumed, and with wear limited to less than the small amount required to precipitate a non-start, the gas-bearing wheel provides uniform operating characteristics during its entire life, with improved stability of gyro performance, and with the added advantages of having no ball and retainer dynamics. Life expectancy of 10,000 hours and longer can be expected with close to normal distributions within the population. Improvements in the choice of materials, cleanliness, finish, and lubricants may be expected to increase the life expectancy and decrease the unit-to-unit life-expectancy dispersion. Present technology, however, cannot predict either long or short life for a given gas bearing.

As with the ball bearing, the rate of deterioration is affected by the operating temperature.

2.3 Torquer Characteristics

Torquers are used to perform various tasks. For gimballed systems, the torquer is used as required for test purposes, for prelaunch establishment of the desired inertial reference, for gimbal or stable member realignment in flight, or to introduce correction for gyro drift terms. For body-mounted or "strapdown" systems the gyro torquer is used in the control loop to maintain the gyro float at null. In this case the gyro torquer output becomes the angular position term in the transformation calculation.

Torquers currently in use in precision navigation gyros are typically of either electromagnetic or permanent-magnet construction. The requirements on the torquer are not basically affected by the type of construction.

In strapdown applications certain operating characteristics of the torquer, such as sensitivities of bias and scale factor to radial, axial, and rotary (angular) displacement of the rotor (float) with respect to the stator (case), are of greater importance because float-to-case motion is much greater than for gimballed applications. Another characteristic, frequency sensitivity, results in scale-factor nonlinearities when the instrument is used with pulse-rebalance electronics where the frequency content is directly related to the input rate. The higher torquing rates required by a strapdown application precipitate thermal-gradient problems because of the required dissipation of larger amounts of electrical power in the torquer (Ref. 4).

Of importance in the strapdown configuration is the bias change resulting from the difference in scale factor for positive compared to negative torquing. State-of-the-art torquer design permits control of this difference to 0.1% of the nominal scale factor (Ref. 21). This factor is important in strapdown systems because gyro torque is the gyro-information source, whereas for gimballed systems, the gimbal angles are the source of gyro information.

A variety of gyro torquer characteristics must be appreciated and their impacts upon gyro function established in order to relate the torquer to the overall performance of the instrument (Ref. 56). These elements are discussed in the following sections.

2.3.1 Temperature Effects

The torquer scale factor may change with temperature because of changes in the magnetic gap resulting from different coefficients of expansion in the rotor and stator materials. The effect is on the order of 20 to 200 ppm per degree F.

The torquer encapsulating-compound characteristics may change with temperature, producing changes in stator permeability which modify the scale factor. Differential expansion of the encapsulating compounds near individual stator poles produces gyro bias shifts.

2.3.2 Aging Characteristics

Encapsulating materials can change characteristics with time, and affect scale factor and bias torque levels through stator permeability changes. Differential changes (around the stator poles) cause bias shifts.

The possibility that aging of stator lamination-bonding materials could affect the stator permeability has not yet been established as fact.

2.3.3 Hysteresis Effect

Disaccommodation in the soft magnetic materials used for microsyn and suspension rotors can cause changes in gyro bias and in torquer scale factor. Other hysteresis effects can be produced by electrical transients inducing overshoots in torquer excitation.

Variations in the gyro operating temperature change the flux density via stator permeability and air-gap size changes. Because of magnetic hysteresis the flux density does not return to the original value and a change in torque level results.

2.3.4 Symmetry

Torquers require electrical, magnetic, and mechanical symmetry to minimize side-loading problems. Side loading is identified as the radial force applied to the float as a result of exciting the torquer. Side-loading effects, causing changes in the torquer scale factor of the gyro, are on the order of 0.1 percent of full-scale torque (Ref. 21).

2.3.5 Time Constants

Most microsyn torquers have a basic electrical time constant in the 300- to 600- μs range. In operation, the time constants vary from 10 to 50 μs as a function of the torquing-electronics technique.

2.3.6 Linearity

Using high-frequency (1- to 10-kHz) ac torquing, the linearity of some microsyn designs has been verified to levels as low as 0.2 percent of full scale, with improvement prospects favorable.

Microsyn torquers are characterized by an OA torque-angle sensitivity (normalized to scale factor) on the order of 2 ppm/arc-sec. This nonlinearity can be reduced as required, however, by changes to the rotor geometry.

2.3.7 Rotor Displacement Effects

Microsyn torquers have a sensitivity to both axial and radial displacement. The microsyn torquer has a tendency to produce higher torques when the rotor is displaced radially. This change is dependent on the suspension gap and can be estimated by the following formula:

$$\frac{\Delta M}{M} = \frac{1}{2}\left(\frac{\Delta g}{g_o}\right)^2 \text{ \% per unit displacement}$$

where

M = torque-level reference at initial gap size,
ΔM = change in torque level,
Δg = change in suspension gap,
g_o = nominal or initial gap.

The axial sensitivity of the microsyn torquer can be controlled to less than 15 ppm/0.001 inch of axial travel by proper dimensioning and tolerancing. The goal is to insure proper coverage of the stator by the rotor regardless of float axial position.

2.3.8 Frequency Sensitivity

Microsyn torquers are basically insensitive to operating frequency; however, distributed capacitance can influence torques due to resulting tuning effects for both high-frequency ac torquing and pulse torquing.

Pulse torquing (Ref. 54) can influence the torque in another way. At higher frequencies, a residual bias torque can be introduced that is a function of, and has the same polarity as, the last applied torque pulse. One technique used to overcome this sensitivity consists of placing an additional winding on the stator and exciting it with ac (Ref. 4).

This has the effect of "washing" the stator to maintain a steady magnetic state in the stator core. A similar result can be obtained through the incorporation of controlled decay times in the torquing electronics when space for a "wash" winding is unavailable in the torquer (Ref. 6).

2.3.9 Magnetic Field Effects

Environmental magnetic fields having a frequency equal to that used in the torquer can induce changes in bias drift and torquer scale factor. The torques introduced in E-type torquers are first-order torques adding to all of the poles, whereas in V-type torquers the effects are second-order and greatly reduced (see Appendix A). Fields of frequencies somewhat different from those used in the torquer produce no deleterious effects.

2.3.10 Shielding

Magnetic shielding is a necessity on E-type torquers and desirable on V-type torquers. To be effective, the shielding must cover the entire torquer (small holes in the shielding at predetermined points are acceptable). Partial shields can be more harmful than no shield at all because of asymmetric reinforcement of the field.

2.4 Signal-Generator Characteristics

Signal Generator is the name normally given to the SDF gyro output-axis angle-to-voltage transducer (Ref. 22). This device is similar in construction to the torquer, but it is different in that its pole configuration and wiring are such that the sum of all torques on the float resulting from its use will ideally equal zero, and its output voltage will be related to output axis angle in constant ratio (S_{SG}). Sharing some concerns in common with the torquer (aging, symmetry, rotor displacement effects), it requires additional considerations for other characteristics intrinsic to its use, among which are elements affecting servo design:

1) Voltage-angle gradient, S_{SG}.
2) Null quadrature voltage.
3) Phase shift.
4) Dynamic lag, operating frequency, and bandwidth.
5) Output impedance.
6) Noise.
7) Excitation stability.
8) Temperature effects.
9) Linearity.
10) Torques.
11) Magnetic-field effects.

These elements are discussed in the following paragraphs.

2.4.1 Voltage-Angle Gradient (S_{SG})

Present values for this parameter are in the 5- 150-volt/radian range. The design value represents the minimum value which is consistent with gyro gain stability, output impedance, tuning stability, dynamic lag, and noise susceptibility.

2.4.2 Null Quadrature Voltage

Quadrature voltage in gyro signal generators is an undesirable feature resulting from nonideal transformation characteristics of the device. Although minimized by design, residual quadrature may have to be compensated to even lower levels as required by system usage.

Null voltages, presently in the 1- to 20-mV range, are related to demodulator rejection ratio, servo saturation level, and gyro input-axis misalignment (about OA) tolerance (see section 2.4.3).

2.4.3 Phase Shift

Although signal generators are usually tuned in systems to produce an output voltage in phase with the reference (primary) excitation, residual phase shift exists in the tuned SG along with some quadrature voltage. The result is gyro input-axis misalignment (see Appendix B). Phase-shift may usually be controlled to within acceptable limits by system-to-gyro interface design; when this solution provides insufficient control, signal generators are individually custom-tuned when integrated into the system.

2.4.4 Operating Frequency, Dynamic Lag, and Bandwidth

Servo dynamic response can become a problem if the signal generator is operated at high values of Q when high-bandwidth servos are desired — excessive phase shift is imparted to the side-band information from the SG suppressed-carrier output voltage.

The carrier frequency typically is high enough (1 to 10 kHz) to provide for adequate bandwidth at reasonably low Q values, which relaxes SG tuning-element problems. The gyro I_{OA}/C_{OA} limits errors measurable by the gyro to 100-200 Hz for strapdown configurations. An upper constraint on carrier frequency is higher radial-offset sensitivity for some signal-generator parameters. Higher frequencies also tend to introduce more system noise. Different frequencies for SG and magnetic suspensions reduce crosstalk effects deleterious to the system.

2.4.5 Output Impedance

Signal Generators are characterized by 100- to 1000-ohm secondary output impedances. Because they are usually tuned, they are sensitive with respect to gain and phase-to-load changes. Minimum loading amplifier input resistance of >25K ohms is common.

2.4.6 Noise

Noise sources (refer to Appendix C) which appear in the signal generator can be any of the following:

1) Wheel hunt (3 to 5 Hz).
2) Rotor dynamic unbalance (200 to 400 Hz).

3) Bearing & retainer dynamics (100 to 200 Hz).

4) Electrical noise coupled from wheel or suspension circuits into SG secondary.

Measures of servo actuating signal facilitate quantitative knowledge of any of these errors within the servo bandwidth, except for those which can rectify, producing unmeasurable errors. The extent of these errors depends upon the type of demodulator used and the relationship of the operating frequency to the error-source frequency.

2.4.7 Excitation Stability

Signal-Generator sensitivity is directly proportional to primary excitation current and is therefore only as stable as the current which varies with the source voltage, the primary impedance and reflected secondary impedance.

2.4.8 Temperature Effects

In addition to sensitivity to the effects observed in section 2.3.1, the temperature affects the windings' impedances on the order of 1 to 2%/°F; the result can be S_{SG} changes and/or phase-shift changes which must be examined for each system design.

2.4.9 Linearity

Linearity of the Signal Generator is important only in non-integrating gyros.

2.4.10 Torques

The microsyn signal generator contains elements of both magnetic-reaction torque and spring-restraint torque, the first of which is independent of OA angle, and the second proportional to OA angle. Both result from magnetic imperfections and components of secondary current in phase with the primary current (Ref. 23). Reaction torques range up to about 1.0 dyn-cm, depending on the excitation levels, while elastic restraint torques are in the range of 100 to 500 dyn-cm/rad. (These are totals for the gyro; individual contributors are usually not measured in the assembled gyro.)

2.4.11 Magnetic-Field Effects

Signal-generator mechanization may employ either standard double-wound, or "E" construction; external fields produce very small torques of little or no consequence in the SG. But electrical-signal problems can occur if the external-field frequency is equal to, or a multiple of, the operating frequency (depending upon the servo demodulator). False null indication (IA misalignment about OA) can result.

To preclude electrical-signal problems, signal generators in inertial-reference gyros are normally shielded in a manner similar to the torquer.

2.5 Float-Support Characteristics

In precision gyros, the float containing the wheel assembly is normally suspended so that a minimum of friction is introduced about the output axis. For floated inertial-quality reference gyros, the float weight is reduced to essentially zero by immersion in a fluid of appropriate density. The residual weight is usually supported by supplemental suspension forces. Of the several methods available for this purpose, the most commonly used is the magnetic suspension (Ref. 23). A magnetic suspension can be packaged conveniently for use in an SDF gyro, providing a maximum of 30 to 40 grams of restoring force on the float at large radial displacements. In addition to providing both radial and axial support, magnetic suspension makes it possible to monitor the radial and axial position of the float on a continuous basis (Ref. 24).

Other suspension methods sometimes used for inertial reference gyros are pivot and jewel, dithered jewel, flexure member, and hydrostatic supports.

2.5.1 Force Gradients

Generally the force gradients for electromagnetic suspensions vary from 0.5 to 8 milligrams per microinch radial displacement for the possible variations of suspensions. Active suspensions can have larger gradients over small displacements. In all cases the maximum radial restoring force is limited to 30 or 40 grams due to size limitations.

2.5.2 Float Displacement Limits

There are definite constraints on the allowable axial and radial movement of the rotor (attached to the float) with respect to the stator (attached to the case) on all microsyn suspensions, and there is an interdependency between the two displacements. In general, maximum displacements on the order of ±0.002 inch axial and ±0.0005 inch radial must be maintained to preclude the possibility of float hangup. Hangup occurs when the rotor-to-stator displacement exceeds the limit of positive force and the force gradient becomes negative (Fig. 2-4), thus forcing the gyro float against a mechanical stop, degrading the gyro's performance (Ref. 23).

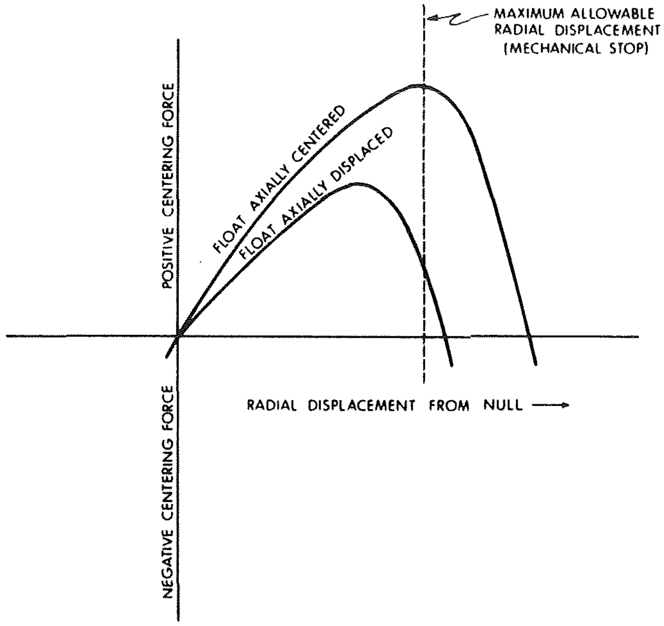


Fig. 2-4. Graphic representation of suspension forces as a function of radial and axial float offsets.

2.5.3 Outputs as Useful Information

Each microsyn suspension can be instrumented to monitor radial outputs so that the radial position of the rotor (float) with respect to the stator (case) is known. When axial suspension (along the output axis) is used, the suspensions provide the means to monitor the axial position of the float as well. The limits of linearity are on the order of +0.0005 inch for radial motion and ±0.002 inch for axial motion for a suspension-taper included angle of 15 degrees.

2.5.4 Required Excitation

Most units are designed to operate in the range of 2 to 10 volts. A constant-current source is generally specified for best suspension stability. Frequencies can vary from 1 to 10 kHz, depending on the specific design.

2.5.5 Error Mechanisms

Suspensions contribute to the bias drift of the gyro to the extent of the asymmetry of the hardware. In a ducosyn configuration, where the rotor is cylindrical or conical in shape with no salient poles, the bias-drift contribution is small.

Suspensions can produce error torques (bias drift) with total decay times in the two- to four-hour range. This type of error can be induced by holding the rotor rotationally displaced (±10 milliradians or more) from its nominal operating position for a period of time (10 minutes or more) with the suspension excited. This effect is attributable to disaccomodation in the soft magnetic material (ferrite) used to fabricate the rotor. Work directed at reducing or perhaps eliminating this effect is underway.

Also, there may be uncertainty torques resulting from radial and axial displacement of the rotor with respect to the stator. These torques with their inherent measurement difficulties have not been completely verified.

2.5.6 Active Suspension Systems (Ref. 25,26)

Active suspension systems (i.e., systems using amplifying circuits to increase the stiffness gradient around the operating point) have been used in the past and are currently attractive due to the availability of micro-circuits. Their use is indicated for strapdown systems where the error resulting from float misalignment can become substantial. The design of such a system must be consistent with the reliability requirements of the suspension.

2.5.7 Gas Float Support System

Another method of supplying float support has been used in systems developed at Marshall Space Center. In these systems the float is supported hydrostatically using nitrogen at a 2000-cc-per-minute flow rate. Symmetrical diffusion of the gas is accomplished by introducing it to the gap through a multiplicity of micron-size filters. Torsional damping is provided by appropriate electronic circuits. A benefit from this technique is the thermal-control capability provided by the relatively large flow rate around the float body. Another interesting feature is the electronic damping which provides a system flexibility not available in a liquid-floated gyro installation. Compensating disadvantages exist, the most obvious being the requirement for the nitrogen source (Ref. 3).

2.6 Thermal Characteristics

Control of the thermal environment is necessary for proper operation of any inertial-reference gyroscope (Ref. 27). This section discusses thermal characteristics of gyro performance, major gyro subassemblies, and the elements associated with the gyro temperature-control function.

2.6.1 Gyro Performance

Gyro performance continuity between tests in different locations, including the system, depends largely upon the capability to repeat the gyro-to-heat-sink heat-flow characteristics established as the standard.

The precision with which gyro temperature must be maintained is a function of system performance requirements and the thermal sensitivities of the gyro. Thermal sensitivities generally exist because of mechanical and electrical asymmetries, whose effects may become more (or less) prominent with temperature variations. Gyro thermal sensitivities can be estimated or extrapolated on the basis of past experience, but ultimately require verification measurements.

2.6.2 Wheel and Float Elements

Nonsymetrical elements become unbalanced because of mass center shifts resulting from temperature-induced dimensional changes. All elements become unbalanced because of asymmetric dimensional changes resulting from temperature gradients along the element. The temperature of the bearing assembly is critical to all elements of the wheel-bearing assembly, including lubricant.

2.6.3 Torquer

Both the size of the torquer gap and the permeability of the magnetic material of the torquer are affected by the operating temperature. The result of temperature variation is an undesirable change in the torquer scale factor. Thermal gradients also tend to cause bias changes.

2.6.4 Signal Generator

The preceding section on the torquer applies equally well to the signal-generator mechanism, affecting its voltage-angle sensitivity and bias contribution. Changes in null quadrature effected by temperature may cause a problem (Section 2.4).

Phase shift can also change, resulting from resistive and reactive temperature sensitivities related to the windings and magnetic elements.

2.6.5 Flotation Fluid

Thermal gradients perpendicular to the OA of the gyro induce a convection flow in the fluid that results in viscous torques on the float. Temperature variations (Ref. 28) result in viscosity changes with a corresponding change in damping on the order of 5%/°F. The gyro transfer function varies inversely with the damping. Fluid density changes inversely with temperature, causing float translation.

2.6.6 Temperature-Control Elements

Sensing and control elements are required to provide the temperature stability and control features necessary to satisfy the system-performance requirements. A temperature-control system consists of six elements; the parameters of each element are chosen to contribute to the desired loop characteristics. These elements are:

1. Gyro mounts.
2. Sensors and heaters.
3. Controller amplifiers.
4. Gyro insulation.
5. Heat sink.
6. Monitors.

A description of how these elements relate to each other and to the control problem is provided below.

2.6.6.1 Gyro Mounts

Mounting the gyro involves the combined requirements of attachment, alignment, and thermal resistance. These requirements are not compatible without compromise. For instance, a straightforward mount is an annular ring located on the cylindrical body of the gyro facilitating a simple wedge-ring alignment technique. However, the resulting thermal resistance to structure (heat sink) is relatively high. High thermal resistance constrains either the instrument to a high operating temperature, or the heat sink to a low temperature. This case is exemplified by the Honeywell GG87B16 gyro which operates at a temperature of 185° F. A high thermal resistance to structure here is an advantage, for it reduces heater power requirements. The reverse condition, low heat-sink temperature, is shown by an MIT/IL 18 IRIG gyro which when mounted with the annular ring described above, results in a thermal resistance to structure of 6°F/watt. This gyro operates at a temperature of 135°F with a power dissipation of 8 watts; the maximum heat-sink temperature, including a 10°F margin to assure control, is 77°F.

To provide a low thermal resistance of $<$ 2°F/watt requires attachment with a minimum of surface interfaces. The thermal properties of the attachment material are of minor importance compared to the interface geometry. It is the degree of gyro alignment capability and mechanical stability that compromises the thermal design. The system heat-sink temperature, the gyro operating temperature, and the gyro power input must be compatible in an optimized thermal design.

2.6.6.2 Sensors and Heaters (Ref. 29,30)

The important sensor parameters are stability and sensitivity. Metallic foil or wire-sensor material, installed with a minimum of residual stress, provides good stability. By comparison, solid-state sensors (thermistors) provide a higher sensitivity by almost an order of magnitude, but instability from both drift and self heating tends to be greater. Selection and burn-in can materially improve the stability of thermistors. Both foil and wire sensors can be accurately trimmed to a specific value during manufacture. Thermistor variation is such that padding is required.

The location and mounting of sensors and heaters with respect to the gyro are important to the operation of the control loop. The following three methods are in common usage:

1. Heater and sensor interwound and distributed along the body wall or on the end-mount surface.

   Attachment of the heating and sensing elements at these locations minimizes the distributed lag* between the heater and sensor and generally eliminates the need for loop compensation. However, problems both with loss resistance to the external ambient and with sensor response to the heater directly can result if the thermal resistance of each element to the body wall or end mount is not negligibly low compared to the heater-to-sensor resistance.

* Systems where there are no pure delays between input and output and which exhibit both attenuation and a progressive frequency-dependent phase shift are a special case of distributed systems that are referred to as distributed-lag systems characterized by a particular form of partial differential equation. The most common use of this analog is for predicting transient temperatures and heat-flux distribution; however, other systems may fall into this category, notably inductanceless electrical lines, viscous flow liquids, and the molecular diffusion of materials (Ref. 31).

2. Heater and sensor at each end of the gyro.

This arrangement places a sensor in each end of the gyro as close as practicable to the damping fluid. The heaters are located at the end mounts to control the heat flow rate out of the instrument. This arrangement almost always requires control-loop compensation for distributed lag, and the resulting temperature represents an average of two "point" sources.

3. Sensor body-wrapped and heater in end mount.

A combination of the best features of 1 and 2 above probably provides the best average temperature control, but distributed lag-loop compensation is required.

2.6.6.3 Controller Amplifiers (Ref. 30,32,33,34)

Controllers are typically not an integral part of the gyro. Typical gain requirements for these amplifiers are in excess of 100 dB. Several types currently used as integral components of the control loop are:

1. Magnetic Amplifiers.

These devices are characterized by low equivalent input-drift, good reliability, and resistance to radiation. Undesirable features are switching radiation (RFI), and the requirements for a separate, high-frequency, square-wave supply.

2. AC Amplifiers.

This type avoids the drift associated with the usual dc amplifier, but it complicates the calibration of each system because of variations in impedance from harness and interconnections.

3. DC Amplifiers.

Solid-state low-drift amplifiers are particularly suitable for temperature controllers. Imaginative design and proper location of components results in low values for total control-loop input-power requirements.

2.6.6.4 Gyro-Insulation Provisions (Ref. 35,36,37,38,39)

An insulating shroud around the body of the gyroscope provides thermal smoothing of diametral environmental gradients and reduces the magnitude of these variations as sensed by the gyro. Many configurations have been designed:

1. A dual-walled evacuated sleeve provides the best insulation as long as the vacuum is maintained.
2. A single-walled sleeve with an air gap sized to minimize convective heat transfer.
3. A single-walled sleeve with foam.
4. Multiple sleeves with alternating layers of conductor and insulator.
5. More exotic types, among which are phase-change (heat-pipe transfer), body-wrapped cooling coils, and a rotating smoothing shield.

2.6.6.5 Heat Sink (Ref. 36,40)

Until techniques are developed to completely isolate the gyro thermally from the system, the structure (heat sink) is an integral component of the temperature-control loop. Various methods are used to modify the thermal condition of the structure in order to reduce the overall effect of the individual heat sources mounted on the structure and to minimize the dynamic perturbations. These techniques include the use of temperature-controlled fluid flowing through the structure, temperature-controlled fans, gaseous environment proportioned for specific thermal conductivity, a separate temperature-control system, and variable thermal-resistance mounting provisions.

2.6.6.6 Temperature Monitors

While not in the direct control loop, provision for temperature monitoring is of importance to the gyro for correlation of test experience, for failure analysis, and for alarm capability.

2.7 Gyro Testing (Ref. 21,41)

This section suggests types of tests usually performed on inertial gyros, and sources of problems encountered in testing.

2.7.1 Test Types

A number of different tests can be performed on the gyro, with the type of test selected depending upon intended gyro use (gimballed or strapdown) (Ref. 42,43), required test-result accuracy, and economic considerations. Each type of test (Ref. 41) — Inertial, Stable Azimuth, Six-position Servo, Torque-to-Balance — can give the gyro an apparently different total-drift characteristic. Consider that, for a body-mounted system, torque-to-balance testing at the gyro test level is more appropriate than servo-turntable testing.

2.7.2 Gyro Test Model

For each possible gyro test, correct results depend upon selection of a proper performance model equation.

Extraneous inputs must be properly identified. Variations due to such things as room-temperature or coolant-temperature cycling, building tilt, work shifts, etc., may influence the apparent gyro characteristics.

The gyro equations must consider all inputs pertinent to the system application. An omitted term in the equation that turns up as an instability in drift at the system level can precipitate costly and time-consuming investigations.

The lack of accurate definition for a drift term can result in a source of apparent drift. For example, gyros sequenced through two test routines at the gyro level and a similar sequence at the system level to derive a particular set of drift terms may indicate a consistent difference in the value of the derived terms. Such results are often attributed to a lower test sensitivity in the system compared to the gyro test stand, when in fact they can be traced to an improperly defined term or an improper set of tests to isolate that term.

2.7.3 Influence of Gyro History and Environment

The test program can introduce disparities in the apparent drift characteristics of a gyro. This area should be thoroughly investigated to hold the number of these contributors to a minimum (Ref. 44).

Previous storage history, settling times, test sequences, data sampling periods, servo vs torque-to-balance, inertial vs stable azimuth, and disturbances between test sequences may produce a deleterious performance image of the gyro.

Previous storage, settling times, test sequence, and disturbances between test sequences may have interrelated effects on gyro performance. Storage becomes important when fluid stratification and its effect on "g"-sensitive drift measurements is considered. Settling times, for both the gyro and the test equipment, (due to radial and axial centering of the gyro float, thermal stability of the gyro and test equipment, and the effect of testing geometry) must be factored into the test sequencing and testing time to best represent the actual operating conditions of the system. Disturbances between test sequences that result from gyro repositioning, and from inputs such as excessive test-table rates, open-loop vs closed-loop table positioning, and the magnitude of angular rates about the gyro input axis all have an effect on the short-time and long-time drift characteristics of the gyro. They should, therefore, be controlled in the test procedure to ensure meaningful data.

The test environment, as a lumped parameter, has a considerable effect on the drift characteristics of a gyro. Ambient temperature level and its stability, noise level, vibration levels, test-station-to-test-station differences and test-station-to-system differences are all well known but often overlooked. An example of test-station differences is the electronic power supplies used in the gyro test laboratory. For the gyro test-program phase of system-development schedules, these are usually chosen to provide significantly better stability than the system supplies which are constrained by other factors such as size, weight, and cost.

2.8 Reliability

Reliability has a special and atypical significance when applied to the inertial instruments operating in a space guidance and navigation system (Ref. 45,46,47). This is true for several reasons:

1) Cost, size, and complexity tend to discourage redundancy.
2) Cost and availability limit the accumulation of reliability data early in the life of a program.
3) Degradation rather than catastrophic failure is the typical failure mode.
4) Performance vs life is difficult to establish for a given design and generally exhibits a wide dispersion among gyro units for a given design.

The existence of these obstacles to the normal development of reliability criteria for gyroscopes does not reduce the vital need for these criteria. The extended volume of testing required to assure a successful mission may lead to the accumulation of a large number of operating hours on the inertial instruments prior to the start of the flight. Whether the remaining life is sufficient to fulfill the mission is always open to question.

All gyro programs for space and missile applications go through an initial period during which failure modes include such typical production problems as electrical shorts and opens, contaminated fluid, computation errors, and the like.

Typically, these failures are eliminated at the system manufacturer's level. Wheel failures and float hang-ups constitute the majority of field failures. Table 2-3 summarizes principal failure sources for SDF floated gyros with magnetic suspension. What techniques are available to evaluate the reliability of the gyroscope at a particular point in time? Basically, two approaches are used, and the choice is dependent on the mission-reliability confidence-level requirement. These are discussed below.

2.8.1 System-Performance Error Band

The first reliability evaluation technique is a missile approach where extensive hardware back-up coverage is available and is exemplified by the Polaris system. Polaris guidance systems are tested periodically in the operating environment. Failure to achieve a required overall performance level results in replacement of the complete guidance system. A system repair program isolates the failure, removes and replaces the faulty component, and returns the equipment to a normal operating condition. The performance level at which rejection is necessary is determined by experience and analysis to optimize the combination of guidance accuracy and premature replacement. This level is fixed until a new level is indicated by program experience.

2.8.2 Gyro Parameter Monitoring

The second approach is more characteristic of space flights where the requirements of safety and mission dependability call for the highest confidence levels. The technique used for this type of mission may be described as "parameter monitoring". It consists of maintaining records of a large quantity of applicable parameters and analyzing the changes which have occurred in each during the life of the guidance system. Such parameters as gyro drifts, wheel run-down times, wheel run-up times, wheel torque levels, noise levels, power levels, ball beat and retainer frequencies, starting voltage, minimum wheel "synchronizing" voltage, and drop-out voltage for wheels have been used to determine the "health" of a gyro in the system.

Wheel power-supply variations can upset stabilized thermal gradients within the gyro and cause drift changes through center-of-mass shifts. These changes may occur because of a degraded power supply or because of wheel-package phenomena, i.e., an increase in bearing noise or oil "jogs" (both indicating a change in bearing-friction characteristics). The early detection of degradation of this nature is very important, as inpending catastrophic failure could be indicated by the degradation.

Table 2-3. Gyro Failure Modes (Ref. 47, 48)

Failure	Cause	Controls to Preclude	Test to Verify Integrity
Wheel Bearing	Lubricant or running surface deterioration.	Long prescreening cycle; i.e., dynamometer and wattmeter testing.	Wattmeter; dynamometer; ball beat; rundown time; runup time; ADIA drift stability.
Fluid Contamination	Foreign particle in damping gap.	Quality control and monitor techniques during build and test cycle.	Float freedom drift stability.
Gravity Transient	Fluid entrapment in partly filled cavity.	Cementing techniques to insure no high resistance voids.	Gravity transient; drift measurement across storage.
Electrical	Wire, solder or connection break inside or outside of gyro; partial to complete loss of instrument.	Quality control and inspection across vibration.	Visual; resistance and continuity; megger.
Drift Instability	Inadequate gyro structural integrity.	Drift measurement across cooldown and vibration.	Drift measurement.
High Drift Instability	Magnetic suspension hangup or failure.	Extensive magnetic suspension tests on subsystem and instrument level.	Centering ratio; suspension setup.
Alignment Shift	Inadequate structural integrity.	Alignment test across vibration; more stringent torque requirements.	Alignment.

Generally, the above-mentioned parameters do not have a known and consistent correlation with performance required during the following time period representing "mission time" operation. Their use, therefore, is restricted to providing a "case history" on which a more or less arbitrary engineering judgement may be based.

Unless or until the accumulated reliability statistics for a particular gyro design show that the expected life consistently exceeds the required life at a high confidence level, "parameter monitoring" coupled with engineering judgement is the only practical process for use in this class of program.

2.8.3 Large Program-Reliability Comparisons

A comparison of Project Apollo and Polaris Program gyro-failure experience (Ref. 49) provides insight into the nature of the reliability assessment problem described above. The gyros used in each program are very similar, with identical wheel packages. The results of the comparison show that neither the long-term stability charactertistics of the two gyros nor the failure rates during the first 600 hours of operation are significantly different. This indicates that the rejection criteria for each were of approximately equal severity; the Polaris data, however, does not extend much beyond the 600-hour point. Beyond 600 hours the Apollo failures increased, indicating that the criteria should include weighting to reflect the operating hours accumulated. The Polaris data provides no assistance in establishing the long-term criteria for Apollo gyros beyond the 600-hour level. The Apollo indication for Polaris is to expect a continuing increase in failure rate.

SECTION 3

GYRO DESIGN CRITERIA

This section identifies and describes the important system-related design features of the gyro and its principal subassemblies.

3.1 Gyro Performance

The following basic aspects of gyro design and application are presented first because of their pertinence to gyro performance:

1) Gyro operating life is ultimately limited by the angular-momentum support elements (bearings). Because the integrity of bearings is difficult to verify and predict, all aspects of their performance are of prime concern.

2) Mechanical, thermal, electrical, and magnetic symmetries are basic criteria of good design. It is often necessary to compromise these criteria due to constraints such as size, weight, power consumption, etc.

3) Thermal and magnetic sensitivities will determine the performance limits of a gyroscope in a specific environment. These parameters should, therefore, be evaluated to determine if the specified requirements are consistent with the state of the art.

4) Because of their impact on gyro design, test procedures and system-interface decisions concerned with the inclusion of wheel-speed verification or other operational monitors, and optimized system power sequencing, must be made early in the program.

5) People build, test, transport, and install gyroscopes. Appreciation of the importance of the human factor is necessary by both gyro and system designers. Controls are required to preclude gyro loss or performance degradation resulting from shock due to careless handling, temperature extremes due to unprotected-controller failure, connector abuse, and gaussing due to improper choice of checkout instrumentation.

6) Gyro parameters and performance specifications should be realistic in relation to the system requirements and consistent with manufacturing feasibility.

7) Gyro acceptance tests should be such as to verify conformance of the gyroscope to the specified parameters and the elemental interface requirements. The qualification-test program should be consistent with the gyro specification.

With regard to gyro performance as modelled in Section 2.1, the criteria for each performance-error contributor are the system tolerances for these errors. The effects delineated in the State-of-the-Art Chapter describe magnitudes and mechanisms for the errors. These must be weighed by the system designer against his design requirements. It must be remembered, however, that parameters such as anisoelastic coefficients cannot be simply constrained without regard to their effects on other related dependencies (i.e., wheel power). These dependencies are discussed with regard to performance coefficients throughout the remainder of this section.

3.2 Wheel and Bearing Structure

The wheel and bearing structure shall be examined for specification considerations in the areas of:

1) Angular momentum,
2) Motor,
3) Bearing assembly.

3.2.1 Angular Momentum

Angular momentum shall be examined for gyro transfer constant $\frac{H_s}{C_{OA}}$ (S_{SG}) effects with regard to the following:

1) H_s shall be as large as practicable, except that it is size-limited by its mass (it requires flotation) and by its angular velocity (limited by friction and windage torques, which can introduce power problems).

2) Adequate gain shall be assured by the proper consideration for C_{OA} and S_{SG} values.

3.2.2 Motor

The motor shall be specified in a manner to assure wheel synchronism (set by the operating frequency and the number of poles) under worst-case system environmental conditions, as well as providing excess torque to satisfy rotor run-up time requirements. Motor contribution to power stability may require specification, as may driving-source frequency stability.

3.2.3 Bearing Assembly

The gyro application should be closely examined to determine whether the proper choice for the wheel rotational interface should be ball bearing or gas bearing. In either case, evaluate the bearing-assembly parameters with respect to:

1) Power required (temperature related) and its stability.
2) Starting/running torque
3) Voltage (an electrical noise source)
4) Wheel-assembly motion perturbations (mechanical noise sources)
5) Anisoelasticity
6) Life restart reliability
7) Mechanical environments (linear and angular rates)
8) Acceleration
9) Vibration and shock (inside and outside the system)
10) Run-up time
11) Lubricant
12) Running life
13) Transmissibility
14) Shelf life
15) Manufacturability
16) Spin-motor reaction torque
17) Wheel speed

The decision to select a ball- or gas-bearing wheel for a given mission is a difficult one to make. One criterion for making the choice is to evaluate the history of proven bearings in view of system requirements, with respect to life expectancy, performance, and design environment.

3.2.3.1 Ball Bearings

The following items must be considered for ball-bearing usage:

1) Wheel-mass stability required
2) Bearing stiffness (contact angle; preload)
3) Mechanical environments
4) Start- and run-torque margins
5) Lubricant compatability with operating temperature range
6) Required stability of operating temperature
7) Run-up/run-down time
8) Motor-running power
9) Thermal resistance to the control point or heat sink
10) Ball-bearing and retainer dynamic frequencies and their amplitudes
11) Wheel-synchronization monitor
12) Torque margins

3.2.3.2 Gas Bearings

Gas bearings should be specified for use if highest performance is required, and if the ball and retainer dynamics of the ball bearing are intolerable. The specification should be firmed, however, only after consideration of:

1) Wheel-mass stability
2) Bearing stiffness (gas pressures and running support forces)
3) Mechanical environments (especially those such as slew rate, which can cause bottoming of the wheel at speed)
4) Bearing type and materials, including lubricant thermal characteristics
5) Start/stop life expectancy
6) Torque margins
7) Motor-power stability
8) Run-up/run-down times
9) Motor-running power
10) Permissible operating-temperature range
11) Required operating-temperature stability
12) Thermal resistance to the control point or heatsink
13) Wheel-synchronization monitor.

3.3 Torquer Characteristics

The torque generator shall be specified to fulfill maximum torque (or rate) requirements consistent with acceptably small torque uncertainties. Requirements shall be determined for torque-generator drive with regard for gyro-bias contribution, torquer linearity, torque scale factor, and reaction torque. Another set of trade-offs must be considered among torquer time constant, torque-loop bandwidth, operating frequency (wheel noise and quantization), torquing mode (high-frequency carrier-type, continuous 2-state pulse train, or 3-state-pulse-on-demand) (Ref. 54), and electronics complexity. Undesirable effects requiring limiting specifications are hysteresis, disaccommodation, and elastic-restraint torques.

Temperature sensitivities, radial- and axial-offset sensitivities, and time stabilities of torquer scale factor, reaction torque, impedance, positive- vs negative-torque scale factor, and torquer-current stability must be considered and specified.

Torquer external magnetic-field sensitivities must be identified and necessary shielding specified. Such shielding shall not introduce vibration nor shock problems; it shall be compatible with thermal insulation (as required) and temperature-control heater and sensor locations (as required); and the shield's thermal-expansion coefficient combined with temperature range-possibilities shall result in acceptable stresses on the gyro case and mounts (as applicable).

3.4 Signal-Generator Characteristics

The output-axis, angle-transducer transfer constant shall be examined for its effects on the overall gyro transfer function. The relationships among its scale factor, exciting current, linearity, reaction torque, and elastic-restraint torque shall be examined for optimum system solution. The relationship among null quadrature, phase shift, and input axis misalignment about OA shall be similarly resolved. (See Appendix B.) Consideration shall be given to operating frequency, radial-offset effects, and output-voltage distortation and noise content (Appendix C).

3.5 Float-Support Characteristics

The float structure should be as symmetrical and rigid as practicable, with limitations specified for gyro errors attributable to $I_{SA} - I_{IA}$ inertia mismatch and products of inertia. Configuration of float design shall be considered versus the need for float-balance-adjustment mechanisms (and their disturbing torques). The need for balance adjustments shall be dictated by gyro g-sensitive coefficient effects on system performance. The thermal conductivity of the float assembly shall be such that wheel power, bearing temperature, and the thermal characteristics of the fluid and damping gap provide the required heat-flow paths consistent with system constraints.

The output-axis pivot and jewel clearances shall be evaluated with regard for:

1) Interference with float motion during gyro operational modes,
2) Provisions for the expected differences between mechanical and electrical float centering,
3) Mechanical float freedom versus float self-centering ability,
4) Ability to withstand all specified environmental inputs without pivot deformation,
5) Manufactoring difficulties involved.

Float electrical grounding and OA angular-stop provisions shall be specified.

The damping requirements, including translational and rotational characteristic-time dependencies with respect to each axis, must be specified consistent with the gyro operating temperature.

Thermal transfer characteristics of the fluid and the effects on the thermal model should be compared with the operating problems resulting from varying the damping-gap size; other fluid characteristics shall be compatible with instrument thermal environments (shelf storage, shipping, system storage, standby, and possible failure modes and transients), and they shall not introduce effects deleterious to required gyro or system performance. Since bellows are employed to compensate for fluid volumetric changes, symmetry of bellows design and placement shall constrain float-disturbance effects to within the system performance requirements.

If forced fluid or gas is used to provide float suspension, the material shall be evaluated for all of the preceding environmental conditions, and additional attention shall be given to temperature-control perturbations, float torque-uncertainty problems, and source complexity upon system performance and reliability.

Wheel-power leads shall be configured symmetrically (electrically, magnetically, mechanically) as practicable within system-performance tolerances. If required, limits shall be placed on the resulting bias contribution.

The addition of mechanical adjustments to reduce the bias torque from wheel-power leads shall be balanced against system requirements, manufacturing costs, and the effects of asymmetries and uncertainties introduced by the adjustability features.

The float-suspension type shall be specified to provide an optimum system solution for trade-offs among stiffness (characteristic times), power required, operating float-position stability, tolerable uncertainties associated with suspension, thermal stability, float-position monitoring requirements, and the complexity and reliability of system support required to provide adequate suspension.

3.6 Thermal Characteristics (Ref. 30,35,36)

Elements related thermally to gyro performance — wheel and float elements, the torquer, signal generator and flotation fluid — have been discussed in their respective parts of Chapter 3 and will not be repeated here.

The specification for the temperature controller may be entirely within the realm of the system designer; but that specification must be consistent with the elements of section 2.6 which will be integral parts of the delivered gyro.

The specification for a thermal insulator shall be established on the basis of expected thermal sensitivities for gyro-drift coefficients and parameters and on the heat-flow characteristics necessary to facilitate acceptable performance of the gyro in the system.

The design of the insulator and its attachment to the gyro shall not introduce vibration problems nor excessive residual stresses in the gyro case and mounts. The temperature control and monitor sensors shall be reviewed both for material and environmental capabilities.

Active systems for providing required thermal isolation (flowing fluid, pumped vacuum) shall be carefully considered for reliability, servicability, and hazards.

The gyro case shall be compatible with the jacketing, mounting, and environmental requirements (Ref. 50,51,52). Temperature-control sensors and monitors located on or imbedded in the case shall be compatible with the case external configuration and with any jacketing devices required to provide temperature control. The philosophy of design symmetry shall be maintained consistent with the heat-flow requirements and the effects of residual mechanical stress on the geometric stability of the case.

The gyro-mounting arrangement shall be specified after due consideration for its effects on temperature control, material compatibility (Ref. 52) with the gyro case, and the heat-sink surface materials. The mounting technique shall provide, to the greatest degree possible, rigidity, symmetry, ease of gyro-axes orientation, stability of gyro axes after adjustment, and access space for gyro cables and alignment tooling.

Case and mounts together must be reviewed for thermal conductivity, rigidity, mechanical stability, mounting repeatability, transmissibility at critical frequencies (wheel-related), surface integrity, and surface-integrity protection provisions.

3.7 Gyro Testing

Test requirements for any gyro shall be carefully specified in the gyro-to-system-interface specification, as well as in the gyro specification. Allowance must be made in the gyro-coefficient test specification for gyro-to-heat-sink heat-flow differences between test stations and between the test station and the system. Provision should be made early in the program for gyro system monitors, with special emphasis on diagnostic tests that may be necessary, especially at higher levels of integration in the spacecraft.

The test program shall include the following:

1) Gyro fabrication tests (build-start thru final assembly)
2) Gyro acceptance tests (completed gyro — all gyros)
3) Gyro qualification tests (completed gyro — as large a sample as practicable)
4) Gyro engineering evaluation tests (completed gyro — as large a sample as practicable)

Consideration shall be given to the inclusion of any or all of the following items in the specification:

1) Pre-acceptance test-temperature cycling for aging purposes.
2) The physical configuration of the gyro when acceptance tested.
3) A definition of the relationship between the test electronics and the system electronics.
4) A schedule of the gyro qualification and engineering tests.
5) Applicable data to be reported from the system-level test program.

3.8 Reliability

A definition of reliability must be established within context of the program in which the gyro is used. Availability of data may make the use of statistical specification feasible; but the treatment of reliability, in the absence of populations on which such estimates are based, requires other techniques:

1) Histories of failure modes (as in Table 2-4) should be made to determine areas in which improvement will enhance gyro reliability.

2) Provision for system monitors of the gyro should be specified to obtain "health" indicators to provide an in-system gyro-profile history on an individual basis (refer to Section 2.8.2).

Other important elements related to reliability should be specified as follows:

1) Gyro shelf storage and gyro transport modes shall be adequately controlled to prevent gyro exterior corrosion as the result of exposure to harmful gases (type and pressure), humidity, salt spray, and other similar deterioration sources. These non-operational modes shall be constrained to adequately safeguard the gyro with respect to all other mechanical, thermal, and magnetic environments as well.

2) Ease of gyro replacement in the system in the event of gyro failure shall be adequately considered.

3) Care shall be taken to assure that failure in a system electronic excitation source will not result in catastrophic dc application to internal gyro circuits.

4) Space radiation effects on the gyro shall be specified according to types and levels of radiation expected, but verification testing will probably be necessary to establish the shielding requirements.

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SECTION 4

RECOMMENDED PRACTICES

This section contains guidelines to improve the operation of programs involving the system application of gyros. In addition it provides recommendations regarding each of the important elements of the gyroscope.

It should be recognized that the gyro-to-system interface has elements of flexibility. Within the confines of the system-performance requirements, a degree of flexibility permits compromise in both the gyro and the system designs.

Generally, a successful gyro design results from the use of a proven gyro to which minimum-risk improvements and modifications are made to achieve the most suitable match between gyro characteristics and system requirements.

4.1 Gyro Performance

Early in the design of a guidance and control system using gyros, an error budget is developed which assigns allowable errors for all system contributors. A portion of this error budget is allotted to the gyros, and within this confine the gyro must be specified for model coefficients, parameters, and related stabilities. Other characteristics must also be specified in sufficient detail to assure that gyro life, environmental tolerance, economic producibility, and reliability are consistent with the mission requirements.

A common problem is that excess conservatism in the gyro specification can result from the insertion of arbitrary safety margins by various engineering levels participating in the system effort, thereby imposing unnecessary demands upon the gyro design. Good gyro-system-interface documentation will serve as a check against such occurrances, and assure realism in both gyro design goals and gyro test-program requirements.

Traceability requirements on gyros should be established to preclude voids in gyro history during test and handling. The importance of these requirements increases with program size; oversights can result in acceptance of marginal gyros as well as in rejection of good gyros.

4.1.1. Environmental Effects on Performance

Changes of environment between test laboratory and mounting location within the system may be considerable. All of the following represent possible changes in environment which would affect the measured drift rate at each location:

1) Mounting provisions
2) Thermal conditions
3) Power-supply characteristics
4) Test sequence
5) Data handling
6) Noise effects
7) Magnetic fields
8) Resonance
9) System moding

Whenever possible, the nominal conditions at both the test and system levels should be identical. The relaxation of performance requirements from the gyro test level through the various system-integration stages can be determined by experience or by analysis.

4.1.2 Storage Effects on Performance

The following storage conditions can affect the drift performance of a gyro:

1) Temperature
2) Instrument attitude
3) Applied excitation(s) (i.e. suspensions might be operative)
4) Length of storage time

Any storage can produce instabilities, such as short-term transient changes for temperature-stabilization operations and for disaccomodation in ferrous materials. Small permanent shifts result from hysteresis in the various construction materials; and from misalignment due to residual clamping stresses on the case.

These storage-induced shifts in drift level and stability must be considered in the test routines set up for the system and in the evaluation of gyro operation in the system environment.

4.2 Wheel and Bearing Structure

The following recommendations apply to:

1) Angular momentum
2) Motor
3) Bearing assembly
4) General precautions

4.2.1 Angular Momentum

The value of H_s properly falls within the judgement of the gyro designer, to whom the system designer will specify gyro gain, and with whom he must be prepared to negotiate the following factors before H_s is finalized:

1) Wheel mass
2) OA damping
3) S_{SG}
4) Wheel angular velocity
5) Wheel power and required drive voltage
6) Maximum torquer output (OA)
7) Run-up and run-down times
8) Thermal conductivity of wheel structure, and temperature peaks associated with transients
9) Required wheel axial stability vs anisoelasticity
10) Structure transmissibilty
11) Vibration levels, shock, and acceleration requirements vs structure resonances
12) Bearing life and yield requirements.

4.2.2 Motor

The following specific recommendations are made regarding the wheel drive motor:

1) Wheel power can be reduced significantly through a technique of periodic over-excitation of the wheel (Ref. 16), thus increasing motor efficiency at the cost of additional complexity in the wheel-drive electronics. Wheel-power requirements must consider power margins, the heat-conduction characteristics of the float, gap, and fluid, and the effect on the dynamic range requirements of the temperature controllers.

2) If wheel-power-supply line losses or driving-supply power demands cause problems in the system-electronics design, the reactive wheel motors may be tuned to resonance. Some spacecraft configurations which use long cables between gyros and their power supplies require large wire sizes or feedback around the cables to preclude gyro-drift changes; these are caused by varying gyro excitations which result from wide-range cable-resistance variations induced by environmental temperature extremes.

4.2.3 Bearing Assembly

Recognizing the wheels to be the most important single gyro element, vital not only to performance but also to reliability and life, major recommendations follow:

1) In general, both gas-bearing and ball-bearing wheels are designed to provide 25,000 — 50,000 hours of running life. A combined requirement for long life with interrupted operation, especially in severe mechanical environments, favors the choice of a ball-bearing wheel. A requirement for long life with uninterrupted operation favors the choice of a gas-bearing wheel.

2) Attention should be focused on the wheel bearings, lubricant, and associated parts with regard to handling and possible deterioration during manufacture, testing, shelf storage, shipping, and system installation.

3) The production run of wheels in any gyro program should include a quality monitoring plan in which sample wheels are operated to failure according to appropriately specified failure criteria. These wheels should then be inspected for the condition of the materials in the wheel assembly. The results, representing typical conditions of the entire run, provide a basis for extrapolation of wheel-failure rates, operating life, and reliability factors. They also provide a basis for failure analysis, product and yield improvement, and comparison with similar records from other programs.

4) Provision should be made for monitoring parameter operating levels and stabilities in the system to establish a record against which observed changes can be evaluated.

5) Wheel dynamic unbalance (including retainer motion in ball-bearing wheels) requires design control levels which limit the induced float OA oscillations to an amplitude acceptable to the system. The OA oscillations

generate a modulated error signal from the Signal Generator which, in a digital loop, can cause more timing uncertainty and, in an analog loop, can cause a reduction in torque-motor dynamic range.

An effective test to eliminate bearings with excessive retainer freedom subjects the gyro to sinusoidal vibration at the retainer frequency. The resulting change in drift rate due to synchronously rectified torques about the output axis reflects the retainer freedom condition.

4.2.4 Wheel-Safety Precautions

The following safety measures should be incorporated:

1) Provide protection against catastrophic bearing failure which can result from exciting gas-bearing wheels in a negative rotation direction.

2) Assure that the float electrical grounding scheme cannot burn out a flexlead in the event that the polarity of a drive supply is reversed with the float pivot against the case.

3) Provide protection from high slew rates (gimbal runaway).

4.3 Torquer Characteristics

The maximum gyro-torque requirements are set by the spacecraft or gimbal environment. (Note: the foregoing implies that wheel-speed reductions can be considered as an alternate solution for providing higher slew-rate tolerance for a given torquer scale factor). Since torque uncertainties increase with higher maximum torquer capability, it may be useful to consider multiple-torquer winding sets and multiple-torque modes to achieve high-torque capability coupled with low-torquer uncertainty.

Torquer linearity is usually more important in strapdown systems than in gimballed systems. Bias contributions by the torquer arising from elastic restraint and reaction torque require review similar to that for the signal generator. Additional gyro bias arises from the difference between positive-torque sensitivity and negative-torque sensitivity of the torque generator. Torquer design can provide plus-to-minus SF matching to less than 0.1 percent of full scale. The stability of the match can be more than an order of magnitude less than the absolute difference value; needed compensation can be provided.

Pulse torquing, presently used in both gimballed and strapdown systems because of efficiency and natural compatibility with computer interfaces, usually employs three-state torquing (torque on demand) (Ref. 4,54) when power is a prime concern (the cost is increased electronics complexity), or two-state torquing (Ref. 6) when simpler electronics are desired and power is a de-emphasized consideration.

Hysteresis or memory effects associated with pulse torquing can be reduced to required levels either by the addition of a torquer "wash" winding (always excited with ac) when space is available on the torquer, or by "washing" techniques applied in the torquer drive electronics. For reduced transient effects in the gyro, constant-power inputs should be incorporated to the extent possible.

Other considerations related to the pulse-rebalance system are torquing frequency and torquer-pulse magnitude. The pulse area represents a command-angle input to the gyro, for which the gyro response is set by the OA characteristic time, resulting in IA motion about OA constrained by the torque mode employed. Angle size must not reduce system performance, therefore implying high torquing-current amplitudes and high torquing frequencies. But high torque current requires high voltages, which become potential noise sources and failure hazards. High frequencies tend to increase torquing errors because of the torquer time constant (and its stability) which introduces exponentials into the torque pulses. Low torquing frequencies are more compatible with torquer time constants, and the use of lower currents (and voltage), are generally favored.

Magnetic shielding is an absolute necessity on E-type torquers and desirable on V-type torquers (Appendix A). To be effective, the shielding must cover the entire torquer (this can imply shielding the entire gyro); small holes in the shield at predetermined points are acceptable. Partial shields can be more harmful than no shield at all, as instabilities in magnetic fields within the instrument can result.

Torquer parameters must be examined by the system designer for radial- and axial-offset sensitivities of scale factor, reaction torque, linearity and elastic restraint, and torquer-current stability. Torquer aging effects cannot be ignored. The above parameters are also sensitive to torquer aging.

4.4 Signal-Generator Characteristics

The total gyro transfer constant includes the OA transducer characteristic (S_{SG}). Generally the stability of S_{SG} is of greater importance in gimballed applications than in strapdown systems, but, regardless of application, possible sources of error in S_{SG} must be reviewed.

Transducer linearity and hysteresis must be examined versus the OA angular-stop angle (or the used portion thereof). With S_{SG} stability directly proportional to excitation stability, signal-generator tuning techniques must be examined for contributions to S_{SG} drift. The device's elastic-restraint torque (proportional to OA float angle with respect to null), elastic-restraint stability and reaction-torque stability are proportional to the square of the exciting-current stability; these considerations constrain excitation stability to levels dictated by system performance. In addition, null quadrature voltage in the presence of residual SG phase shift produces IA misalignment about OA (Appendix B). This effect must be constrained to acceptable system limits by controls over the two contributors.

The supressed-carrier torque loops usually employed in conjunction with the SG must have sufficiently high carrier frequencies to provide adequate bandwidth and dynamic response characteristics of the loop. The sensitivity of the SG to float radial offset imposes an upper bound upon carrier frequency. The use of full-wave synchronous demodulators is desirable to reduce effects of harmonics in the signal-generator output voltage which could otherwise be electronically rectified, producing effects similar to real signal components. Further, different frequencies are recommended for the signal generation and suspension mechanisms (Ref. 58). This will reduce cross-talk errors which can exist through electromagnetic and electric coupling between the two mechanisms.

Servo bandwidth, usually set by the gyro I_{OA}/C_{OA} at 100-200 Hz, limits the gyro errors which are measurable by the gyro in the system. These errors, which may be caused by mechanical wheel noise, must be specified for the gyro designer to maintain adequate control over them.

Efforts toward magnetic, electrical, and mechanical design symmetry in the signal generator are recommended.

4.5 Float-Support Characteristics

Good float design is a function of the symmetry and simplicity of the exterior configuration, limited by requirements for maximum $I_{IA} - I_{SA}$ inertia mismatch, structural rigidity, float products of inertia (usually negligible except with high input rates), and the density constraint (flotation). The OA float inertia must be small enough to limit the output-axis coupling errors to acceptable levels and to assure adequate servo bandwidth. For space (free-fall) applications (Ref. 6,53), float unbalances produce no torque; it may be possible to eliminate float-balance adjustments (for torque-uncertainty improvement) if g-sensitive torques on the order of 1 dyn-cm/g can be tolerated in ground-calibration routines.

Suspension stiffness must be high enough to provide low float-characteristic times (see Table 2-2) and to keep the float pivots clear of their stops in the presence of the OA rates specified for the system. Mechanical stops, for a magnetically suspended gyro, provide a nominal ± 0.0005-inch pivot clearance, but manufacturing and assembly tolerance buildup may reduce the minimum clearance to about 0.0003-inch freedom of motion in the gyro. Axial float freedom (endshake) is nominally ± 0.002 inch. Greater axial freedom can destroy the self-centering feature, causing unacceptable gyro performance (Ref. 23). For the ducosyn configuration, tuning changes can provide limited compensation for greater mechanical freedom at the cost of reduced suspension-spring constants. Suspension stiffness must be adequate to limit float shifts due to fluid density changes with temperature offsets (buoyancy effects) resulting from gyro power changes in the system (wheel on/off). With 1 to 10 microinches per degree F displacement possible, it may be advisable to consider providing substantially constant power into the float for all system modes. This would circumvent the need to examine the gyro coefficient and parameter sensitivities to float-temperature offset possibilities and recovery transients. Suspension capacitors should be conservatively rated and located in a protective environment. The failure (opening or shorting) of any suspension circuit element (except possibly all of them) results in unacceptable gyro performance. Suspension excitation cables exposed to temperature extremes may require treatment as suggested for the wheel cables in section 4.2.2.

Suspension-monitoring capability in the system is recommended for diagnostic use, but monitoring capability must not impair the suspension reliability.

Flotation-fluid characteristics should remain stable under all expected thermal and mechanical environments, as well as providing the necessary flotation density and the damping for required gyro gain.

Output-axis angular stops should be positioned to facilitate adequate OA freedom, acceptable system erection times from storage or standby modes (gimballed systems), and OA transducer linearity.

Flexlead installation and operation should be as magnetically, mechanically, and electrically symmetrical as practicable. Absolute torque tolerances of up to 0.6 dyne-cm permit consideration of the removal of mechanical bias adjustments in the gyro for cleaner design. For evaluation, a measurement should be made of the output-axis spring rate in both excited and unexcited flexlead conditions.

4.6 Thermal Characteristics (Ref. 30, 35, 36, 38, 39,51)

If analysis indicates the need for thermal insulation of the gyro, a jacket with the following characteristics should be provided:

1) A controlled heat path to the heat sink consistent with wattage and temperature requirements.
2) Insulation which will not deteriorate with time and exposure to any expected system environment.
3) Freedom from mounting or alignment problems or loosening in service.
4) Materials and finishes compatible with exterior gyro materials in all environments to which the gyro and jacket will be subjected.

The thermal insulation and magnetic shield may often be integrated into a single manufactured element. In any case, the use of a magnetic shield covering the entire gyro is recommended. The configuration of the shield should be finalized only after the temperature-control sensor locations are established.

The gyro case must be considered for temperature-control sensor location; both the case and mounts are candidates for heater location.

Before the thermal jacket and shield solution may be considered complete, location of the gyro-temperature sensors must be established (with as much intimacy with the fluid as practicable), along with the gyro heater location on the gyro, on the jacket, or on the mounts.

For maximum stability and reliability, the use of metallic (usually nickel or nickel-alloy) thermal sensors is recommended. The attractiveness of greater inherent sensitivity of thermistors is reduced by their lower self-heating threshold, and the requirement for protection of the junction to insure reliability which limits the response speed.

Mechanically, the gyro case should be as symmetrical about all axes as is practicable, and fabricated from a material which, in addition to having high thermal conductivity to minimize thermal gradients, represents the best combination of rigidity, geometric stability, and materials compatibility. The thermal jacket and shield solution must also encompass heat-flow characteristics required by the system, as well as minimizing stress in the gyro case-to-mount and the mount-to-frame interfaces.

The mounts, while providing acceptably low vibration contributions and thermal asymmetries, must facilitate gyro axes alignment at system installation. With gyro IA-to-mounting-frame alignment shifts from test-to-system installation typically >1 arc-minute, consideration must be given to providing gyro-to-mount and mount-to-frame adjustment tooling in the system. Ease of gyro replacement in the system should be evaluated in gyro-mount design. To minimize IA shifts, attention must be given to the material finishes of the mount mechanical interfaces (galling must be precluded). This precaution, along with judicious use of thermal grease, will improve control over the thermal resistance to the frame.

4.7 Gyro Testing

At acceptance testing, the gyro should be configured as nearly like the system-ready gyro as is practicable.

Acceptance tests should be based upon a necessary-and-sufficient philosophy consistent with the end-item use of the gyro. Gyro-test monitors should be nondisturbing by design. Manual making and breaking of circuits (except for throwing a switch) is not recommended. Test personnel should be trained to minimize gyro disturbances resulting from carelessness or ignorance (such as to cause float motion against a mechanical stop).

Acceptance-test modes should be limited to those required for verifying gyro integrity. Generally the precise test content will be different for each application. The tests should be specified completely, including equipment, test content and sequence, test positions, conditions, times, and model reduction equations. Gyro fixturing and thermal-environment stability must be consistent with required test times and accuracy.

Test electronics should employ system designs to the greatest extent possible (electronics meeting system specification is an alternate solution) and gyro-excitation sequencing should conform to system sequencing consistent with test requirements.

Two-gyro, simultaneous test capability is strongly recommended for each test station except when servo testing (Ref. 41) is employed. The resulting performance correlation reduces the need for subjective judgement in data interpretation as aids in early discovery of test-station malfunctions which might otherwise cause performance anomalies to be attributed erroneously to the gyro.

Adequate protection from stray magnetic fields and high-velocity air currents in the area of the test station must be ensured.

Repeated temperature cycling of a gyro prior to acceptance testing, through a range representative of the expected life, will speed up aging and improve drift stability.

Completion of qualification tests and engineering evaluation tests early in the program is recommended. In addition, qualification tests must provide a reasonable match with realistic system requirements.

A frequent cause for concern is the variation in performance of the gyros from the test stand to the system. A principal cause of variation is the thermal condition of each location. If the program includes a large number of gyros and more than one manufacturer, the effort necessary to provide reasonably identical equipment and production conditions in all locations is justified.

Consistent test results demand extreme thoroughness in specifying adequate controls over switching, on-off control, known and controlled mode changes, well-defined initializing procedures, and gyro-data accumulation.

4.8 Reliability

The statistical treatment of reliability requires a suitable mathematical model supported by realistic assumptions acceptable to the system designer and to the designers of subsystem elements (Ref. 46, 47).

Reliability recommendations in the areas of (1) Gyro-Parameter Monitoring, and (2) Failure Analysis follow:

4.8.1 Gyro-Parameter Monitoring

A gyro in operation represents the interaction of a large number of elements in a specific environment. The variation in the measurable parameters from gyro to gyro and from time to time is largely a measure of these interactions.

The record of these variations with the attendant environment carefully and accurately defined at each measurement provides an opportunity to analyze the performance of the design. An evaluation of these results is a worthwhile goal of a reliability program.

To be a meaningful evaluation, data must be rigorously defined and carefully controlled as to source and method throughout the life of the program. If the data are carelessly collected and annotated, the confidence level in the conlusions drawn from the data will suffer.

The specific data to be recorded and the techniques to be utilized depend on the system requirements, the cost involved, and the specific objectives defined. The program developed for the inertial components of the Poseidon system (Ref. 57) probably represents the furthest extension of this philosophy to date.

4.8.2 Failure Analysis

Failures of gyroscopes can be identified in two major classifications: performance degradation, and catastrophic failure.

The former includes sporadic variations in parameters which may have been specified more stringently than necessary for system operation as a quality-control provision. Such gyros, when supported by failure-analysis records, can frequently be accepted for use without loss of confidence because the performance degradation can be predicted and there is no likelihood of catastrophic failure.

The latter classification includes either total loss of gyro function, or such performance degradation that an unsuccessful mission or a mission abort would occur, or that crew safety would be jeopardized. Failure analysis of these gyros can help to provide knowledge of the mechanisms, within the bearing assembly, that precipitated the failures. A statistical evaluation of the analysis findings can be used to feed back and establish more quantitative specifications to identify the onset of failure, and to estimate accurately the remaining useful life of gyros still in service.

4.8.3 Reliability Enhancement Factors

The following reliability-related practices are recommended as the result of experience, to preclude problems in future programs.

1) Protect the gyro exterior from possible environmental chemical-deterioration sources. Specify controls, over such likelihoods, including containers with dessicant when necessary, to preclude damage from gaseous environments, salt spray, humidity, and similar sources.

2) Specify treatment of "shelved" or "stored" gyros with regard for mechanical, thermal, and magnetic environments.

3) Protect the gyro connectors by attaching "stub" connector mates at the earliest feasible time, and remove the tooling connectors only for assembly to the system.

4) Safeguards should be imposed to protect the gyro from electrical parameter or coefficient changes through careless use of ohmmeters, which can disturb magnetic gyro circuits.

5) A safety consideration to protect system electronics is the use of connectors with male pins on the gyro.

6) The system designer should be cognizant of hazardous gyro excitation levels: his electronic design reviews should include checks to verify that electronic failures will not catastrophically affect the gyro.

7) Electrical monitors of the gyro should not impair gyro performance or require circuit breaking and making procedures in the system.

8) Systematic gyro drift induced by cable-resistance changes (associated with wheel, suspension, torque-generator and signal-generator drives) because of spacecraft cable temperature cycling must be reduced to acceptable levels by use of large conductor sizes, multiple conductors, or techniques which include the cables in the power-supply feedback loops.

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APPENDIX A

MAGNETIC EFFECTS ON E AND V TORQUERS

This appendix illustrates the reason why the E-type torquers are more sensitive than the V-type torquers to externally applied magnetic fields.

The names E and V, as used to designate different types of torque generators, represent a mixture of pole configuration and wiring configuration. Type E torquers utilize stator poles in sets of three, with the resulting core configuration approximating the shape of the letter "E", whereas V torquers utilize sets of two stator poles. The following table shows the difference in pole configurations for the two torquers.

	E Torquer	V Torquer
No. of Stator Poles	3n (n = 1)	m (even)
No. of Rotor Poles	2n or n	$\frac{m}{2}$ (even)

where

n = 2, 3, 4, 5, ...

m = 4, 8, 12, ...

A quick check of the table shows that the stator with the least pole count (as n and/or m increase) that meets the requirements of both E and V configurations has 12 poles. This stator will serve as the basis for comparison of magnetic field effects on the two torquers.

The E Torquer

The figure below shows an E-type torquer consisting of 12 poles (4 E's). Only one E is shown operating with the primary flux represented by the heavy line energized by pole (2). Poles (3) and (1) are secondary poles used for torquing. The fluxes reinforce on pole (1) and are subtractive on pole (3).

The external fields enter through the end of the instrument (into the page), then into the magnetic suspension rotor, leaving radially as shown through the microsyn poles. These fields add to pole (1) and subtract at pole (3) from the secondary torquing flux. This is a first-order effect that imparts scale factor.

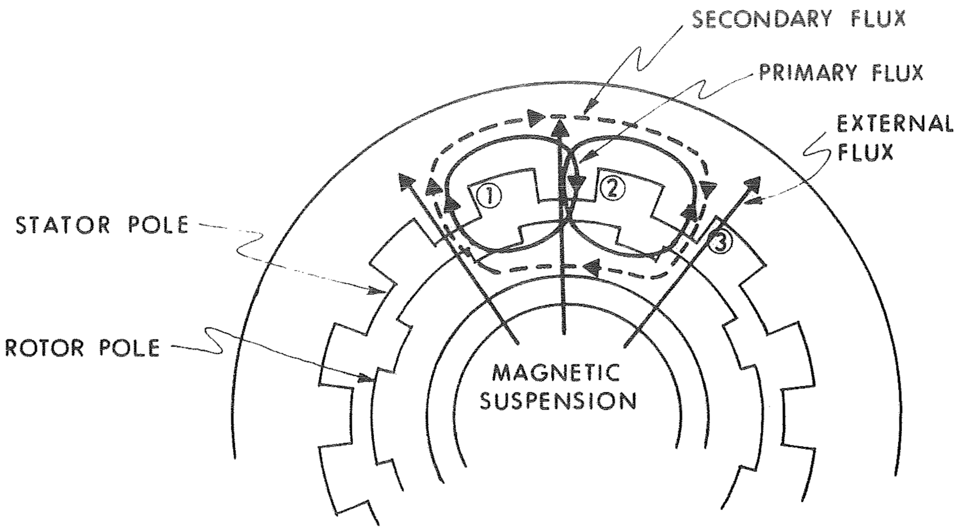

Fig. A-1. E-type torquer.

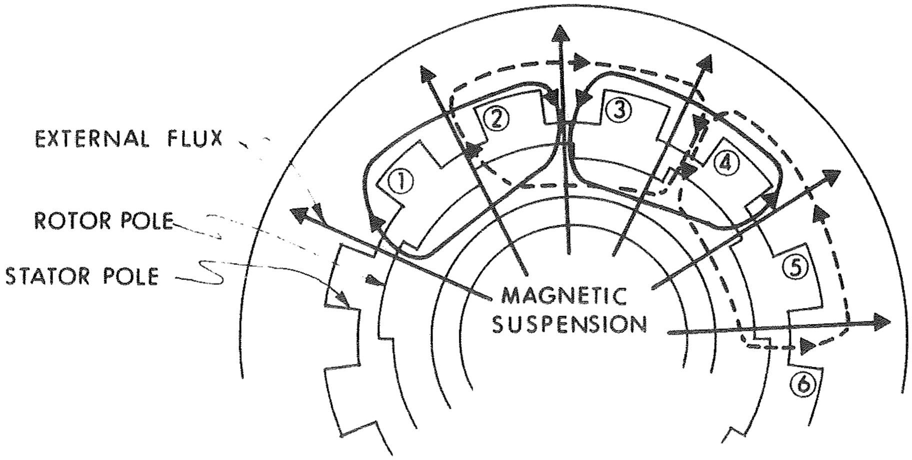

Fig. A-2. V-type torquer.

The reason is that all four pole sets torquing clockwise on the unit are made stronger and the four pole sets torquing counterclockwise are made weaker.

Analysis:

From the basic torque equation $M = K\phi^2$, where ϕ = flux,

$$M = K\phi_1^2 - K\phi_3^2$$

for each E at a given level of secondary excitation. As shown in the sketch, let

$$\phi_{12} = \phi_1 + \Delta\phi$$

and

$$\phi_{32} = \phi_3 - \Delta\phi$$

$$M' = K(\phi_1^2 + 2\phi_1\Delta\phi + \Delta\phi^2 - \phi_3^2 + 2\phi_3\Delta\phi - \Delta\phi^2)$$

$$M' = K(\phi_1^2 - \phi_3^2) + 2K\Delta\phi(\phi_1 + \phi_3)$$

and the error term $2K\Delta\phi(\phi_1 + \phi_3)$ is first order.

The V Torquer

Figure A-2 shows a V-type torquer with the odd-pole flux shown in the solid line and the even-pole flux by the dashed line. The external flux is shown radially coming from the suspension rotor. Only one pole set is energized at a particular time, depending on the polarity of torque required. Note that in this type of torquer the flux adds in three poles and subtracts in the other three, all of which are torquing in the same direction. This results in a second-order type of change which is very small by comparison with the E-type torquer.

Analysis:

$$M = 3K\phi_1^2 + 3K\phi_2^2 = 3K(\phi_1^2 + \phi_2^2)$$

where ϕ_1 is the flux in poles 1, 5, and 9 and ϕ_2 is the flux in poles 3, 7, and 11.

Let

$$\phi_{11} = \phi_1 + \Delta\phi$$

and

$$\phi_{21} = \phi_2 - \Delta\phi$$

$$M' = 3K(\phi_1^2 + 2\phi_1\Delta\phi + \Delta\phi^2 + \phi_2^2 - 2\phi_2\Delta\phi + \Delta\phi^2)$$

$$= 3K(\phi_1^2 + \phi_2^2) + 3K \times 2\Delta\phi(\phi_1 - \phi_2) + 3K\Delta\phi^2.$$

Since $\phi_1 \approx \phi_2$,

$$M' = 3K(\phi_1^2 + \phi_2^2) + 3K\Delta\phi^2.$$

The error term $3K\Delta\phi^2$ is very small compared to the error in the E torquer.

The preceding discussion supports the conclusion that while V-torquer shielding might be desirable, E-torquer shielding is virtually mandatory to assure gyro insensitivity to local magnetic fields.

APPENDIX B

GYRO SIGNAL-GENERATOR NULL QUADRATURE AND ITS EFFECT ON INPUT-AXIS LOCATION

The following treatment demonstrates that input-axis angular error about the output axis results because the torque loop interprets the quadrature voltage is an actuating signal in the presence of phase shift. When the effect is defined, limits and controls can be imposed to constrain the IA to acceptable levels.

Definitions:

$\overline{V}_s$ = signal-generator output voltage, neglecting null quadrature voltage

$\overline{V}_t$ = signal-generator output voltage, including null quadrature voltage

$\overline{R}_e$ = real component of V_s

$\overline{P}$ = imaginary component of V_s

$\overline{Q}$ = null quadrature voltage

ϕ = signal-generator-output phase angle with respect to the reference excitation

null = condition of minimum signal-generator output voltage

Generally

$$\overline{R}_e = \overline{V}_s \cos\phi,$$

$$\overline{P} = \overline{V}_s \sin\phi,$$

and

$$\overline{V}_t = \overline{R}_e + j(\overline{Q} + \overline{P}) = \overline{V}_s \cos\phi + j(\overline{Q} + \overline{V}_s \sin\phi) \quad (1)$$

From Fig. B-1 it can be seen that null cannot occur when $\overline{V}_s = 0$; rather, it occurs when $\overline{V}_s = \overline{Q} \sin\phi$.

Null error,

$$\overline{V}_t - \overline{V}_s = (\overline{V}_s \cos\phi - \overline{Q} \sin\phi) + j(\overline{Q} + \overline{V}_s \sin\phi) \quad (2)$$

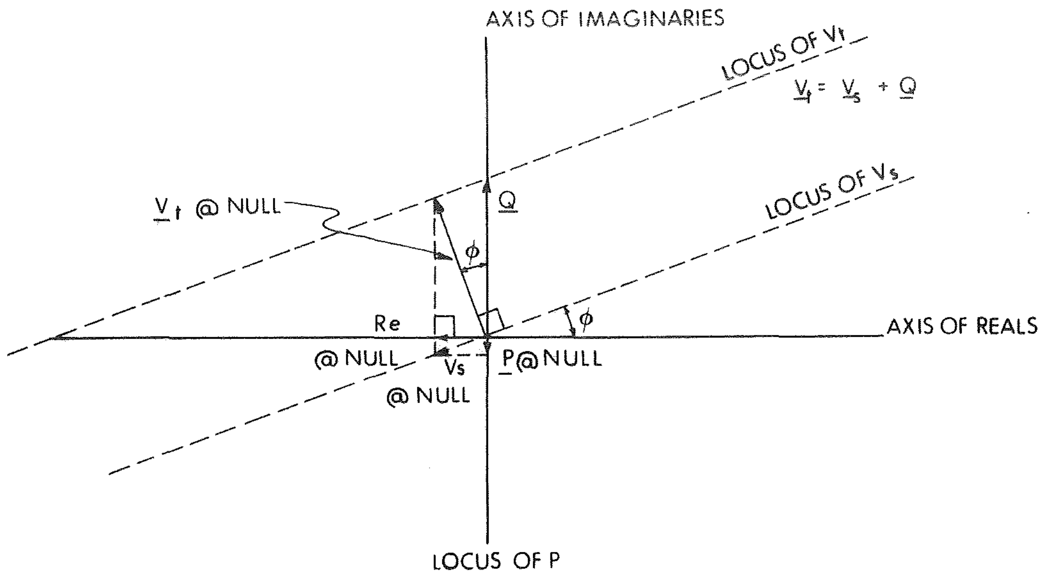

Fig. B-1. Signal Generator output voltage components at null.

Since from Eq. (1),

$$\bar{V}_s \cos\phi = \bar{R}_e,$$

we may rewrite Eq. (2) as

$$\bar{V}_t - \bar{V}_s = (\bar{R}_e - \bar{Q} \sin\phi) + j(\bar{Q} + \bar{V}_s \sin\phi) \tag{3}$$

real signal component	null quad. and signal quad. components

The servo balances the quantity $(\bar{R}_e - \bar{Q} \sin\phi)$ by causing float motion about OA to produce a signal such that

$$\bar{R}_e = \bar{Q} \sin\phi \tag{4}$$

the result is IA misalignment about OA from the true null position.

In a test station, oscilloscope Lissajous techniques and gyro-case motion facilitate separation and reduction of both contributors to input-axis error, but in the system, where the gyro operates either at null (where phase shift can not be separated), or with large offsets (swamping the quadrature), gyro-case motion is generally restricted, and the electrical separation is more difficult. Calibration sequences, however, mechanically demonstrate the amount of misalignment that results.

Note that misalignment disappears if either quadrature voltage or phase shift is zero. The misalignment of IA may be controlled by restricting either the phase shift or the quadrature voltage or both as system requirements may dictate.

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APPENDIX C

LOOP NOISE IN SDF INTEGRATING GYROSCOPES

As the requirements for platform alignment stabilities become more and more stringent, the amplitude of the gyro output noise across a broad frequency range attains major importance. Earlier practice which permitted evaluation of random drift based on a 10-minute integration time constant effectively avoided the problem. The following describes the sources, magnitudes, and characteristics of gyro output noise and suggests techniques for evaluating and reducing noise levels. A list of references is included at the end of this appendix.

An appropriate model for discussion of noise sources and characteristics is shown as Fig. C-1 (Ref. C-8). In the figure, W is the intentional input angular

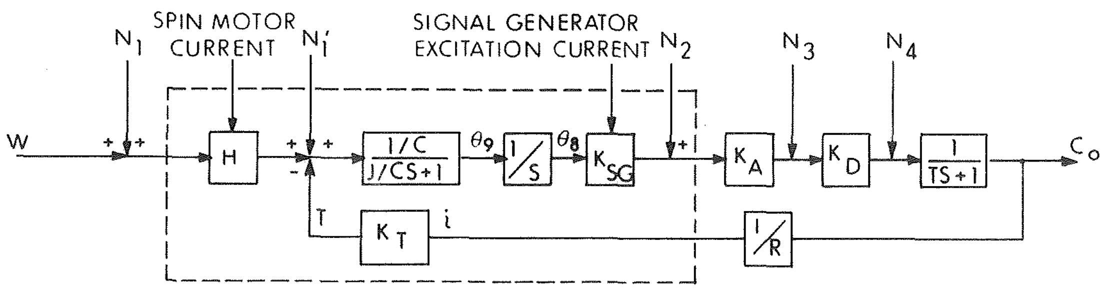

Fig. C-1. Gyro and rate loop model.

velocity, H is the gyro angular momentum, C is the damping constant provided by viscous shear of the damping-flotation fluid, J is the gimbal output-axis polar moment of inertia, and K_{SG} and K_T are, respectively, gains associated with an ac signal generator and a dc permanent-magnet torque generator. The closed loop is shown as consisting of an ac preamplifier having a gain K_A, a demodulator having a gain K_D, a ripple filter, and a sampling resistor, R. Noise sources are N_1, N_1', N_2, N_3, and N_4. The following paragraphs will discuss these noise sources.

The noise source shown as N_1 is an actual input angular velocity. The presence of such input rotational disturbances at test sites and on test stands has been the subject of much study, and has resulted in design of several servo-controlled test-stand stabilizing devices (Ref. C-1,C-2,C-3). Finding a naturally quiet location appears most unlikely, based on many thorough studies (Ref. C-4,C-5,C-6,C-7).

In addition to severe long-term (beyond 60-day period, or perhaps random) tilting of most test sites, due primarily, it appears, to temperature gradients in the earth, there are also high-frequency translational and rotational disturbances having both geological and cultural origins. Figure 1-1 of the Weinstock paper, (Ref. C-1) indicates that these rotational disturbances can exceed 0.1 arc second rms per decade of frequency in the range from 1 to near 100 Hz, and can reach a peak in excess of 10 arc seconds rms per decade between 10^5 and 10^6 Hz. This wide distribution suggests that servo-stabilized tables similar to Mr. Weinstock's, mounted on a spring-mass vibration isolator, offer the only real hope, at present, for actual isolation of the gyro during test so that its inherent capabilities can be evaluated. Some work has, however, been done on a different approach. Cross-correlation studies of the simultaneous outputs of accelerometers and seismometers with gyro-test outputs have been attempted, but as yet results which can be applied to practical gyro testing have not been obtained. Of particular interest (Ref. C-8) is the presence of a sharp, high peak due to test-site disturbances occurring at 19 to 20 Hz. Discussions with test engineers from a number of facilities tend to support the idea that most test sites exhibit a similar peak in this general frequency range.

The noise source shown as N_1' is, like N_1, associated with rotational motion of the gimbal about its output axis, but is not due to the operation of the rotor's angular momentum upon actual input-axis angular velocities whether intentional or unintentional. It would include noise due to changes in mass center of the gimbal, changes in the rest point of the various sources of elastic-restraint torques, fluid-convection torques, and the operation of gimbal-mass imbalance upon test-stand translational disturbances. By far the most significant torque source, however, appears to be the acceleration and deceleration torques which are applied to the gimbal as the hysteresis synchronous-spin motor hunts above and below synchronism at a frequency ranging from 3 to 5 Hz. Since these torques appear about the spin axis, it would seem that they would not cause gimbal output-axis rotations. However, since generally the rotor spin axis is not exactly 90 degrees to the gimbal's effective output (pivot) axis, rotation does result. Further torque sources in the higher frequency range would include rotor dynamic imbalance and bearing component noises.

Noise input N_2 is due, primarily, to electromagnetic coupling of spin-motor fields, (and spin-motor running detector if such a feature is provided) into the secondary of the signal generator. Due to the structure of these sources, harmonic content of the fields tends to be high, leading to peaks in noise output at frequencies well beyond the spin-motor excitation frequency.

Noise sources N_3 and N_4 are due to system operation. N_3 is the noise contributed by the ac preamplifier typical of such systems. Source N_4 is noise produced by the demodulator. An analysis of this noise source (Ref. C-8) indicates that while it is produced partially by switching transients, the major effect is due to foldback, or aliasing, an effect which results in frequency components higher than the foldback frequency for the demodulator used, appearing at frequencies spaced an equal distance below the foldback frequency, and thus in the range of interest.

Noise sources N_2, N_3, and N_4 enter the system at points after the gyro's integration effect, so that this integration does not appear in their forward loops. The system dynamics which result act, therefore, to high-pass N_2, N_3, and N_4. By contrast, N_1 and N_1' appear ahead of the integration, which acts to attenuate their higher-frequency components.

A few general rules for reducing noise output are:

1) Since the voltages coupled into the signal-generator secondary are quite independent of the primary-to-secondary turns ratio, and since gimbal disturbance torques are independent of gyro gain, the best choice is to obtain a gyro gain as high as possible at points ahead of the signal-generator secondary in the forward loop. This would imply that the damping constant should be selected for each application so that the maximum input angular velocity expected would produce the maximum gimbal displacement attainable at the required total loop gain. Similarly, a signal generator gain as high as practical should be used. Fortunately, obtaining as much of the required total loop gain as is practical within the gyro permits use of lower gain in the external loop. With N_3 proportional to gain K_A, it too will be reduced.

2) Both the electromagnetic coupling phenomenon within the gyro, and the demodulator frequency folding effect suggest that the carrier or signal-generator excitation frequency should be high, though not at a harmonic of either the spin-motor supply, or of the spin-motor running detector output. This, again, is consonant with the need to obtain high gain ahead of the signal-generator secondary since signal-generator gain increases with carrier frequency. The actual frequency chosen should be optimized for each gyro design to coincide with a relatively noise-free frequency in the spectrum of the signal-generator outputs caused by electromagnetic coupling from the spin motor and spin-motor running detector.

3) Analysis to obtain an "optimal" ripple filter might be productive, as the noise input is fairly predictable statistically.

Gyro Noise Evaluation and Data Reduction

One of the major constraints imposed by the wide frequency range over which output noise spectra must be evaluated is that immense amounts of data must be taken, frequently in a very short time, and then reduced. A typical test might require 1000 to 16,000 data points, and, depending on the frequency range of interest, a sampling rate that could vary from 0.1 to 10,000 samples per second. This problem alone almost necessitates the use of a digital computer, both to control the sampling, and to reduce the data.

The gyro may be operated in a loop similar to, or even identical to, that in which it is to be used, and in any position. If the data-taking interval is small enough to avoid the gyro drifting from null, it is even possible to obtain open-loop data. If the gyro is operated in a pulse-rebalance loop, storage registers may well be the only interface required between the gyro output and the computer input. Use of an analog loop, such as that shown in Fig. C-1, however, will require an analog-to-digital converter. In this case, a more complex interface may be required since a suitable computer may be located some several hundred feet from an even reasonably stable test site. A noise filter, a dc amplifier, and a sharp-cutoff low-pass filter at the test site, coaxial cable from the test site to the computer site, followed by an additional amplifier, and a noise filter, prior to the analog-to-digital converter has proven to be a reasonably satisfactory arrangement. By contrast, due to inherent noise levels in the recording and reproduction processes, recording analog data on tape at the test site for later analog-to-digital conversion and processing at the computer site is not, in the current state-of-the-art, a satisfactory arrangement.

When the sampling run has been completed, and the data converted to digital form and entered into the computer memory, a power-spectral-density program is used to reduce the data. A flow diagram for a satisfactory program is shown in Fig. C-2. Choice of a sampling rate is dictated by the upper frequency limit to which the power spectrum must be defined. The sampling rate must be at least twice this figure. Like the demodulator, aliasing (or frequency foldback) occurs here, with the foldback frequency one-half the sampling rate. The previously mentioned sharp cut-off low-pass filter must be adjusted to cut off just above the folding frequency to avoid foldback contamination in the frequency region of interest.

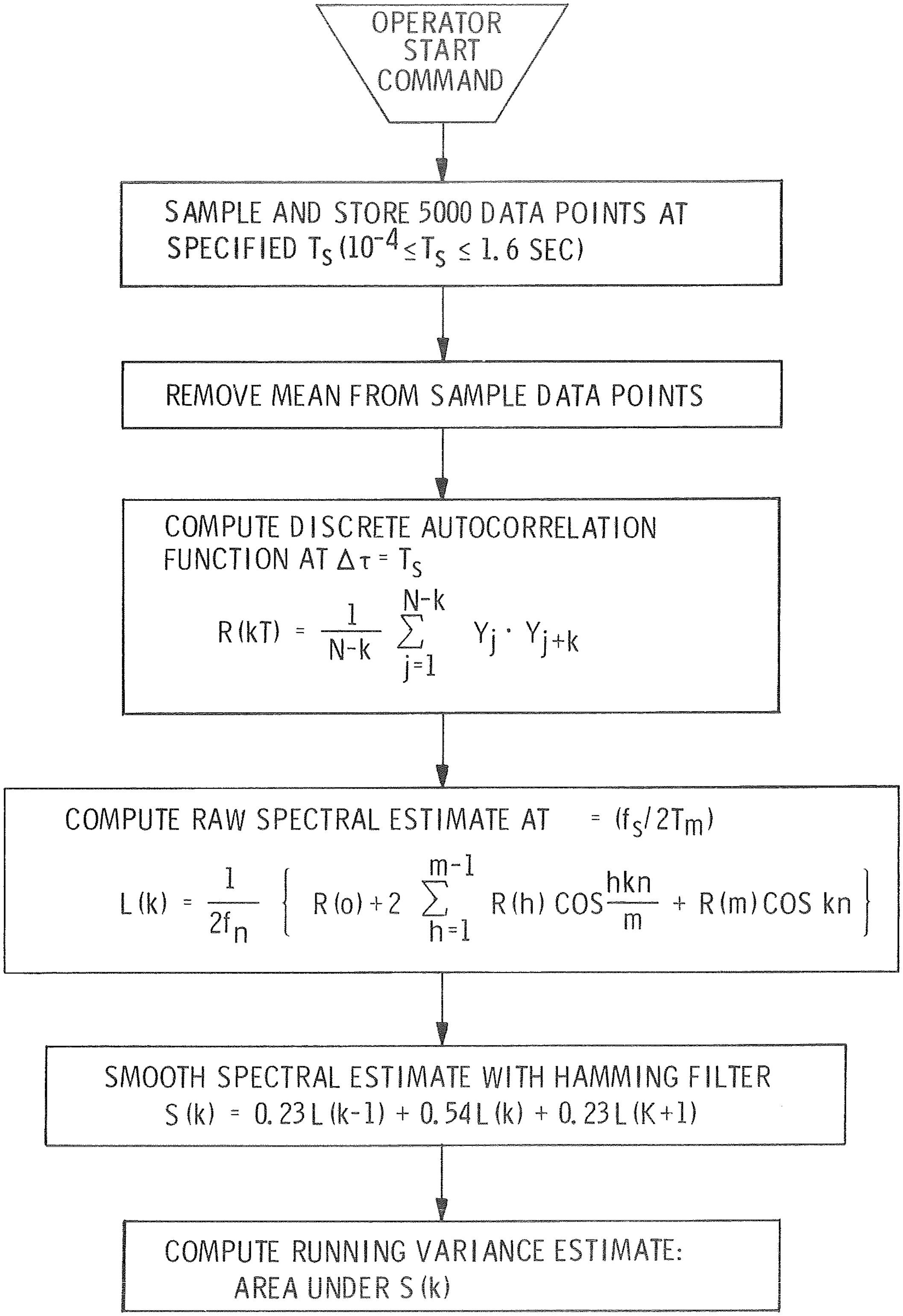

Fig. C-2. One specific power spectral density program flow diagram. (Ref. 8)

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