

AC SPARK PLUG DIVISION
General Motors Corporation
Milwaukee, Wisconsin

XDE - 34 - S - 519

ENGINEERING
DESIGN INFORMATION
EXHIBIT

PRELIMINARY PERFORMANCE
SPECIFICATION
STABILIZATION LOOPS

By J. Goclowski

Date 31 Dec 62

1. SCOPE

1.1 This specification establishes the preliminary performance requirements for the Apollo G & N stabilization loops.

2. APPLICABLE DOCUMENTS

2.1 Unless otherwise indicated, the following documents shall form a part of this specification to the extent specified herein.

NASA Procurement Specifications
PS-1000075 (Torque Motor)
PS-1000097 (Angular Differentiating Accelerometer)

3. REQUIREMENTS

3.1 GENERAL - The purpose of the three stabilization loops is to maintain the orientation of the three PIP accelerometers fixed with respect to inertial space within specified limits under all specified external disturbances. The system block diagram is shown in Figure 1.

3.2 COMPONENTS. - The components which make up the three stabilization loops are identical with two exceptions. (1) The resistor connections used in the torque motor to provide current feedback to the stabilization amplifier differs in order to account for the difference in the load inertia of the loops. (2) The gyro output signals in the X and Z loops are resolved through the inner gimbal angle in order to maintain the gain of these two loops independent of the orientation of the inner gimbal. A description of the major components of the stabilization loop follows.

3.2.1 GYRO - The 25 IRIG senses angular displacements of the gimbal with respect to inertial space.

- a. GAIN (H/C) - 0.942
- b. TIME CONSTANT (I/C) - 0.75 msec.
- c. SIGNAL GENERATOR SENSITIVITY - 12.5 mv(rms)/mrad

3.2.2 GYRO PREAMPLIFIER. - The gyro preamplifier is an AC amplifier with transformer-coupled input and output.

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REV.

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Approved: *Bernard F. Brandt*

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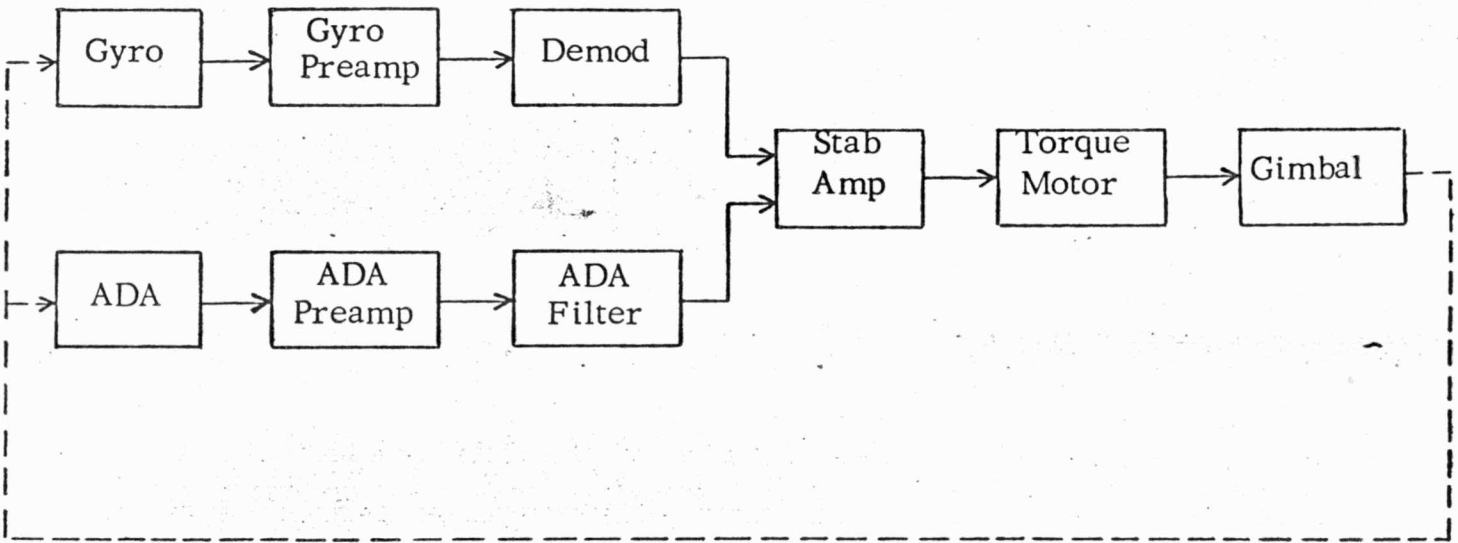
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System Block Diagram

Figure 1

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<p>a. <u>GAIN.</u> - 127 v/v (nom.) The gain shall be adjusted to indicate gimbal angles with a sensitivity of 1.5 volts (rms)/mrad \pm 1%.</p> <p>b. <u>OUTPUT SATURATION LEVEL.</u> - 14 v.</p>		
<p>NOTE: The gyro outputs are termed gyro error signals. The gyro error signals in the X and Z loops are resolved about the inner gimbal angle. The outputs of the resolver are then termed gimbal error signals.</p>		
<p>3.2.3 <u>DEMODULATOR.</u> - A D-C gimbal error signal is provided to the stabilization amplifier by means of the demodulator.</p> <p>a. TYPE. - Full wave, diode bridge</p> <p>b. FREQUENCY. - 3200 cps</p> <p>c. OUTPUT SATURATION LEVEL. - 6 v.</p> <p>d. GAIN. - 1 v.dc/v. (rms)</p>		
<p>3.2.4 <u>ANGULAR DIFFERENTIATING ACCELEROMETER.</u> - The ADA senses the angular rate of the gimbal with respect to inertial space.</p> <p>a. NATURAL FREQUENCY. - 6 ± 2 rad/sec.</p> <p>b. DAMPING FACTOR. - $0.65 \pm .15$ at 110 deg. F.</p> <p>c. OUTPUT SENSITIVITY. - 0.03 vdc/rad/sec.</p>		
<p>3.2.5 <u>ADA PREAMPLIFIER</u> GAIN. - 68 vdc/vdc at 0 cps, 1200 v/v above 0.2 cps</p>		
<p>3.2.6 <u>ADA FILTER.</u> - This low pass filter is a fourth order Butterworth filter.</p> <p>CUTOFF FREQUENCY - 4000 rad/sec.</p>		
<p>3.2.7 <u>STABILIZATION AMPLIFIER.</u> - This amplifier sums the signals from the gyro, the ADA and the current sampling resistor. The output stage acts as a constant current source to the torque motors.</p> <p>a. GAIN. - Inner Gimbal Loop: 2.83 amps/volt Middle Gimbal Loop: 14.2 amps/volt Outer Gimbal Loop: 28.3 amps/volt</p> <p>b. DEADZONE. - 0.1mv at the input at DC</p> <p>c. OUTPUT SATURATION LEVEL. - \pm 28 v.</p>		
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3.2.8 TORQUE MOTOR. - There are two torque motors mounted on opposite ends of each gimbal and they are operated in parallel. The only effects of having two motors are (1) the effective armature resistance is halved and (2) the maximum torque is doubled. All the other parameters of the parallel combination remain the same as for a single unit. The characteristics of a single torque motor are as follows:

- a. TORQUE CONSTANT. - 1.07 ft. lbs. /amp.
- b. VOLTAGE CONSTANT. - 1.45 v/rad/sec.
- c. ARMATURE RESISTANCE. - 82 ohms
- d. ARMATURE INDUCTANCE. - 0.05 henrys

3.2.9 GIMBAL. - The orientation of the three gimbals and the inertial sensors is shown in Figure 2.

MOMENT OF INERTIA.

Inner Axis: 0.317 lb (mass) ft²
 Middle Axis: 1.47 lb (mass) ft²
 Outer Axis: 2.95 lb (mass) ft²

3.3 PERFORMANCE. - The dynamics and static performance characteristics of the stabilization loops shall meet the following specifications.

3.3.1 FREQUENCY RESPONSE - The frequency response of the gyro, ADA and stabilization amplifier to a test input is developed analytically in section 6. The system shall be tested to indicate agreement with these curves to within tolerances yet to be determined.

3.3.2 GYRO NULL. - The gyro steady-state null, as measured at the gyro preamplifier output shall not exceed millivolts.

3.3.3 LOOP DEADZONE (DUE TO STATIC FRICTION). - With the stabilization amplifier output to the torque motor removed, apply increasing values of positive and negative voltages to the torque motor until the gyro preamplifier output changes from its null value. This indication of gimbal motion should require a voltage which is equivalent to less than ft. lbs. of static friction torque.

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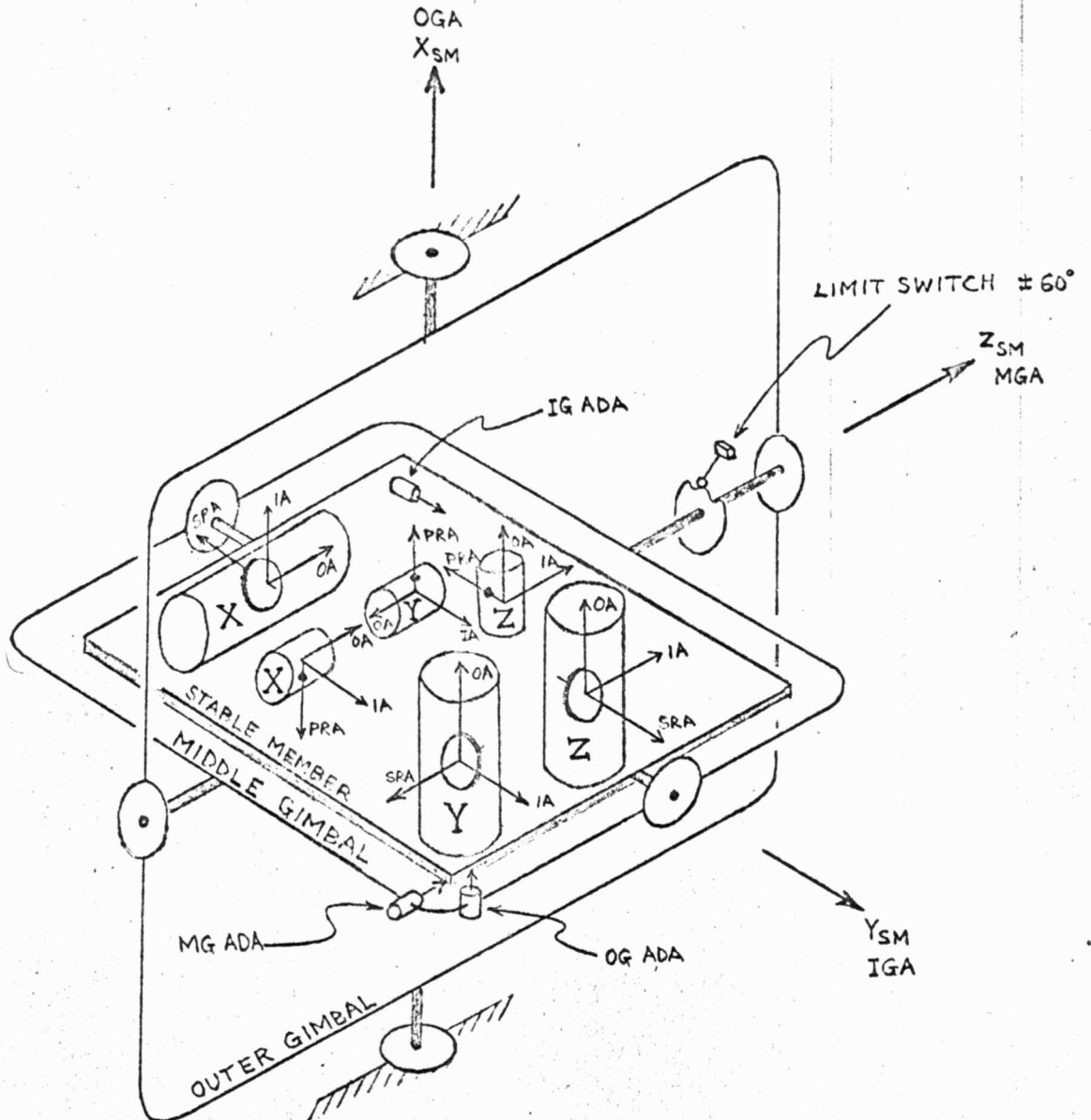


Figure 2

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4. QUALITY ASSURANCE PROVISIONS

Quality assurance shall conform to requirements specified at a later date.

5. PREPARATION FOR DELIVERY

Not applicable.

6. NOTES

6.1 INTRODUCTION TO ANALYSIS. - It is required that the stable member maintain a reference coordinate system in order for the three mutually perpendicular PIPA's to properly measure the components of vehicular linear acceleration with respect to inertial space. This "stabilization" of the stable member must be achieved in spite of interfering torques and motions of the navigation base on which the inertial measurement unit is mounted. The stable member is located within a gimbal system which provides the three degrees of rotational freedom so that the servo system can control the stable member independent of external disturbances. The gyros and angular differentiating accelerometers are the angle sensors which provide the error signals to the servo system.

The transfer functions of the loop components will be determined so that the complete loop can be described analytically. Various analytic techniques will be employed to provide an indication of the loop stability and to predict the static and dynamic performance characteristics of the loop. The practical considerations which must be made in the physical realization of the stabilization loop will be discussed. Finally, the loop test procedure will be presented.

6.2 LOOP COMPONENT TRANSFER FUNCTIONS. - The three stabilization loops have identical components with two exceptions. (1) The connection on the current sampling resistor which is in series with the torque motor winding differs between the three loops in order to have the same open loop gain in spite of the different gimbal inertias. (2) The gyro output signals in the X and Z loops are resolved through the inner gimbal angle in order to maintain the gain of these two loops independent of the inner gimbal orientation.

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- 6.2.1 GYRO. - The performance equation of the gyro is
- $$\left(\frac{I}{C}S+1\right)A_g = \frac{H}{SC}W_{IA} + \frac{1}{SC}M_{cmd} - \frac{H}{SC}A_g W_{SRA} + \frac{1}{SC}(U)M_g - \frac{I}{C}W_{OA} \quad (1)$$
- where I = effective output axis moment of inertia
 c = damping constant about the output axis
 H = angular momentum
 W_{IA} = angular rate about the input axis
 W_{SRA} = Angular rate about the spin reference axis
 W_{OA} = Angular rate about the output axis
 M_{cmd} = command torque about the output axis
 $(U)M_g$ = uncertainty torque about the output axis
 S = Laplace operator
 A_g = gyro output angle

The last three terms in the right member of eq (1) are all undesirable inputs to the gyro. The cross-coupling of the spin reference axis component of angular velocity is controlled primarily by keeping the gyro output angle very small. The uncertainty torque is kept within tolerable limits by proper design and production techniques. The reaction torque due to angular acceleration of the gyro about the output axis will be shown in section 6.4.1 to have a negligible effect on the stabilization loop.

With no command torque being applied to the gyro, the transfer function of the gyro can be expressed as

$$\frac{e_o}{\theta_{IA}} = \frac{\frac{H}{C}S_{SG}}{(\tau S + 1)} \quad (2)$$

where $S_{SG} = \frac{e_o}{\theta_{OA}} = 12.5 \text{ mv. (rms)/mrad.}$

$$\frac{H}{C} = .942$$

$$\tau = \frac{I}{C} = .75 \times 10^{-3} \text{ sec.}$$

Therefore,

$$\frac{e_o}{\theta_{IA}} = \frac{11.8}{\frac{S}{1333} + 1} \text{ v./rad.} \quad (3)$$

6.2.2 GYRO PREAMPLIFIER. - The gyro preamplifier is an A-C amplifier with transformer-coupled input and output which conditions the gyro output signal prior to transmission from the stable member to the PSA electronics.

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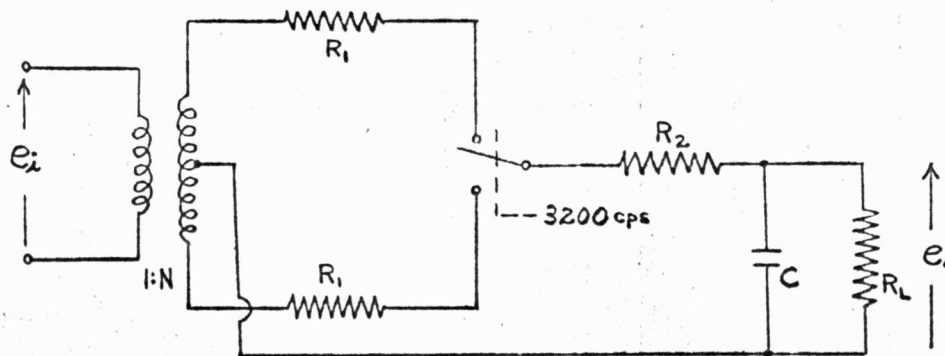
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The transfer function of the preamplifier is a pure gain over the frequency band of interest.

$$\frac{e_o}{e_i} = 127 \text{ v./v.} \quad (4)$$

6.2.3 DEMODULATOR . - The 3200 cps full wave demodulator is of the diode bridge type followed by a first order filter.



DEMODULATOR
Figure 3

The transfer function is

$$\frac{e_o}{e_i} = \frac{\frac{R_L}{R_1 + R_2 + R_L} KN}{\frac{(R_1 + R_2)R_L C s}{R_1 + R_2 + R_L} + 1} \quad (5)$$

where K relates the average value of a full wave rectified signal and the rms value of the input sinusoid.

Since $R_1 = 5K$ (10K in parallel with 10K)

$$R_2 = 4.7K$$

$$R_L = 100K$$

$$C = .1 \text{ uf.}$$

$$K = \frac{2\sqrt{2}}{\pi} = .9$$

$$N = 1.2 \text{ (turns ratio)}$$

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the transfer function becomes

$$\frac{e_o}{e_i} = \frac{1}{\frac{s}{1130} + 1} \quad v./v. (rms) \quad (6)$$

6.2.4 ANGULAR DIFFERENTIATING ACCELEROMETER. - The ADA is a mass-damper-spring system which senses relative motion of its case about its sensitive axis. For oscillatory angular inputs above the natural frequency of the instrument, the voltage output is proportional to the angular velocity of the input. The ADA provides a method of stabilizing the loop and extending the bandwidth which does not present the severe noise and stability problems encountered when passive circuit equalizers (lead-lag networks) are used.

The ADA is basically a fluid damped, torsional pendulum. The pendulum consists of a rotor which generates a voltage as a result of its relative motion in a permanent magnetic field fixed to the case. The rate of change of angular momentum is equal to the summation of torques about the sensitive axis.

$$\begin{aligned} Js^2\theta_R &= \sum \text{torques} \\ &= -K(\theta_R - \theta_C) - Bs(\theta_R - \theta_C) \end{aligned} \quad (7)$$

where J = moment of inertia
B = damping constant
K = spring constant
 θ_R = rotor angle
 θ_C = case angle

$$\begin{aligned} \theta_o &= \text{output angle} = \theta_C - \theta_R \\ \text{Therefore, } Js^2\theta_C &= (Js^2 + Bs + K)\theta_o \end{aligned} \quad (8)$$

Since the output voltage is proportional to the rate of change of the output angle ($K_V = \frac{e_o}{s\theta_o} = .03 \text{ v/rad/sec}$), the transfer function can be obtained from eq. (8).

$$\begin{aligned} \frac{e_o}{\theta_C} &= \frac{\frac{J}{K} K_V s^3}{\frac{J}{K} s^2 + \frac{B}{K} s + 1} \\ &= \frac{\frac{K_V}{\omega_n^2} s^3}{\left(\frac{s}{\omega_n}\right)^2 + 2(\zeta) \frac{s}{\omega_n} + 1} \end{aligned}$$

where $\omega_n = 6 \text{ rad/sec}$
 $\zeta = .65$

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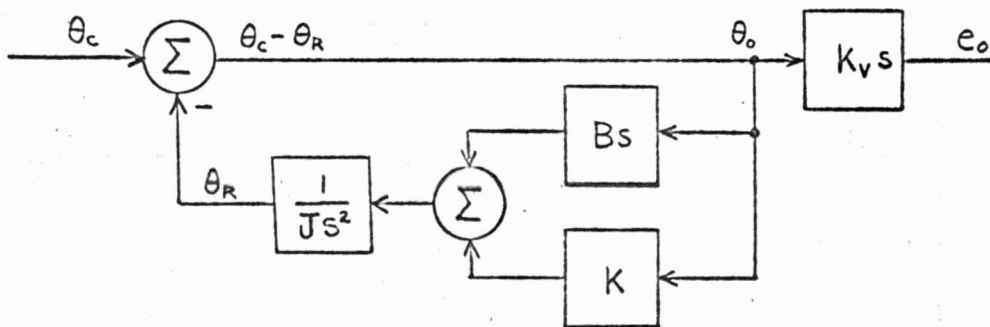
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Therefore,

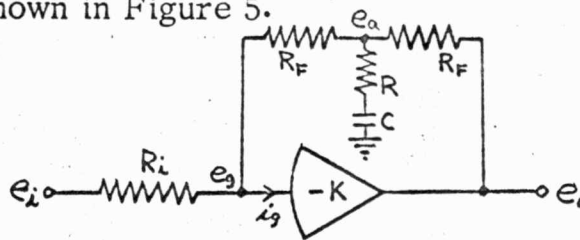
$$\frac{e_o}{\theta_c} = \frac{8.33 \times 10^{-4} s^3}{\left(\frac{s}{6}\right)^2 + 2(.65)\frac{s}{6} + 1} \text{ rad./v.} \quad (9)$$

A block diagram of the ADA can be constructed as follows:



ADA BLOCK DIAGRAM
Figure 4

6.2.5 ADA PREAMPLIFIER. - A simplified circuit diagram of this D-C amplifier is shown in Figure 5.



ADA PREAMPLIFIER
Figure 5

Solving for the current at the e_g and e_a nodes

$$\frac{e_a - e_g}{R_F} + \frac{e_i - e_g}{R_i} = i_g, \quad \frac{e_g - e_a}{R_F} + \frac{e_o - e_a}{R_F} = \frac{e_a}{R + \frac{1}{sC}}$$

Since $e_g = i_g = 0$, the above equations can be written as

$$e_a = -\frac{R_F}{R_i} e_i, \quad e_o = R_F \left(\frac{1}{R + \frac{1}{sC}} + \frac{2}{R_F} \right) e_a$$

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Solving simultaneously for

$$\frac{e_o}{e_i} = \frac{-2R_F}{R_i} \left[\frac{(R + \frac{R_F}{2})sC + 1}{sRC + 1} \right]$$

Since $R_i = R = 20K$, $R_F = 680K$ and $C = 40$ uf,

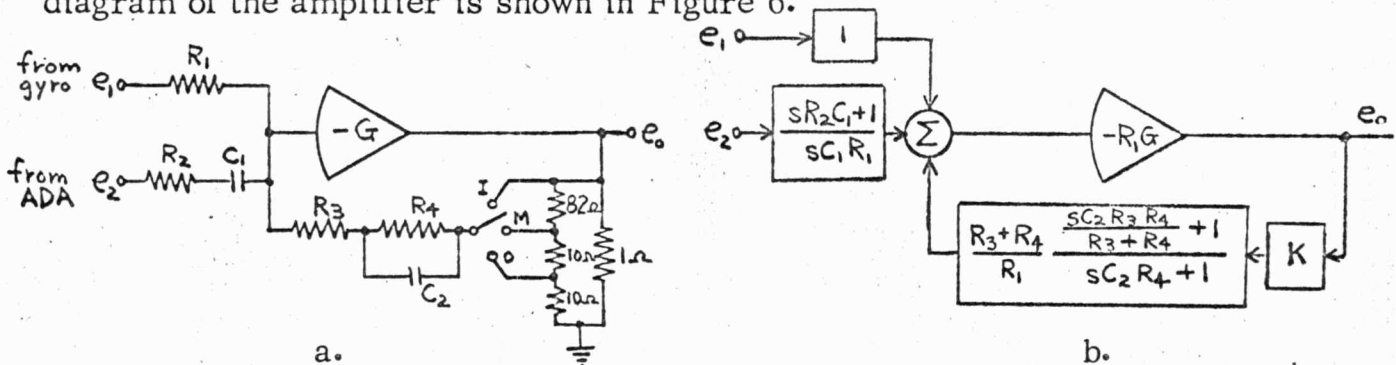
$$\frac{e_o}{e_i} = \frac{68(\frac{s}{.07} + 1)}{(\frac{s}{1.25} + 1)} \text{ v./v.} \quad (10)$$

The feedback network reduces the gain at low frequencies to provide for the D-C stability of the amplifier.

6.2.6 ADA FILTER. - Since mechanical resonances of the gimbal can exist within the bandwidth of the ADA, the purpose of the ADA filter is to provide high frequency attenuation without seriously affecting loop stability by reducing the phase margin at the open loop cross-over frequency. In order to fulfill these requirements, a fourth order Butterworth filter is used. The filter can be represented by the following transfer function.

$$\frac{e_o}{e_i} = \frac{1}{\left[\left(\frac{s}{4000} \right)^2 + 2(.383) \frac{s}{4000} + 1 \right] \left[\left(\frac{s}{4000} \right)^2 + 2(.924) \frac{s}{4000} + 1 \right]} \text{ v./v.} \quad (11)$$

6.2.7 STABILIZATION AMPLIFIER. - This amplifier sums the signals from the gyro and the ADA. The output section of the amplifier acts as a constant current source to drive the torque motors since the torquing current is sampled and fed back to the input of the amplifier through a network. A simplified diagram of the amplifier is shown in Figure 6.



Stabilization Amplifier

Figure 6

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$$\begin{aligned} R_1 &= 100K \\ R_2 &= 102K \text{ (2 ea. 51K resistors in series)} \\ R_3 &= 13K \\ R_4 &= 270K \\ C_1 &= 40 \text{ uf} \\ C_2 &= .5 \text{ uf} \end{aligned}$$

STABILIZATION AMPLIFIER

Figure 6

Since e_i is across a 1 ohm resistor connected to ground, $i_o = e_o$.
Furthermore, since G is very large, the transfer functions are simply the ratios of the feedback impedance to the input impedances, or

$$\frac{i_o}{e_i} = \frac{2.83 \left(\frac{s}{160} + 1 \right)}{K \left(\frac{s}{7.4} + 1 \right)} \quad (12)$$

$$\frac{i_o}{e_2} = \frac{511.3 \left(\frac{s}{160} + 1 \right)}{K \left(\frac{s}{.25} + 1 \right) \left(\frac{s}{7.4} + 1 \right)} \quad (13)$$

where $K = 1$ for inner gimbal loop
 $= .2$ for middle gimbal loop
 $= .1$ for outer gimbal loop

Internal feedback provides an additional lag (at $G(j\omega)H(j\omega) = 1$), for stability purposes, beyond the frequency band of interest. However it does affect the phase margin slightly.

6.2.8 TORQUE MOTOR. - The two torque motors are driven in parallel by the stabilization amplifier. The constant current source makes the motor time constant negligibly small resulting in the transfer function of the torque motor being

$$\frac{T}{i} = K_T = 1.07 \frac{\text{ft. lb. (force)}}{\text{amp.}} \quad (14)$$

The back emf can be considered separately as a disturbance input proportional to the angular rate of the gimbal with respect to the navigation base.

6.2.9 GIMBAL - The moment of inertia of the gimbal is 2.95 K lb. (mass) ft², where $K = 1, .2, .1$ for the inner, middle, outer gimbal respectively. Since 1 lb (force) = 32.2 ft/sec², the transfer function for the gimbal is

$$\frac{\theta}{T} = \frac{95K}{s^2} \frac{\text{rad.}}{\text{ft. lb. (force)}} \quad (15)$$

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6.3 STABILIZATION LOOP ANALYSIS. - Using the transfer functions developed in section 6.2, the block diagram of the loop is shown in Figure 7. The open loop transfer functions for the gyro and ADA outputs as a function of an input to the stabilization amplifier is shown in Figure 8. The curves show that the gyro loop has control up to 43 rad/sec where the ADA loop assumes control. The gyro loop by itself would be unstable because it crosses 0 db at 140 rad/sec. with a slope of -60 db/decade. However, the ADA loop has control at these higher frequencies, extending the bandwidth to 500 rad/sec. The -20 db/decade slope at the cross-over frequency provides for sufficient loop stability.

6.3.1 SIMPLIFIED LOOP BLOCK DIAGRAM. - Since the frequency response of the complete stabilization loop follows the higher of the gyro and the ADA curves, it is evident from Figure 8 that the dominant frequency break points lie between 7 and 1,000 rad/sec. A simplified block diagram can be constructed if the other break points in the loop are neglected. Approximate closed-loop frequency and transient responses can then be readily obtained. The simplified block diagram is shown in Figure 9.

Two of the three significant break points ($\omega=7.4, \omega=160$) are contributed by the stabilization amplifier. The other major breakpoint ($\omega=43$) which occurs at the frequency where the gyro and the ADA interchange control of the stabilization loop depends on the relative gains of the gyro and ADA loops.

6.3.2 FREQUENCY AND TRANSIENT RESPONSES. - The various responses provide a means of predicting, in general, the dynamic performance of the loop as a function of disturbance and test inputs.

The open loop transfer function shown in Figure 9 can be expressed as

$$GH = \frac{\frac{K}{T}(Ts+1)\left(\frac{B}{K}s+1\right)}{s^2(\alpha Ts+1)}$$

Therefore,

$$1+GH = \frac{\frac{J}{K}s^2(\alpha Ts+1)}{\frac{J}{K}\alpha Ts^3 + \left(\frac{J}{K} + \frac{B}{KT}\right)s^2 + \left(T + \frac{B}{K}\right)s + 1} \quad (16)$$

6.3.2.1 GIMBAL ANGLE/TORQUE INPUT. - The main purpose of the platform servo is to maintain the stable member independent of external disturbances. The measure of this ability can be stated as the ratio of the magnitude of

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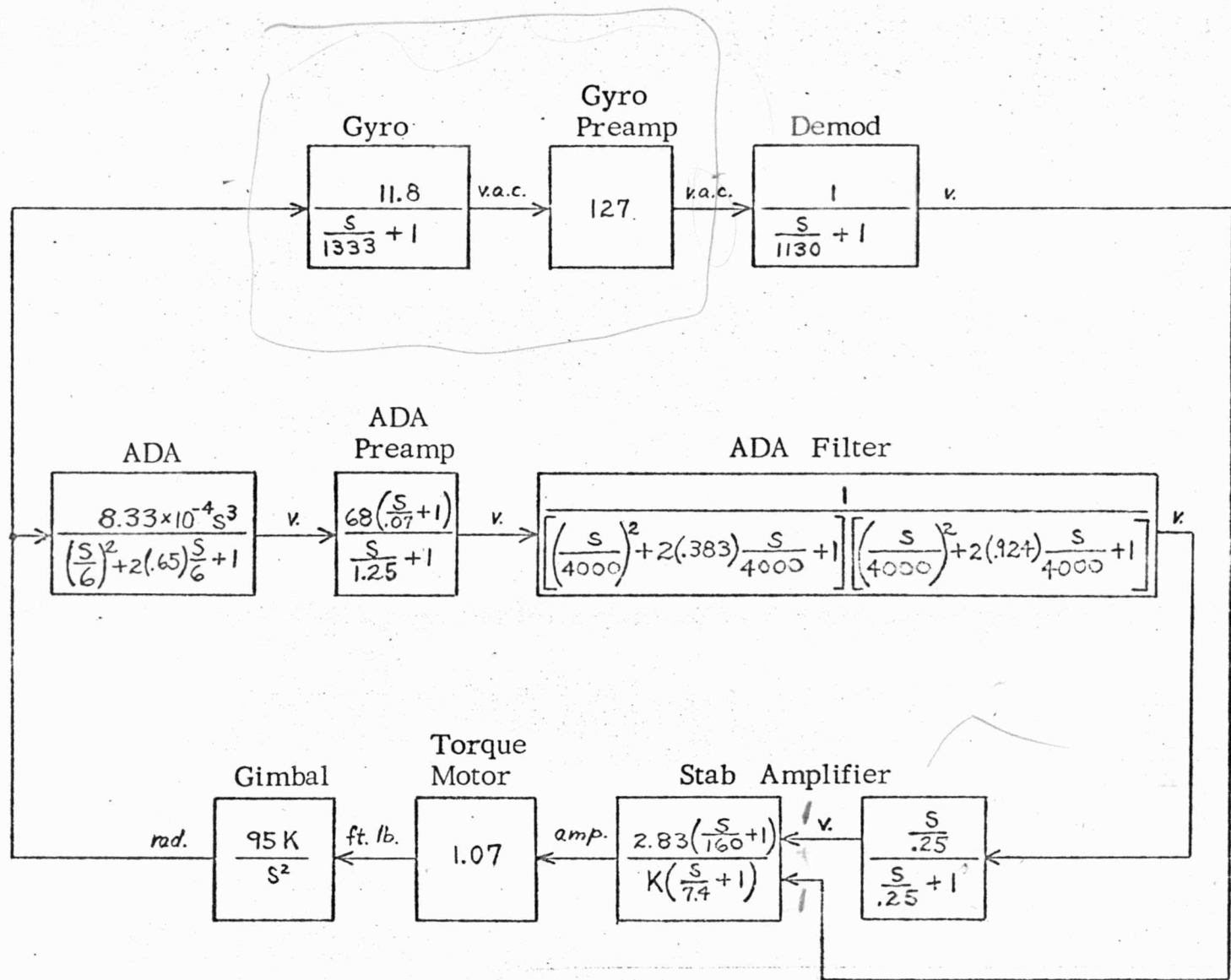
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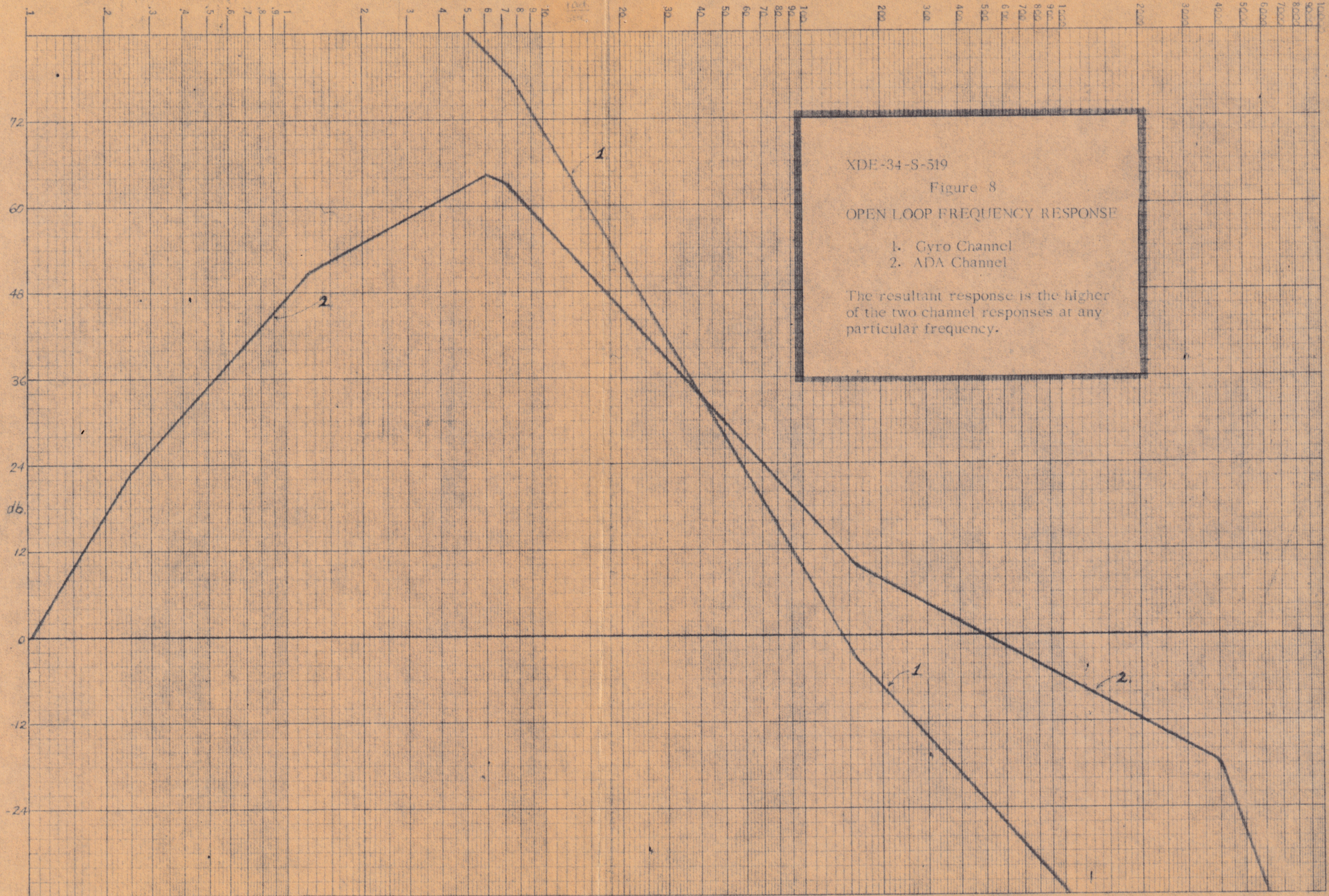
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Note:
 $K = \begin{cases} 1 & \text{(inner gimbal loop)} \\ .2 & \text{(middle gimbal loop)} \\ .1 & \text{(outer gimbal loop)} \end{cases}$

Stabilization Loop
Figure 7

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 Figure 8
 OPEN LOOP FREQUENCY RESPONSE
 1. Gyro Channel
 2. ADA Channel
 The resultant response is the higher of the two channel responses at any particular frequency.

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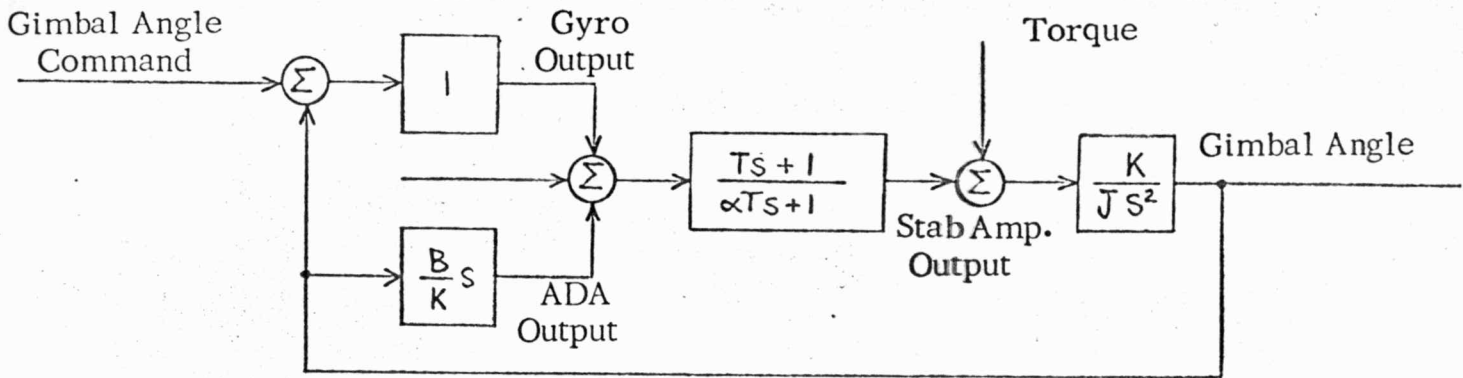
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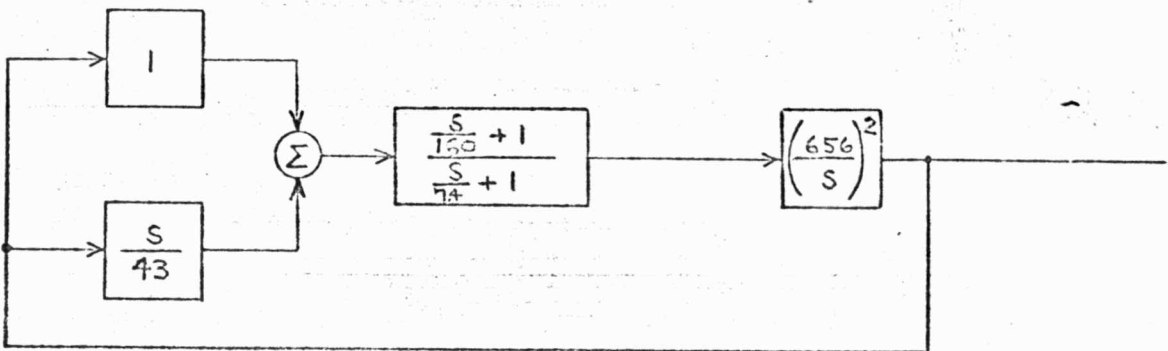
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a.



$$\frac{1}{1+GH} = \frac{\frac{J}{K} s^2 (\alpha T s + 1)}{\frac{J}{K} \alpha T s^3 + \left(\frac{J}{K} + \frac{B}{K} T\right) s^2 + \left(T + \frac{B}{K}\right) s + 1} = \frac{\left(\frac{s}{656}\right)^2 \left(\frac{s}{74} + 1\right)}{\left(\frac{s}{42} + 1\right) \left[\left(\frac{s}{275}\right)^2 + 2(.73) \frac{s}{275} + 1\right]}$$

Simplified Block Diagram

Figure 9

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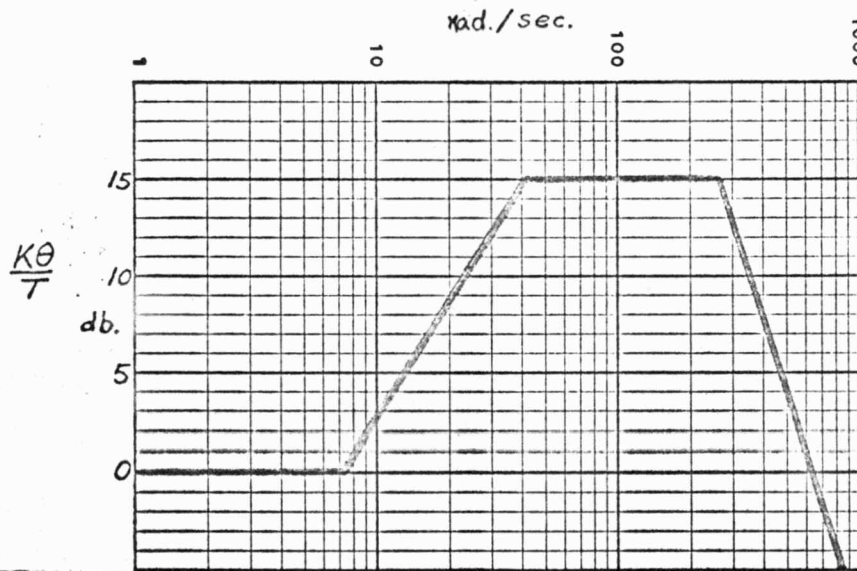
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$$\frac{G}{1+GH} = \frac{\frac{1}{K}(\alpha Ts + 1)}{\frac{J}{K}\alpha Ts^3 + \left(\frac{I}{K} + \frac{B}{KT}\right)s^2 + \left(T + \frac{B}{K}\right)s + 1}$$

$$= \frac{\frac{1}{K}\left(\frac{s}{7.4} + 1\right)}{\left(\frac{s}{42} + 1\right)\left[\left(\frac{s}{275}\right)^2 + 2(.78)\frac{s}{275} + 1\right]}$$

$\frac{1}{K}$ is the D. C. gain from torque input to gimbal angle.

Figure 10
 Frequency Response
 Gimbal Angle/Torque Input

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the gimbale angle developed for a given input of torque - i. e., compliance (reciprocal of stiffness) of the stabilization loop.

Although the three stabilization loops have the same open loop transfer function, this particular closed loop transfer function differs for the three loops because of the different gimbale moments of inertia. The forward transfer function between torque input and gimbale angle is

$$G = \frac{1}{Js^2}$$

$$\text{since } \frac{1}{1+GH} = \frac{\frac{J}{K}s^2(\alpha Ts+1)}{\frac{J}{K}\alpha Ts^3 + \left(\frac{J}{K} + \frac{B}{K}T\right)s^2 + \left(T + \frac{B}{K}\right)s + 1}$$

the closed loop transfer function is

$$\frac{G}{1+GH} = \frac{\frac{1}{K}(\alpha Ts+1)}{\frac{J}{K}\alpha Ts^3 + \left(\frac{J}{K} + \frac{B}{K}T\right)s^2 + \left(T + \frac{B}{K}\right)s + 1}$$

or

$$\frac{G}{1+GH} = \frac{\frac{1}{K}\left(\frac{s}{7.4} + 1\right)}{\left(\frac{s}{42} + 1\right)\left[\left(\frac{s}{275}\right)^2 + 2(.78)\frac{s}{275} + 1\right]}$$

where K is the D-C gain from gimbale angle to torque input

The frequency response is shown in Figure 10 and the bandwidth is 630 rad/sec. The response of the gimbale to a step input of torque is shown in Figure 11.

6.3.2.2 GIMBANG ANGLE/GIMBANG ANGLE COMMAND. - In addition to keeping the stable member insensitive to torque disturbances, the system must also respond properly to commanded angular inputs. Repositioning of the stable member (i. e., the gimbals) is accomplished by applying command inputs to the gyro torquers. The forward transfer function between angular command and gimbale angle is

$$G = \frac{\frac{K}{J}(Ts+1)}{s^2(\alpha Ts+1)}$$

$$\text{Therefore, } \frac{G}{1+GH} = \frac{(Ts+1)}{\frac{J}{K}\alpha Ts^3 + \left(\frac{J}{K} + \frac{B}{K}T\right)s^2 + \left(T + \frac{B}{K}\right)s + 1}$$

$$\text{or } \frac{G}{1+GH} = \frac{\left(\frac{s}{105} + 1\right)}{\left(\frac{s}{42} + 1\right)\left[\left(\frac{s}{275}\right)^2 + 2(.78)\frac{s}{275} + 1\right]}$$

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This closed loop frequency response is shown in Figure 12. The dominant frequency breakpoint, which occurs at 43 rad/sec., is essentially the frequency (see Figure 8) at which the gyro and ADA exchange control of the stabilization loop.

The bandwidth for command inputs, 43 rad/sec., is about fifteen times smaller than that for disturbance inputs. This provides an adequate response to command inputs without passing high frequency noise between the gyro and stabilization amplifier. The transient response to a step input command is shown in Figure 13.

6.3.2.3 GYRO OUTPUT/STABILIZATION AMPLIFIER INPUT. - An input to the stabilization amplifier is provided for test purposes. The response of the gyro output will essentially be the same (with the exception of the D. C. gain between the amplifier input and gyro output) as the response determined in section 6.3.2.2 and shown in Figure 12 and Figure 13.

6.3.2.4 ADA OUTPUT/STABILIZATION AMPLIFIER INPUT. - The forward transfer function in this case is

$$G = \frac{B(Ts+1)}{s(\alpha Ts+1)}$$

This results in the following closed loop transfer function

$$\frac{G}{1+GH} = \frac{\frac{B}{K}s(Ts+1)}{\frac{J}{K}\alpha Ts^3 + \left(\frac{J}{K} + \frac{B}{K}T\right)s^2 + \left(T + \frac{B}{K}\right)s + 1}$$

or

$$\frac{G}{1+GH} = \frac{\frac{S}{43}\left(\frac{S}{160} + 1\right)}{\left(\frac{S}{42} + 1\right)\left[\left(\frac{S}{275}\right)^2 + 2(.78)\frac{S}{275} + 1\right]}$$

The frequency and step responses are shown in Figure 14 and Figure 15, respectively. Whereas the gyro output response falls off above 45 rad/sec., the ADA output responds between 44 and 480 rad/sec. The sum of the gyro and ADA responses is given by the following equation

$$\begin{aligned} \frac{G}{1+GH} &= \frac{\left(\frac{B}{K}s+1\right)(Ts+1)}{\frac{J}{K}\alpha Ts^3 + \left(\frac{J}{K} + \frac{B}{K}T\right)s^2 + \left(T + \frac{B}{K}\right)s + 1} \\ &= \frac{\left(\frac{S}{43} + 1\right)\left(\frac{S}{160} + 1\right)}{\left(\frac{S}{42} + 1\right)\left[\left(\frac{S}{275}\right)^2 + 2(.78)\frac{S}{275} + 1\right]} = \frac{\frac{S}{160} + 1}{\left(\frac{S}{275}\right)^2 + 2(.78)\frac{S}{275} + 1} \end{aligned}$$

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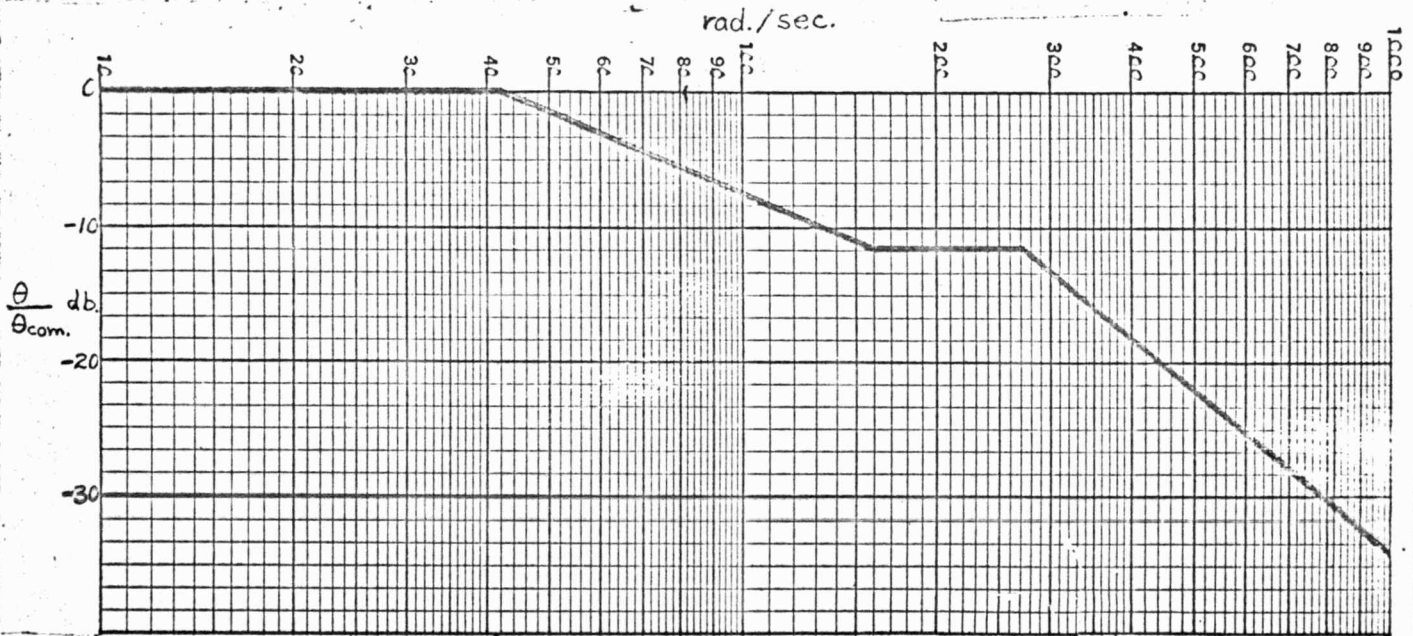
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$$\frac{G}{1+GH} = \frac{Ts+1}{\frac{J}{K} \alpha Ts^3 + \left(\frac{J}{K} + \frac{B}{KT}\right) s^2 + \left(T + \frac{B}{K}\right) s + 1}$$

$$= \frac{\frac{s}{160} + 1}{\left(\frac{s}{43} + 1\right) \left[\left(\frac{s}{275}\right)^2 + 2(.78) \frac{s}{275} + 1\right]}$$

Figure 12

Frequency Response
Gimbal Angle/Gimbal Angle Command
Gyro Output/Test Input

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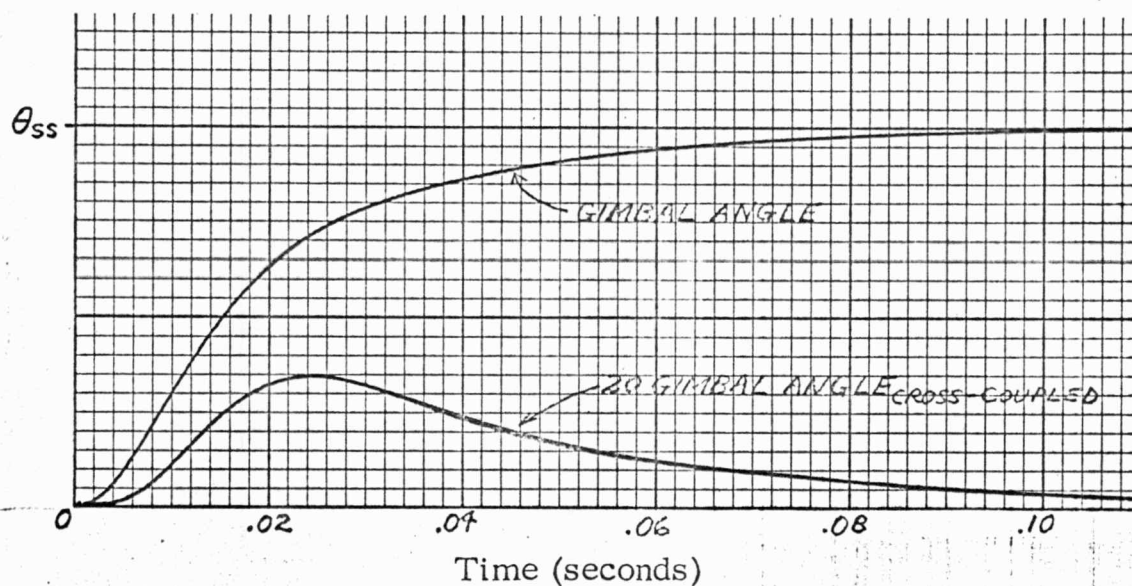


Figure 13

Response of gimbal angle to a step input command at the gyro. Same as response of gyro output to a test step input at the stabilization amplifier. (Response of other loop through output axis coupling is also shown.)

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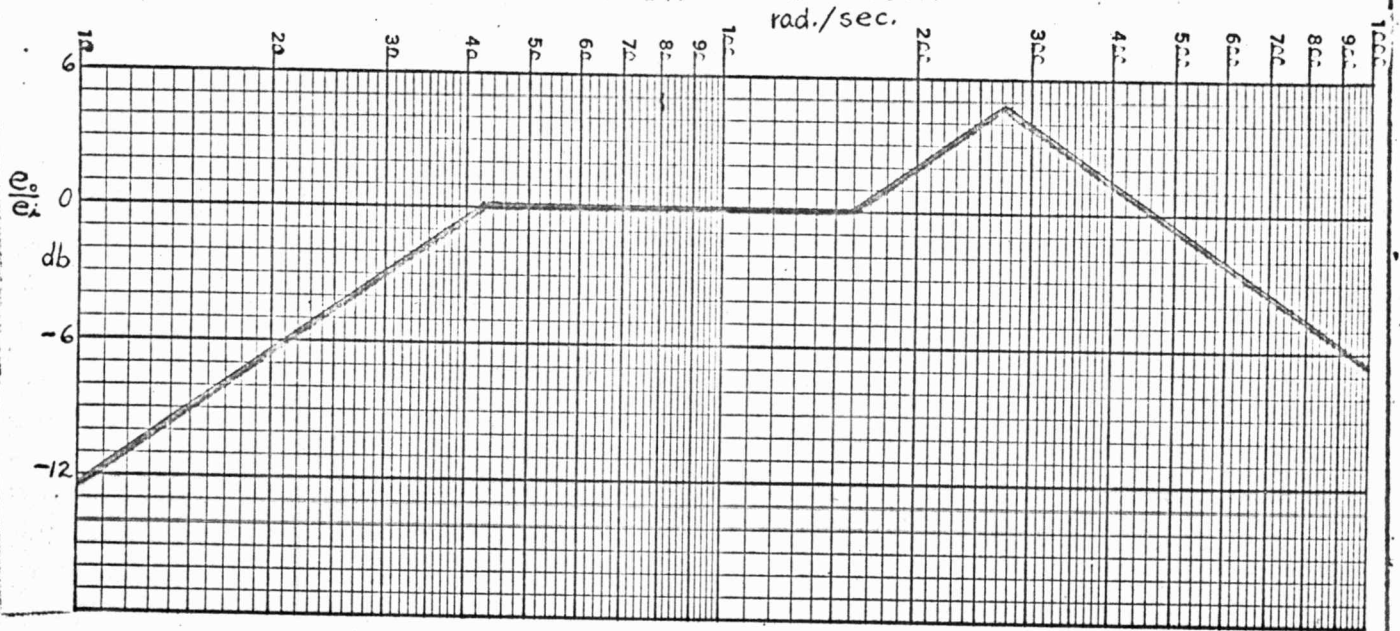
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$$\frac{G}{1+GH} = \frac{\frac{B}{K}s(Ts+1)}{\frac{J}{K}\alpha Ts^3 + \left(\frac{J}{K} + \frac{B}{KT}\right)s^2 + \left(T + \frac{B}{K}\right)s + 1}$$

$$= \frac{\frac{s}{43} \left(\frac{s}{160} + 1\right)}{\left(\frac{s}{42} + 1\right) \left[\left(\frac{s}{275}\right)^2 + 2(.78)\frac{s}{275} + 1\right]}$$

Figure 14
 Frequency Response
 ADA Output/Test Input

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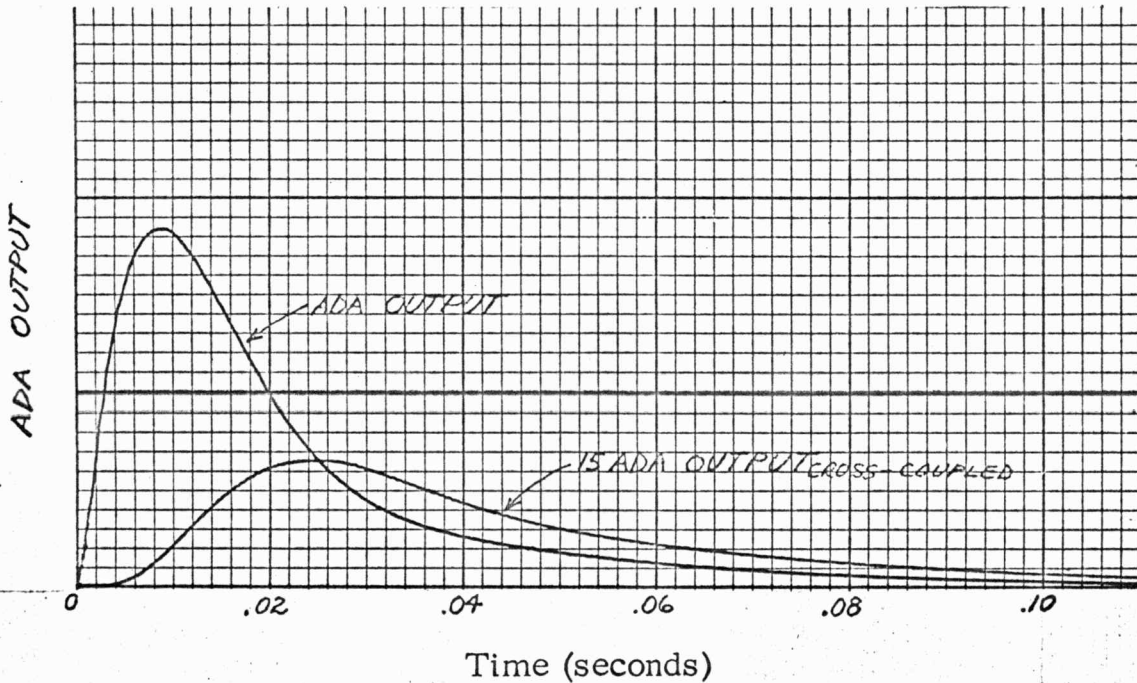


Figure 15

Response of ADA to a step input command at the gyro or test input at the stabilization amplifier.

(Response of other ADA through output axis coupling is also shown.)

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6.3.2.4 STABILIZATION AMPLIFIER; OUTPUT/INPUT. - The forward loop transfer function in this case is the closed loop transfer function of the stabilization amplifier, or

$$G = \frac{Ts+1}{\alpha Ts+1}$$

$$\text{Therefore, } \frac{G}{1+GH} = \frac{As^2(Ts+1)}{\frac{J}{K}\alpha Ts^3 + \left(\frac{J}{K} + \frac{B}{K}T\right)s^2 + \left(T + \frac{B}{K}\right)s + 1}$$

$$\frac{G}{1+GH} = \frac{As^2\left(\frac{s}{160} + 1\right)}{\left(\frac{s}{42} + 1\right)\left[\left(\frac{s}{275}\right)^2 + 2(.78)\frac{s}{275} + 1\right]}$$

Where A = DC gain of stabilization amplifier

This closed loop frequency response is shown in Figure 16. The high frequency breakpoints which had been neglected in this simplified block diagram would cause the response to fall off above 1,000 rad/sec.

6.3.2.5 SIMULATION OF SIMPLIFIED LOOP. - The simplified block diagram shown in Figure 9 was simulated on the analog computer in order to obtain the transient responses of the previous sections.

6.4 PRACTICAL CONSIDERATIONS. - In addition to meeting the requirements for compliance (reciprocal of stiffness) and obedience to command, several other areas must be examined. There is a limitation on how much torque can be developed in the stabilization loops to maintain the stable member fixed in inertial space. Isolation of the stable member from vehicular motion could be hampered if the loop must overcome too many other disturbances and interferences. There are also certain conditions which may affect the relative stability of the loop. In this section, these practical considerations will be described as they pertain to this particular system.

6.4.1 INTER-AXIS COUPLING. - The X and Z gyro signals are resolved about the inner gimbal angle; however, the X and Y gyro signals are not resolved about the middle gimbal angle because this particular angle will not become large during operation of the system. As the middle gimbal angle varies from its zero value, it can be seen from Figure 2 that there are several effects on the stabilization loop.

(The mathematical expressions for these effects are formally derived in XDE-34-A-507).

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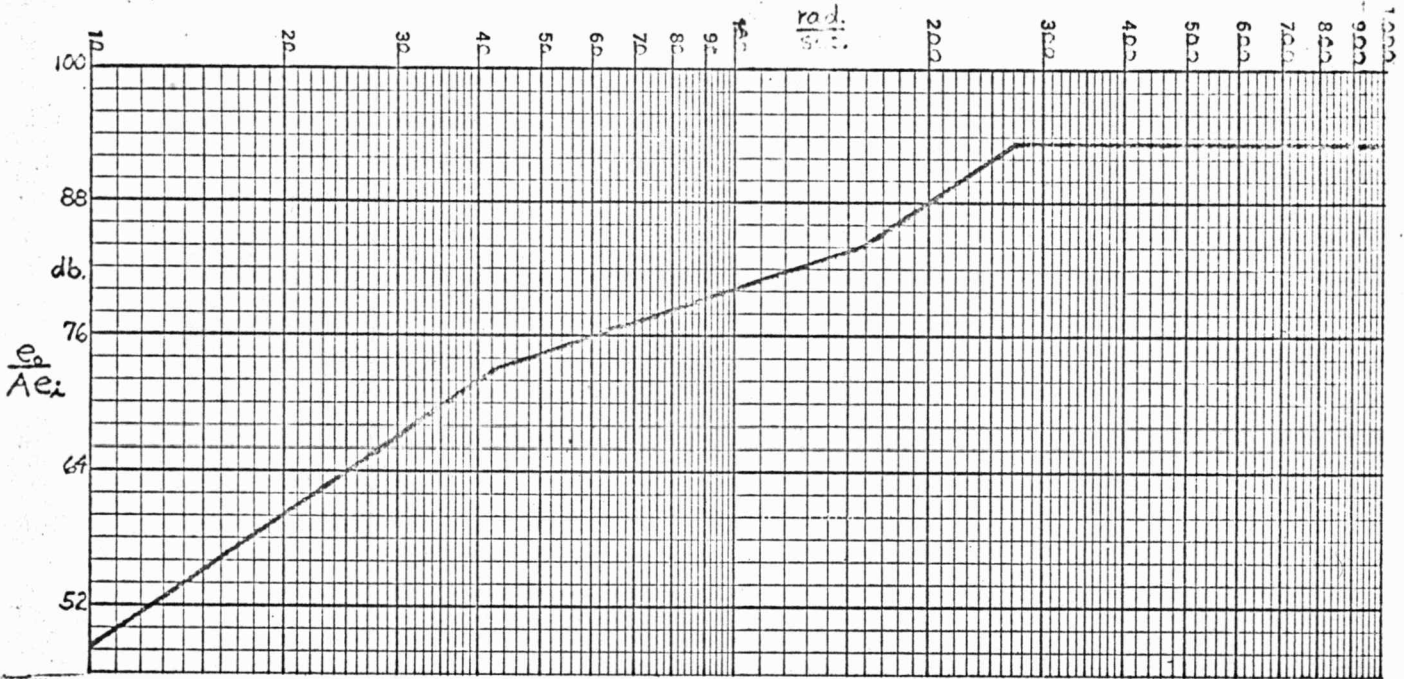
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$$\frac{G}{1+GH} = \frac{As^2(Ts+1)}{\frac{J}{K}Ts^3 + (\frac{J}{K} + \frac{B}{KT})s^2 + (T + \frac{B}{K})s + 1}$$

$$= \frac{As^2(\frac{s}{160} + 1)}{(\frac{s}{43} + 1)[(\frac{s}{275})^2 + 2(.78)\frac{s}{275} + 1]}$$

A is the DC gain between input and output of the Stabilization Amplifier

Figure 16

Frequency Response Stabilization Amplifier Output/Input

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(1) As the Y gyro senses an angular rate and commands a corrective torque for the stable member, the action-reaction effect on the gimbal structure tends to cause a rotation about the output axis. This leads to a coupling between the stable member torque and the outer gimbal proportional to the sine of the middle gimbal angle.

(2) As the middle gimbal angle increases, the motion about the X gyro input axis as a result of torque applied about the outer gimbal axis decreases a function of the cosine of the middle gimbal angle.

(3) The effective inertia load for the outer gimbal torque motor includes the inertia of the middle gimbal and the stable member about the outer gimbal axis. This effective inertia of the gimbal varies as a function of the middle gimbal angle. According to XDE-34-A-507,

$$I_{OG} = I_{OGX} + I_{MGX} + I_{SMX} - (I_{MGX} + I_{SMX} - I_{MGY} - I_{MGZ}) \sin^2 A_{MG}$$

(4) The gyro output signal is proportional to the angle between the output axis and the case. Motion of the case about the output axis, which is controlled by another stabilization loop, produces an undersirable gyro output. According to equation (1), this error is equivalent to an angular rate about the input axis given by

$$W_{IA} = \frac{I}{H} \dot{W}_{OA}$$

The gyro orientation shown in Figure 2 results in motion about the X gyro input axis coupling into the Y gyro through motion of its case about the output axis. The same motion about the X gyro input axis couples into the Z gyro and then back into the X gyro. Although the sense of this feedback is positive, there are no detrimental effects because of the short gyro time constant, high loop gains and frequency characteristics of the loops. The coupling between the three stabilization loops (due to the middle gimbal angle and angular rates about the gyro output axes) shown in Figure 17 was simulated on an analog computer. Although the coupling from one loop to another was discernable (see Figures 11, 13 and 15), the feedback coupling into the first loop produced no detrimental effects because of the short gyro time constant, high loop gains and frequency characteristics of the loops. The coupling back into the first loop was so slight that there was no noticeable difference between positive, negative and no feedback. The effective outer gimbal inertia $\left[\frac{\cos A_{MG}}{J(1 - 0.37 \sin^2 A_{MG})} \right]$ does not seriously affect the outer loop gain except in the immediate region of $A_{MG} = \pm 90$ deg.

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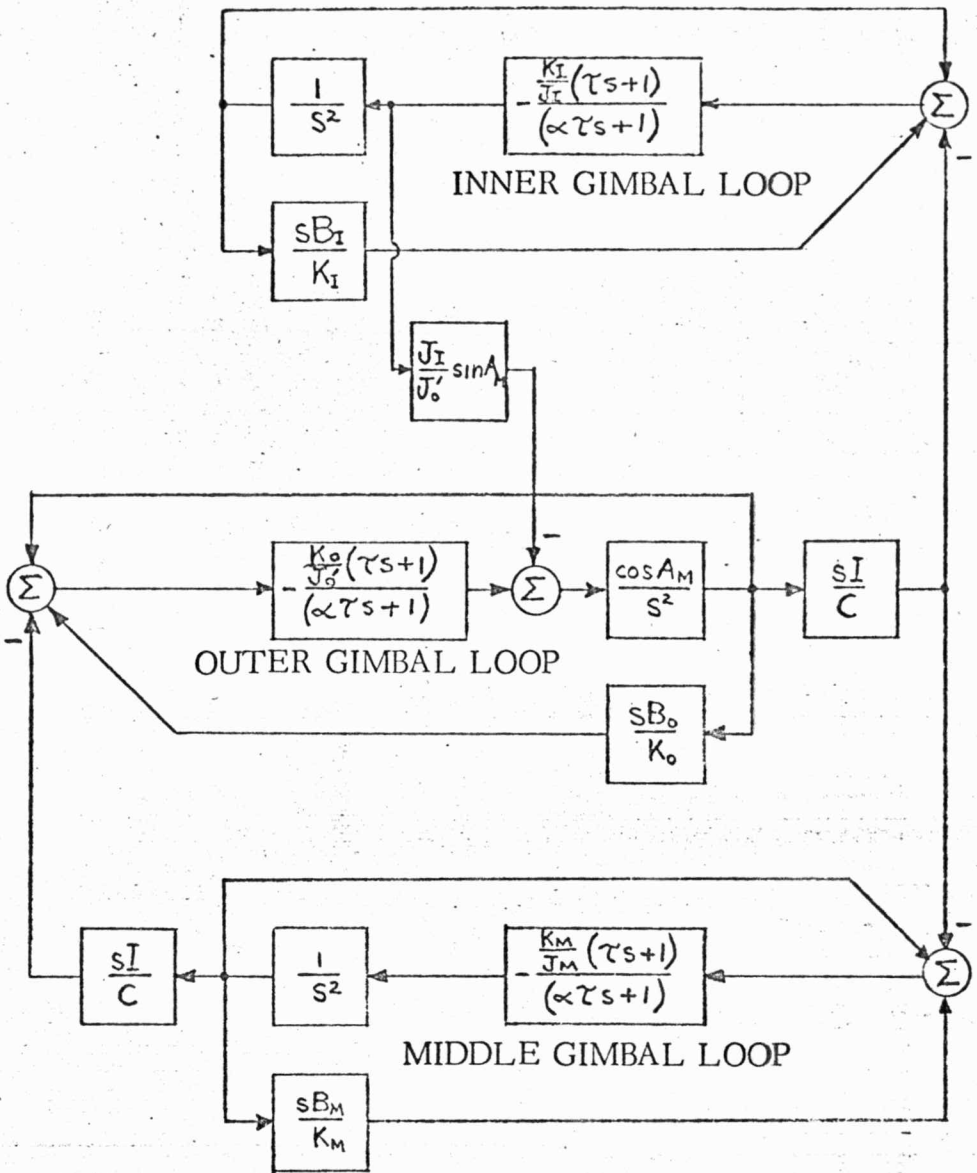
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$$\frac{K_I}{J_I} = \frac{K_0}{J_0} = \frac{K_M}{J_M} =$$

$$\frac{B_I}{K_I} = \frac{B_0}{K_0} = \frac{B_M}{K_M} =$$

$$J_0' = J_0 (1 - .37 \sin^2 A_M)$$

$$J_I = .2 J_M = .1 J_0$$

A_M = middle gimbal angle

$$\tau = \frac{1}{160}$$

$$\alpha = 21.6$$

Figure 17

Simplified block diagram of three-axis stabilization system.

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6.4.2 PLATFORM RESONANCES. - The gimbals may have mechanical resonant peaks occurring between the open-loop cross-over frequency of rad/sec and the region where the majority of the high frequency breaks occur. If these peaks are high enough to cause the open loop frequency response to rise above the 0 db line, high frequency oscillations will result. The ADA has a wide bandwidth and could sense these resonances. This necessitates the inclusion of the $\omega_c = 4000$ fourth order Butterworth filter following the ADA pre-amplifier. This low-pass filter provides a sharp cutoff without seriously affecting loop stability by reducing the phase margin at the open loop cross-over frequency.

6.4.3 TORQUE DISTURBANCES. - The dynamic performance of the torque-providing capacity of the stabilization loop. If some of the developed torque is used to neutralize disturbance torques, there is less torque available to provide the necessary dynamic performance in the presence of vehicular motion. Torque disturbances can be due to unbalance and anisoelasticity of the gimbals. Of course, the middle gimbal angle as discussed under inter-axis coupling in section 6.4.1 introduces a condition which reduces the torque capacity of one of the stabilization loops.

6.4.4 SATURATION. - The presence of saturation in the loop reduces the open loop gain and thereby increases compliance within the stabilization loop. Noise within the loop is kept to a minimum since it tends to saturate the servo system.

6.4.5 GYRO DRIFT. - The major error producing mechanism in the stabilization loop is gyro drift. This drift can be caused by random torques, bias torques, unbalance torques, and anisoelastic torques due to linear motion as well as the rectified effect experienced with vibrations.

6.5 PERFORMANCE TESTS AND TOLERANCES. - The dynamic performance of the stabilization loop can be determined from the frequency-dependent characteristics of the system. The gyro output (proportional to gimbal angle), ADA output (proportional to the angular rate of the gimbal), and the stabilization amplifier output (proportional to the angular acceleration of the gimbal) can be monitored with a test input being applied to the stabilization amplifier to provide sufficient information concerning the dynamic performance of the loop. The frequency response of the system to torque disturbances can be deducted from this information.

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A less conclusive, but expeditious, method of testing the system can involve the determination of the three major breakpoints. The stabilization amplifier could be tested as a sub-system to insure that it has the proper frequency response. When the complete loop is closed, the transient response of the gyro output to a test input to the stabilization amplifier would yield the other major breakpoint, since the time constant is approximately $\frac{1}{\omega}$ ($\omega=43$ rad/sec; the frequency at which the gyro and ADA interchange control of the loop.)

The static performance of the stabilization loop can be determined from the null characteristics of the gyro preamplifier output. Since the other two inputs to the stabilization amplifier are zero under static conditions, the gyro preamplifier output can be related to the gimbal angle. Static friction causes the stabilization loop to have a deadzone, which can be determined by applying increasing values of plus and minus voltages to the torque motor until the gyro preamplifier output indicates that the gimbal has moved.

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