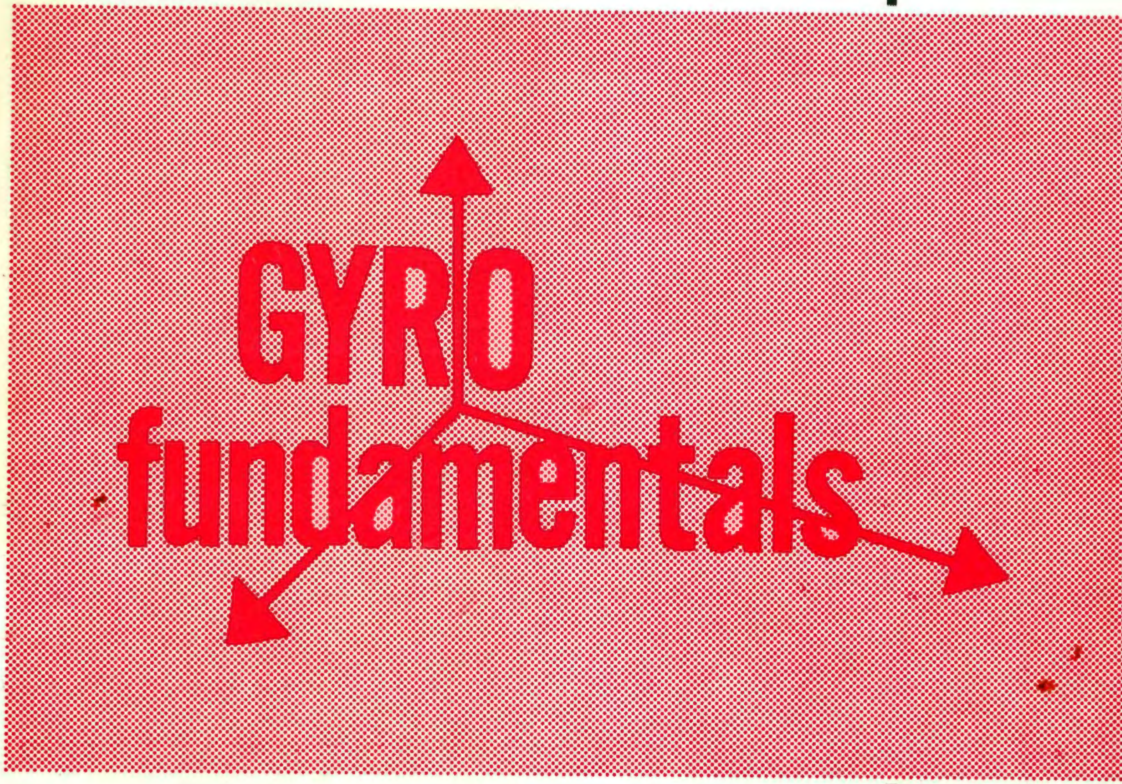


GYRO fundamentals

AC SPARK PLUG THE ELECTRONICS DIVISION OF GENERAL MOTORS CORPORATION

GYROSCOPE FUNDAMENTALS

by

Earl D. Taylor, Gyro Engineering
Robert L. Way, Engineering Publications

AC Spark Plug
The Electronics Division
of
General Motors Corporation
Milwaukee 1, Wisconsin

1 February 1962

TABLE OF CONTENTS

TABLE OF CONTENTS (concluded)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (cont)

LIST OF ILLUSTRATIONS (cont)

LIST OF TABLES

SECTION I

INTRODUCTION

A. BASIC QUANTITIES AND UNITS

1. SYSTEM OF MEASUREMENT

Mass, distance, and time are expressed in the metric system, in which the unit of:

mass = grams (gm)
distance = centimeters (cm)
time = seconds (sec).

The following conversion factors are used to convert the units of mass and distance to the equivalent English system units:

2.54 cm = 1 in.
1000 gm = 1 kg = 2.2 lbs.

2. LINEAR QUANTITIES

a. Mass

The amount of material in an object is its mass (m), measured in grams. More precisely, it is the measure of a body's inertia (tendency to remain at rest when at rest, or in motion when in motion).

$$m = \frac{w}{g} \tag{1-1}$$

where

w = weight of the body
g = gravitational attraction on the body.

On earth $g = 1$ (1 gravity, or 1 g) by definition, so that

$$m = w \tag{1-2}$$

for any body <u>on earth</u>.

b. Velocity

Velocity (v) is the rate of change of position with respect to time, measured in cm/sec.

$$v = \frac{s}{t} \qquad (1\text{-}3)$$

where

s = distance
t = time.

Also,

$$v = at \qquad (1\text{-}4)$$

where

a = acceleration.

These equations are for <u>average</u> velocity (assume a uniform rate).

c. Acceleration

Acceleration (a) is the rate of change of velocity with respect to time, measured in cm/sec^2.

$$a = \frac{v}{t} \text{ (by rearranging equation 1-4)} \qquad (1\text{-}5)$$

Also,

$$a = \frac{2s}{t^2} \qquad (1\text{-}6)$$

for uniform acceleration.

Note that equations 1-3 and 1-6 may be solved for distance, if that quantity is desired and the others are known:

$$s = vt \text{ (by rearranging equation 1-3)} \qquad (1\text{-}7)$$

$$s = \frac{1}{2}at^2 \text{ (by rearranging equation 1-6).} \qquad (1\text{-}8)$$

The acceleration toward the center of the earth caused by the gravitational attraction of the earth's mass is called gravity (g), and is numerically equal to

$$g^* = 32.2 \text{ ft/sec}^2 = 980 \text{ cm/sec}^2. \qquad (1\text{-}9)$$

d. Momentum

Momentum (M) is the product of mass and velocity, measured in gm cm/sec

$$M = mv. \qquad (1\text{-}10)$$

e. Force

Force (F) is the rate of change of momentum with respect to time, or the product of mass and acceleration; measured in dynes (1 dyne = 1 gm cm/sec^2)

$$F = \frac{M}{t} = \frac{mv}{t} = m\frac{v}{t} = ma$$

$$F = m \text{ (gm) } a \text{ (cm/sec}^2\text{)}. \qquad (1\text{-}11)$$

Since g is an acceleration, by rearranging equation 1-1 we see that weight is a force

$$w = mg. \qquad (1\text{-}12)$$

An important theorem that will be used in discussing the gyro float as a torque summing member is: the sum of the forces (or torques) acting on a body is always zero. In equation form

$$\Sigma F = 0 \text{ (condition of equilibrium)}. \qquad (1\text{-}13)$$

This means, of course, that for every force acting on a body there is an equal and opposite force also acting on the body. (The word "force" can be replaced by the word "torque".) An example of this would be: a box resting on the floor exerts a force (its weight) downward on the floor. The floor also exerts an equal force upward on the box. Thus, the sum of the two forces is zero.

f. Work

Work (W) is the product of force times distance, measured in dyne-cm

$$W = Fs = mas. \qquad (1\text{-}14)$$

---

*g varies slightly for different parts of the earth's surface.

Work is closely related to energy — the amount of energy required to do the work (potential energy), or the amount of energy used in performing the work (kinetic energy). These two kinds of energy are also defined as follows. Potential energy is the energy of position, and kinetic energy is the energy of motion. These statements are evident from their formulae, which are developed in the following manner:

$$\text{potential energy} = \text{work that can be done by an object} = Fs = mas = mgh \tag{1-15}$$

where

g = acceleration of gravity
h = height of the object;

$$\text{kinetic energy} = \text{work that is being done by an object} = Fs = mas = ma\,\frac{1}{2}at^2 = \frac{1}{2}mv^2 \tag{1-16}$$

where

v = velocity of the moving object.

3. ROTATIONAL QUANTITIES

a. Moment of Inertia

Moment of inertia is analogous to mass in the linear system, and is taken with respect to the axis about which the body is being rotated. It will be shown later that

$$I = \Sigma mr^2. \tag{1-17}$$

Hence the units of moment of inertia are gm cm^2.

b. Angular Velocity

Angular velocity is the velocity of a rotating body with the distance expressed as an angle (in radians). A radian is an angle that subtends an arc equal to the radius of the circle. Since there are 2π radii in the circumference of a circle, 2π radians = 360 degrees, and 1 radian = 57.3 degrees. The equation for angular velocity is

$$\omega = \frac{\theta}{t}\,\frac{(\text{rad})}{(\text{sec})}. \tag{1-18}$$

Note that the angular velocity of all particles on a rotating body is the same, while the linear velocity of the particles nearer the rim of the body is greater than those nearer the axis.

c. Angular Acceleration

Angular acceleration is analogous to linear acceleration, and is measured in rad/sec^2.

$$\alpha = \frac{\omega}{t} \tag{1-19}$$

d. Angular Momentum

Angular momentum is analogous to linear momentum, and has units of dyne-cm-sec (to be explained later). When speaking of the angular momentum (H) of the gyro wheel, the velocity term is the angular velocity about the spin axis (SA).

$$H = I\omega_{SA} \tag{1-20}$$

e. Torque

Torque is a force acting through a distance (radius), analogous to force in the linear system, and also has the units of dyne-cm. In general terms, torque is equal to the product of moment of inertia and angular acceleration, as shown below.

$$T = I\alpha \tag{1-21}$$

f. Work

$$W = T\theta \tag{1-22}$$

4. COMPARISON OF LINEAR AND ROTATIONAL QUANTITIES

LINEAR	ROTATIONAL
m (gm)	I (gm cm^2)
$v = \frac{s}{t}$ (cm/sec)	$\omega = \frac{\theta}{t}$ (rad/sec)
$v = at$	$\omega = \alpha t$
$a = \frac{v}{t}$ (cm/sec^2)	$\alpha = \frac{\omega}{t}$ (rad/sec^2)
$a = \frac{2s}{t^2}$	$\alpha = \frac{2\theta}{t^2}$
$s = vt$ (cm)	$\theta = \omega t$ (rad)

LINEAR	ROTATIONAL
$s = \frac{1}{2}at^2$	$\theta = \frac{1}{2}\alpha t^2$
$M = mv$ (gm cm/sec)	$H = I\omega_{SA}$ (dyne-cm-sec)
$F = ma$ (dynes)	$T = I\alpha$ (dyne-cm)

5. CONVERSION OF ROTATIONAL TO LINEAR UNITS

$$s = r\theta \tag{1-23}$$

$$v = r\omega \tag{1-24}$$

$$a = r\alpha \tag{1-25}$$

where

r = radius of the rotating body.

We can now show how equation 1-17 is developed. It was stated that torque is a force acting through some radius, or for a concentrated mass, m, beginning to rotate about a center displaced from the mass by radius, r,

$$T = Fr = mar;$$

but

$a = r\alpha$ by equation 1-25

so that

$$T = mr\,\alpha r = mr^2\alpha. \tag{1-26}$$

By equation 1-21

$T = I\alpha$ so mr^2 in equation 1-26 is equal to I.

Since objects consist of many particles of mass, each separated from the center of rotation by its own r, the total I consists of the sum of the individual moments of inertia, or $I = \Sigma mr^2$.

Now it can also be shown that the units of H are dyne-cm-sec. By equation 1-20 and equation 1-17

$$H = I\omega_{SA} = mr^2\,\omega_{SA}. \qquad (1\text{-}27)$$

Substituting the metric units into the right hand side of equation 1-27 gives

$$H = \text{gm cm}^2\ \text{rad/sec} = \text{gm cm cm/sec}.$$

(The rad is dropped since it is only the ratio between the radius and circumference of a circle.)

We can further multiply the right side of the last equation by sec/sec, since this quantity is equal to 1.

$$H = \boxed{\frac{\text{gm cm}}{\text{sec}^2}}\ \underline{\text{cm sec}}$$

The quantity encircled (gm cm/sec^2) is a dyne, so

H = dyne-cm-sec, as was to be proven.

6. VECTOR NOTATION AND MANIPULATION

Quantities that have <u>magnitude only</u> are called scalars (mass, time, etc.). Quantities that have <u>both magnitude and direction</u> are called vectors (velocity, acceleration, force, etc.). A further good example of these two types of quantities is "speed" and "velocity". Speed is a scalar, since we may talk about the top speed of a vehicle without specifying any particular direction. Velocity, on the other hand, is a vector because it always implies a direction (forward, North, clockwise, etc.).

A vector quantity may be represented on paper by means of an arrow, the length of which is proportional to the vector quantity and the direction of which is parallel to the direction of the quantity. Making the length of the arrow proportional to the magnitude of the vector quantity means that we must choose a suitable scale for drawing the arrow. For example, if velocity is to be shown as a vector arrow, we might choose the scale 1 in = 10 cm/sec. Then a velocity of 50 cm/sec would be represented by an arrow 5 in long. Similarly, we must identify the direction on the paper. If the velocity to be drawn were to the North, we might let the right hand side of the paper represent the North, so that the arrowhead would point to that side in the given case. (See figure 1-1.)

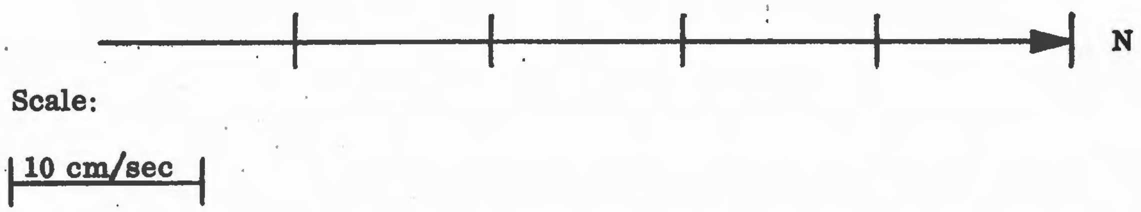
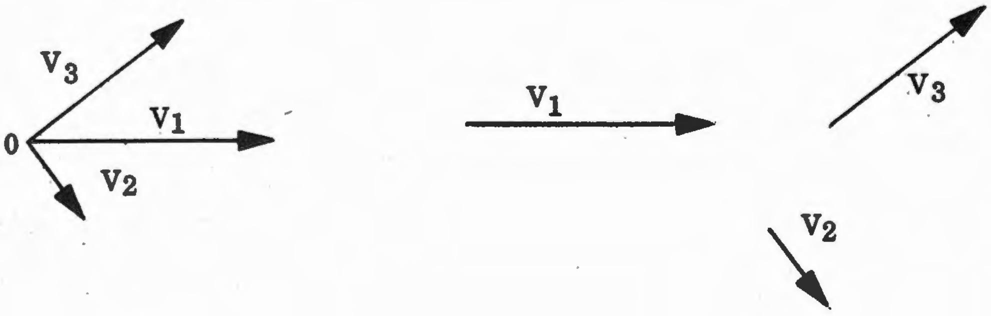


Figure 1-1. Vector Representing a Velocity of 50/cm/sec North

Two simple theorems permit vectors to be manipulated readily. The first is: any vector may be moved to a new location, provided its length is not altered and its new position is parallel to its old position. This means that the three vectors $\vec{V_1}$, $\vec{V_2}$, and $\vec{V_3}$ shown in the random orientation (figure 1-2b) can be brought to a common origin (a), without changing the vectors in any way.



a.

b.

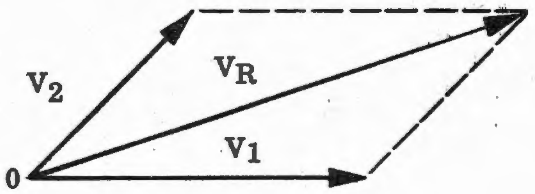
Figure 1-2. Common Vectors

The second theorem is: the negative of a given vector is a vector drawn the same length and direction as the given vector, but with the arrowhead on the opposite end, as shown below.

With these two rules, we can proceed to learn to add, subtract, combine, resolve and project vectors.

a. Addition of Two Vectors

$\overrightarrow{V_1}$ and $\overrightarrow{V_2}$ may be added to produce a <u>resultant</u> vector, $\overrightarrow{V_R}$, by the method of "completing the parallelogram" (figure 1-3).



$$\overrightarrow{V_R} = \overrightarrow{V_1} + \overrightarrow{V_2}$$

Figure 1-3. Vector Addition

This means that $\overrightarrow{V_R}$, in effect, can replace $\overrightarrow{V_1}$ and $\overrightarrow{V_2}$. A common example of the addition of two vectors would be to find the speed and direction of a boat moving across a stream. The forward speed of the boat would be $\overrightarrow{V_1}$ and the stream current $\overrightarrow{V_2}$. The actual path of the boat, then, would be in the direction of $\overrightarrow{V_R}$, and the speed of the boat would be proportional to the length of $\overrightarrow{V_R}$.

b. Subtraction of Two Vectors

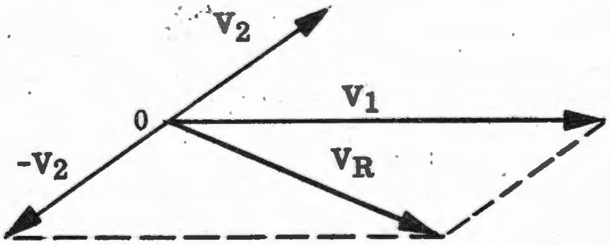
Two vectors may be subtracted by regarding the process as the addition of a negative vector; i.e.,

$$\overrightarrow{V_1} - \overrightarrow{V_2} = \overrightarrow{V_R}$$

is the same as

$$\overrightarrow{V_1} + (-\overrightarrow{V_2}) = \overrightarrow{V_R}.$$

(The second theorem is used to obtain $(-\overrightarrow{V_2})$). The solution then continues by adding the two vectors by completing the parallelogram (figure 1-4).

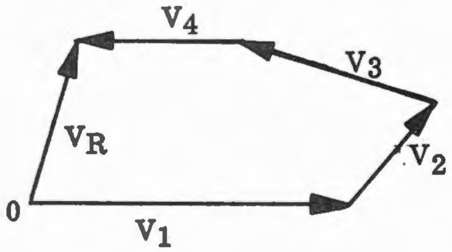


$$\overrightarrow{V_R} = \overrightarrow{V_1} - \overrightarrow{V_2}$$

Figure 1-4. Vector Subtraction

c. Combining Three or More Vectors

The "polygon method" is used; i.e., the second vector is drawn on the end of the first vector, the third onto the end of the second, the fourth onto the end of the third, etc., as shown in figure 1-5. The resultant is then drawn from the origin to the unconnected end of the last vector.



$$\overrightarrow{V_R} = \overrightarrow{V_1} + \overrightarrow{V_2} + \overrightarrow{V_3} + \overrightarrow{V_4}$$

Figure 1-5. Vector Combination

d. Resolving a Vector into Components

Any vector can be broken down into two vectors that when added together will produce the given vector; in fact, it is possible to find a whole family of pairs of vectors that will combine to produce the given vector. (See figure 1-6.) The vector pairs a, a', b, b', c, c', and d, d' are just a few of the many pairs of vectors that could be used to produce $\overrightarrow{V}$. The two vectors (a a', b b', etc.) are called <u>components</u> of the given vector $\overrightarrow{V}$.

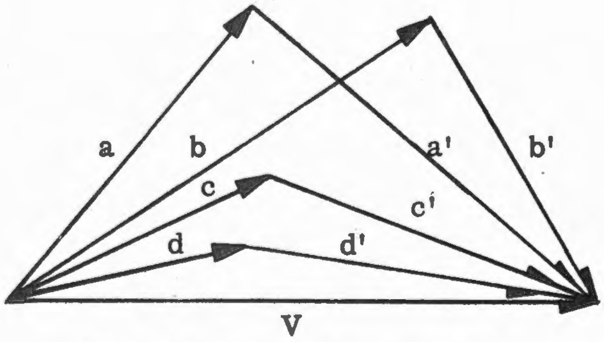


Figure 1-6. Vector Resolution

e. Projecting a Vector onto Coordinate Axes

It is frequently desired to find the components of a vector that lie along coordinate axes (that is, find two components of the vector that are at right angles to each other and lie on the axes). This process is just a special case of d above. It is called "projecting the vector onto the axes", and the components are called "projections of the vector". Figure 1-7 shows the projection of the gravity vector onto two of the gyro axes to obtain the components of g (g_{IA} and g_{SRA}) on those axes.

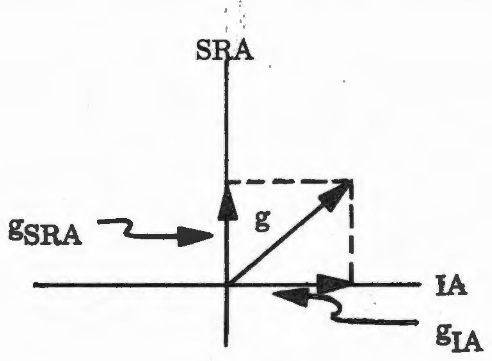
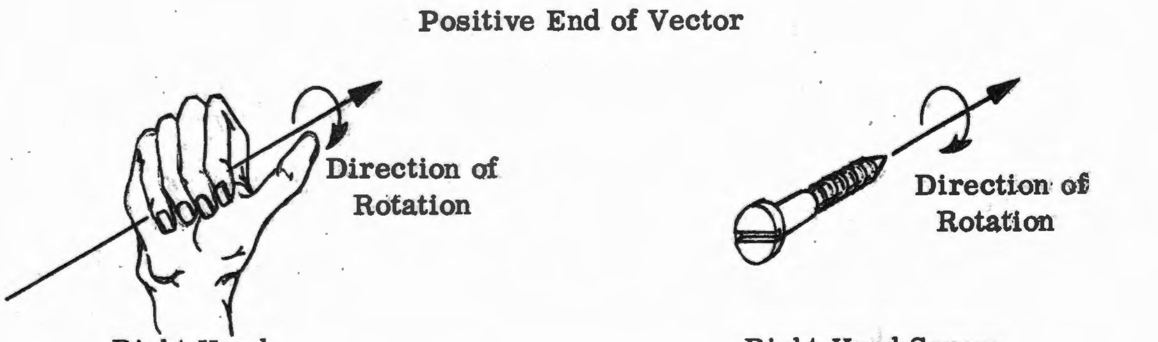


Figure 1-7. Vector Projection onto Coordinate Axes

f. <u>Rotational Vectors</u>

Any of the rotational quantities (angular velocity, angular acceleration, etc.) may be represented as vectors. As with linear vector quantities, the length of the vector arrow is proportional to the magnitude of the rotational quantity, and the direction of the arrow is determined by the right hand rule, which states: "If the fingers of the right hand are curved in the direction of rotation, the thumb points in the positive direction of the vector (arrowhead). Another way of saying this is that the vector points in the direction of advance of a right-hand screw turned in the same sense as the rotational quantity acts. See figures 1-8 and 1-9.



Right Hand

Right Hand Screw

Figure 1-8. Right Hand Rule

EXAMPLE: vector of the angular velocity of a wheel rotating at 300 rad/sec:

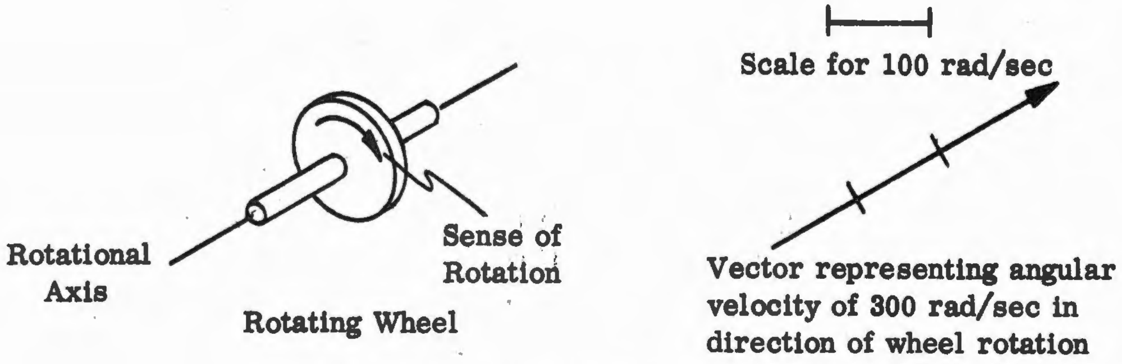
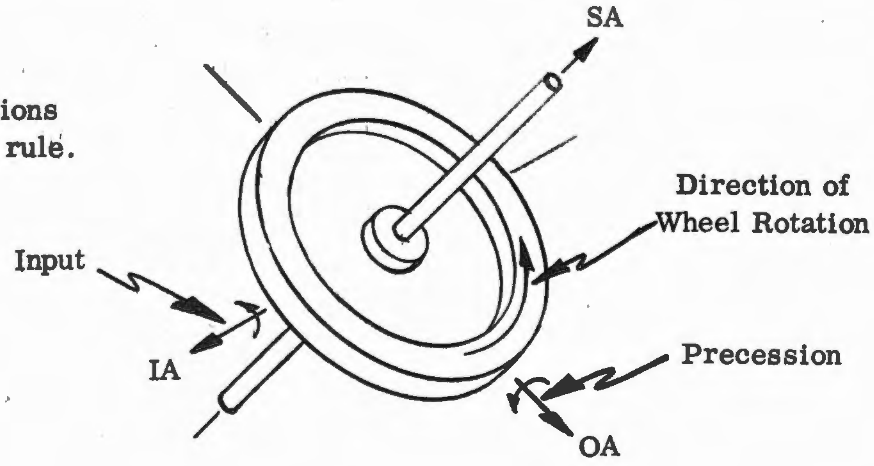


Figure 1-9. Angular Velocity Vector

B. GYRO PRECESSION

Precession is the motion of a rotating wheel resulting from a torque applied to the wheel about an axis perpendicular to the axis of wheel rotation. This motion occurs in a plane mutually perpendicular to the plane of wheel rotation and the plane of the applied torque. (See figure 1-10).



Note applications of right hand rule.

Figure 1-10. Precession of a Rotating Wheel

If the input rotation is in the opposite sense the precession will be in the opposite direction. The axes of the gyro form a right handed, orthogonal system. The quantities can be represented, in their proper orientation, by the thumb and first two fingers of the right hand, as shown in figure 1-11, where

thumb = direction of positive spin axis
first finger = direction of positive input axis
second finger = direction of positive output axis.

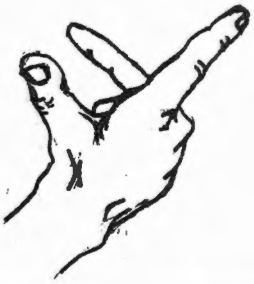


Figure 1-11. Orthogonal System

Upon applying the right hand rule to this system, it is seen that the direction of precession is such as to attempt to align the spin axis with the input axis. At AC Spark Plug the direction of wheel rotation (and hence the positive end of the spin axis by application of the right hand rule) and the positive direction of the output axis are chosen. The positive end of the input axis (and hence the positive sense of input torques) is then defined by the right hand vector system.

Two explanations of why precession occurs will be given. The first of these explanations makes use of vectors. As discussed earlier, torque $T = I\alpha$, and since α is the time rate of change of angular velocity, $T = I\frac{\Delta\omega}{\Delta t}$. Also, angular momentum $H = I\omega$, and $\Delta H = I\Delta\omega$.

Solving both equations for I,

$$I = T\frac{\Delta t}{\Delta\omega} = \frac{\Delta H}{\Delta\omega} \qquad (1\text{-}28)$$

and $\Delta H = T\Delta t$. (1-29)

This latter equation expresses the torque (T) applied about the gyro IA in figure 1-12 for a period of time Δt as a change in angular momentum (ΔH). ΔH is a vector and can be added to the H vector, along the SA, to produce a new angular momentum vector H'. The movement of H to H' is accomplished physically by a rotation (precession) of the gyro SA-IA plane about the output axis (CCW as viewed from the positive end of OA).

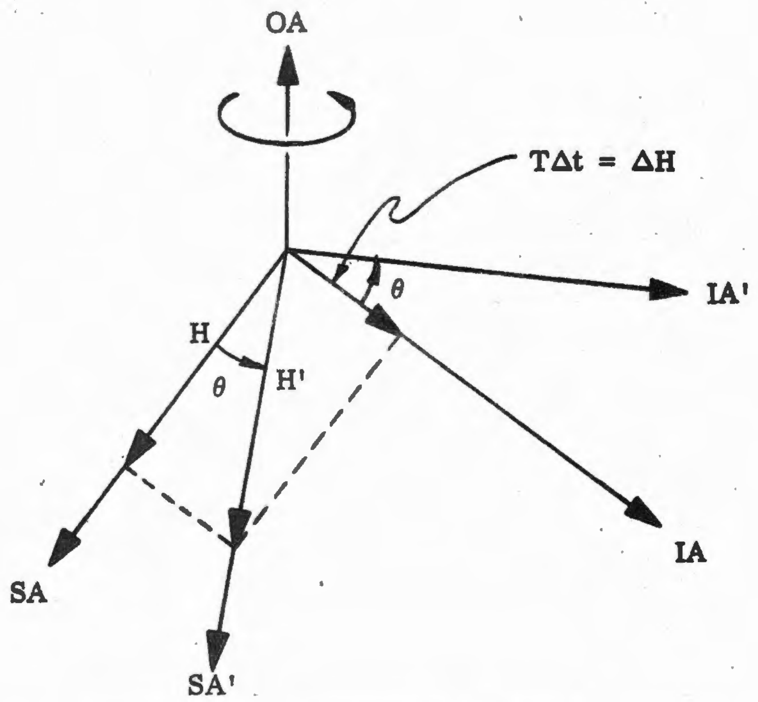


Figure 1-12. Precession Vectors

The second explanation of precession is a physical one. In figure 1-13, the torque about the input axis can be represented as resulting from a couple applied to the wheel by a pair of rollers attached to handles. Any particle in the wheel to the left of the line BD will experience a downward force, and any particle to the right of this line will experience an upward force. Now let us consider the motion of one particle of the wheel as it revolves (actually all of the particles follow the same path or a parallel path). First observe the symmetry of forces upon the particle as it travels through the left and right halves of its path. While the downward portion of the couple exerts a half sinusoid of force upon the particle in the left half, it can be argued that the right force acts in exactly the same manner for the same time in the upward direction.

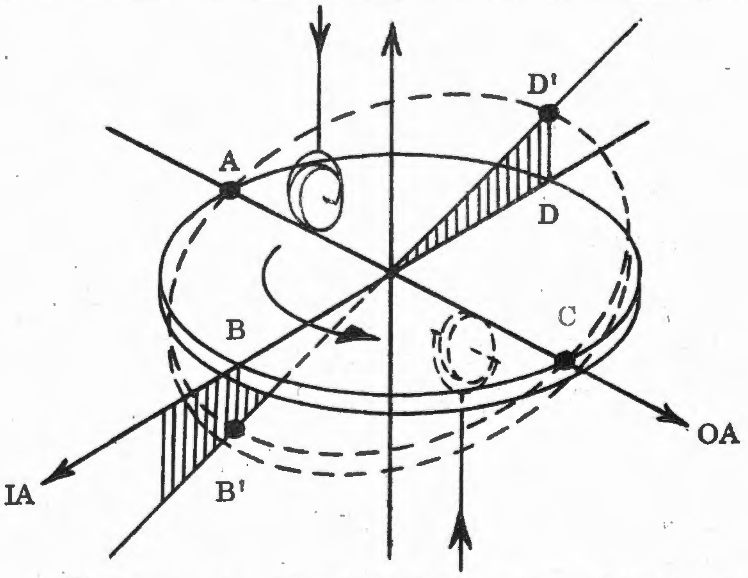


Figure 1-13. Physical Explanation of Precession

If we examine the particle starting at point A, in the first quarter revolution the particle moves downward a certain distance under the influence of the left hand roller. At the instant of passing point B', the particle comes under the influence of the right hand roller and moves upward during its next quarter revolution. When the particle reaches C after one-half revolution, it is again at its original level, since it spent an equal time under the influence of equal and opposing forces. During the third quarter revolution, the particle continues upward under the influence of the right hand roller. In the last quarter of revolution the particle again comes under the influence of the left roller and moves downward the same distance that it moved up in the third quarter revolution. The result at the completion of the full revolution is that the particle has returned to the same point (at the same level) from which it started. As every particle of the wheel follows this same path, or a path parallel to it, the plane of the wheel rotation is tipped so that the front edge of the wheel is moving downward and the rear edge is moving upward (counterclockwise rotation about OA as viewed from the positive end of that axis).

It is important to note that although a torque was applied through the rollers (or through the spin axis shaft in a more practical case), no rotation about IA occurred, yet a precession took place about OA. The action may be expressed by the equation

$$\omega_{OA} = \frac{T_{IA}}{H} \tag{1-30}$$

where ω_{OA}, the angular velocity of precession is directly proportional to T_{IA}, the applied torque about IA, and inversely proportional to H, the angular momentum about the spin axis.

However, in the actual gyroscope, we observe that the application of torque about IA does not result in the infinite resistance to motion indicated by the example, and that, while resisting our input in some measure, a spinning wheel may be positioned as desired. This may be explained by noting that a spinning wheel does not have a unique input axis, and that application of a torque about any axis perpendicular to the spin axis results in an angular velocity about a mutually perpendicular axis. Furthermore, two input torques and two resulting precessions may and frequently do occur simultaneously. This is exactly the case in the practical gyro, where friction, damping, spring restraint, inertia about OA, or a combination of them create a torque about OA during precession, and hence cause a second precession about IA. This is shown in figure 1-14.

In the figure, application of torque about IA results in precession about OA as previously shown, and indicated by solid vectors. (For single degree of freedom gyros, torque is applied to the entire gyro case, which then transmits it through the fluid,

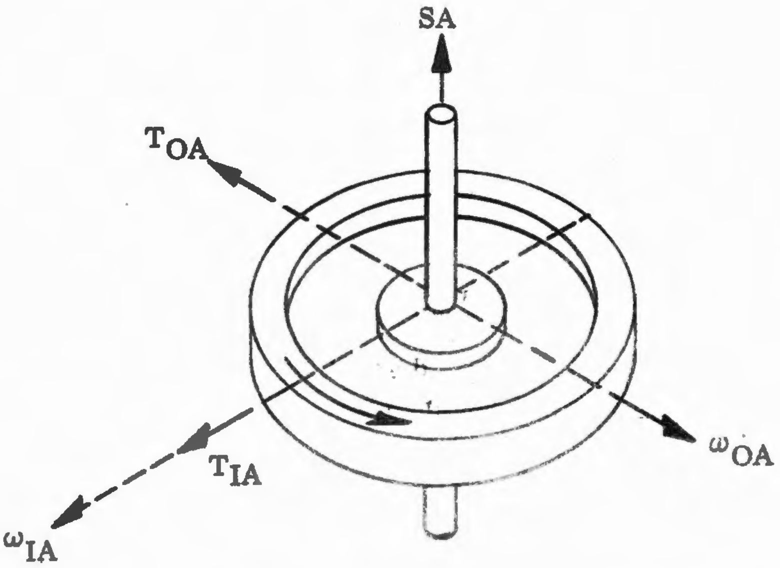


Figure 1-14. Precession Axes

pivots or magnetic suspension to the spinning wheel.) However, damping, friction, spring restraint, and inertia oppose the motion about OA, producing the dotted torque vector shown. By noting the resulting precession about IA, we see that it is in the direction of the original applied torque. The observed effect is thus simultaneous rotation about IA and OA. The two equations may therefore be written

$$T_{IA} = H\,\omega_{OA} \tag{1-31}$$

$$T_{OA} = H\,\omega_{IA}. \tag{1-32}$$

Consideration of the equations explains the ability of a spinning wheel mounted in gimbals to maintain a fixed angular position when the gimbals are rotated. If the gimbal bearings have low friction, the available torque about any input axis is very small, resulting in a very small precession. If the bearings on the precession axis also have low friction, the "secondary" precession of the wheel in the original input direction is small. Hence, stability of the wheel is observed.

Equation 1-32 is generally used when considering the gyro float as a torque summing member. If the damping torque about OA is much greater than the other torques, then

$$T_{OA} = H\,\omega_{IA} = C_D\,\omega_{OA} \tag{1-33}$$

where C_D is the damping coefficient in $\frac{\text{dyne-cm}}{\text{rad/sec}}$, and $$\frac{\omega_{OA}}{\omega_{IA}} = \frac{H}{C_D}. \qquad (1\text{-}34)$$

The ratio H/C_D is constant for a given gyro.

In a given length of time

$$\frac{\omega_{OA}t}{\omega_{IA}t} = \frac{\theta_{OA}}{\theta_{IA}} \qquad (1\text{-}35)$$

and the ratio is called the angular gain of the gyro.

C. GYRO AXES

In the preceding discussions of a rotating wheel, three axes were used: the spin axis, the input axis, and the output axis. These three axes, and a fourth axis (the spin reference axis), will now be defined in terms of the construction of AC Spark Plug gyros.

1. OUTPUT AXIS (OA)

Output axis (OA) is a line passing through the center of the float pivots (also, a line passing through the centers of the microsyn rotors).

2. SPIN AXIS (SA)

Spin axis (SA) is the axis about which the gyro wheel spins. Ideally, this would be a line through the center of the wheel shaft, and would be exactly 90 degrees from the output axis. However, the holes bored through the float cylinder to accept the wheel shaft may not make an exact 90-degree angle with the OA, thus displacing the axis from its ideal position.

3. SPIN REFERENCE AXIS (SRA)

Spin reference axis (SRA) is the position of the spin axis when the float is at the null position. The null position of the float is that position where the signal microsyn is at electrical null.

4. INPUT AXIS (IA)

Input axis is the axis mutually perpendicular to the spin reference and the output axis.

D. BASIC GYROSCOPE CONFIGURATIONS

1. GYROSCOPE FUNCTIONAL TYPES

a. Integrating Gryo

Equation 1-35 above shows that in the damped gyro there exists a fixed ratio between θ_{OA} and θ_{IA}. Thus, the float angular position is proportional to the input rotation angle θ_{IA}. But θ_{IA} is the time integral of the velocity ω_{IA}, hence, the term integrating gyro. It is important to note that if float unbalances and restraints are small, knowledge of input rotations is "stored" in the float position until it is to be used.

b. Rate Gyro

The rate gyro has a spring restraining its output axis rotation. With a rotational spring constant, k, in dyne-cm/rad we may rewrite equation 1-32 as

$$T_{OA} = H\omega_{IA} = k\theta_{OA} \tag{1-36}$$

or

$$\theta_{OA} = \frac{H}{k}\omega_{IA}. \tag{1-37}$$

Notice in this gyro the float position is proportional to the rate ω_{IA} and is thus useful for rate measurement. Upon removal of the input rate, the spring pulls the float to null, and no storage capability exists for this gyro.

This design has primarily elastic restraint about the output axis to make the output signal proportional to the input rate, ω_{IA}. Consequently, the $k\theta_{OA}$ term is important.

c. Rate-Integrating Gyro

The rate-integrating design has primarily viscous restraint about the output axis. In this case, $k\theta_{OA}$ is undesirable, and $C_D\omega_{OA}$ is an essential term. As the name implies, the output signal of the rate-integrating gyro is proportional to the integral of ω_{IA}.

d. Double-Integrating Gyro

This design has essentially no restraint about the output axis, so the output signal is proportional to the second integral of ω_{IA}. Good performance from a double-integrating gyro requires an $H\omega_{IA}$ that is substantially higher than the summation of the undesirable terms.

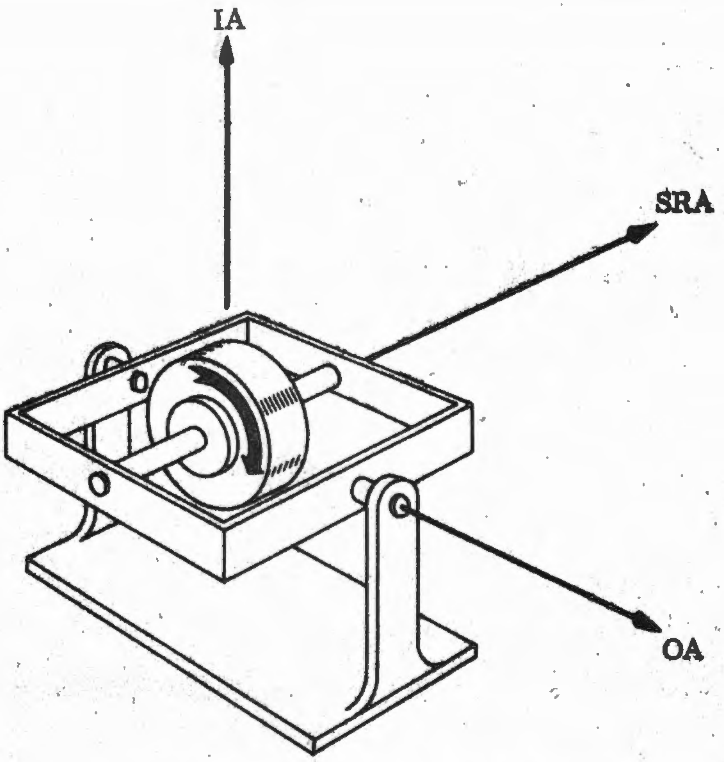


Figure 1-15. Single-Degree-of-Freedom Gyro

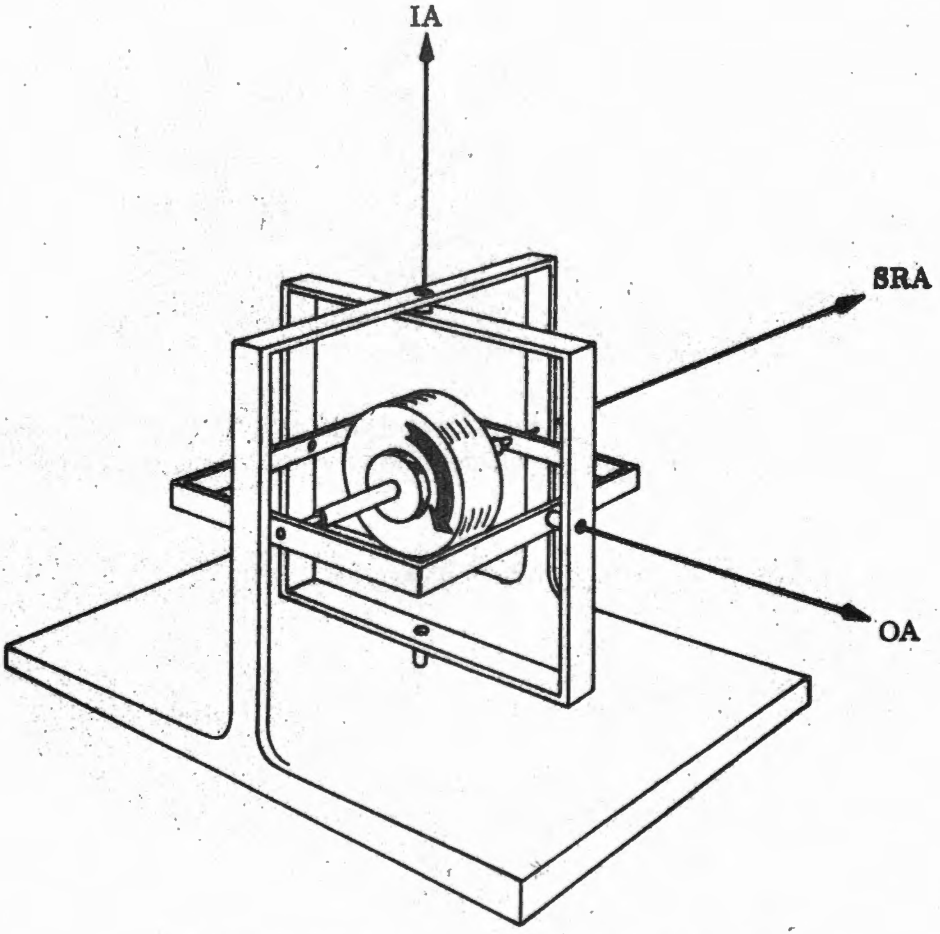


Figure 1-16. Two-Degree -of-Freedom Gyro

2. DEGREES OF FREEDOM

The number of directions in which the gyro wheel can precess is determined by the number of gimbals, and this quantity is called the degree of freedom of the particular gyro. A single-degree-of-freedom gyro (as manufactured by AC Spark Plug) and a two-degree-of-freedom gyro are shown schematically in figures 1-15 and 1-16. Note that a two-degree-of-freedom gyroscope can accept two different inputs, 90 degrees apart, and that the input axis for one input is also the output axis for the other input, and vice-versa.

3. STABILIZATION AND ACCELEROMETER GYROSCOPES

The single-degree-of-freedom, rate-integrating gyroscopes built by AC Spark Plug are used almost exclusively for two basic navigation functions. One is to sense changes from stable reference, the other is to sense force or acceleration. Hence, there are stabilization gyros and accelerometer gyros.

a. Stabilization Gyroscopes

There are several types of stabilization gyroscope designs, including rate gyros, rate-integrating gyros, and double-integrating gyros. In all of these, it is desirable to have the unbalance terms as low as possible.

b. Accelerometer Gyroscopes

In gyroscopes built for use in accelerometers, the gyro float is made sensitive to acceleration along the input axis by designing a relatively large unbalance at right angles to the input axis — along the spin axis. In other words, the float is made pendulous, with the mass (m) and lever arm (l) along the spin axis. Acceleration (a) acting on the pendulum (ml) creates a proportional torque (mla) about the output axis. The accelerometer is operated in a servo loop that drives the gyro about its input axis, thereby developing a precessional torque ($H\omega_{IA}$) that balances the pendulous torque. Thus, the accelerometer provides measures of acceleration and velocity, as shown below.

The precessional torque cancels the pendulous torque:

$$H\omega_{IA} = -mla.$$

Dividing by H,

$$\omega_{IA} = \frac{-mla}{H} = \frac{-ml}{H} (a).$$

Because $\frac{ml}{H}$ is a constant parameter of the gyro,

$$\omega_{IA} \cong a$$

Stating this relationship in terms of time (for simple integration),

$$\frac{\theta_{IA}}{t} \cong \frac{a}{t} \text{ and, dividing by t, } \theta_{IA} \cong v .$$

SECTION II

THE GYRO FLOAT AS A TORQUE SUMMING MEMBER

The complete equation to express all of the torques acting upon the float of a real gyroscope contains many terms. Equation 2-1 gives only the more important torques in very general terms. Each of the quantities on the right hand side of equation 2-1 will be considered individually in the discussion that follows.

$$T_{OA} = \pm H\omega_{IA} \pm C_D\omega_{OA} \pm U \pm K \pm R \pm I_{OA}\alpha_{OA} \pm k\theta_{OA} \pm T_{TG} \qquad (2\text{-}1)$$

Equation 2-1 applies to any gyroscope, without regard to function or type. The various terms in the right member, however, gain or lose significance according to the gyro design and application.

A. PRECESSIONAL TORQUE $H\omega_{IA}$

This torque has been discussed previously. The three conditions giving rise to precession are:

1. A rotating wheel (preferably with a large angular momentum),
2. A torque about the input axis,
3. Freedom to rotate about the precessional axis (OA).

Since the input torque is expressed as an angular velocity about the input axis, the subscript IA is used to distinguish between this angular velocity and the angular velocity contained in $H(H = I\omega_{SRA})$. This latter rate acts about the spin reference axis and, hence, is designated ω_{SRA}.

The magnitude of angular momentum depends only upon the size, weight, and speed of the gyro wheel, and H may be made larger by increasing any of the three variables. The first two quantities, size and weight of the wheel, are fixed during manufacture, and wheel speed is the only variable once the gyro is built.

It is important that H remain as constant as possible in order to have the gyro gain constant. Again, the only significant variable is wheel speed. The gyro wheel is driven by a hysteresis motor, the speed of which is entirely dependent upon the frequency of the excitation voltage.

Rotation of the earth about the earth polar axis (EPA) is an input to gyroscopes, unless some means is used to eliminate it (aligning IA in equatorial plane, rotating gyro about IA at negative earth rate, or torquing float through torque microsyn). If the input axis of the gyro is parallel to the earth polar axis, full earth rate is sensed by the gyro, while if the IA is parallel to the equator no earth rate is sensed by the gyro. At any other orientation, a component of earth rate is sensed that is a

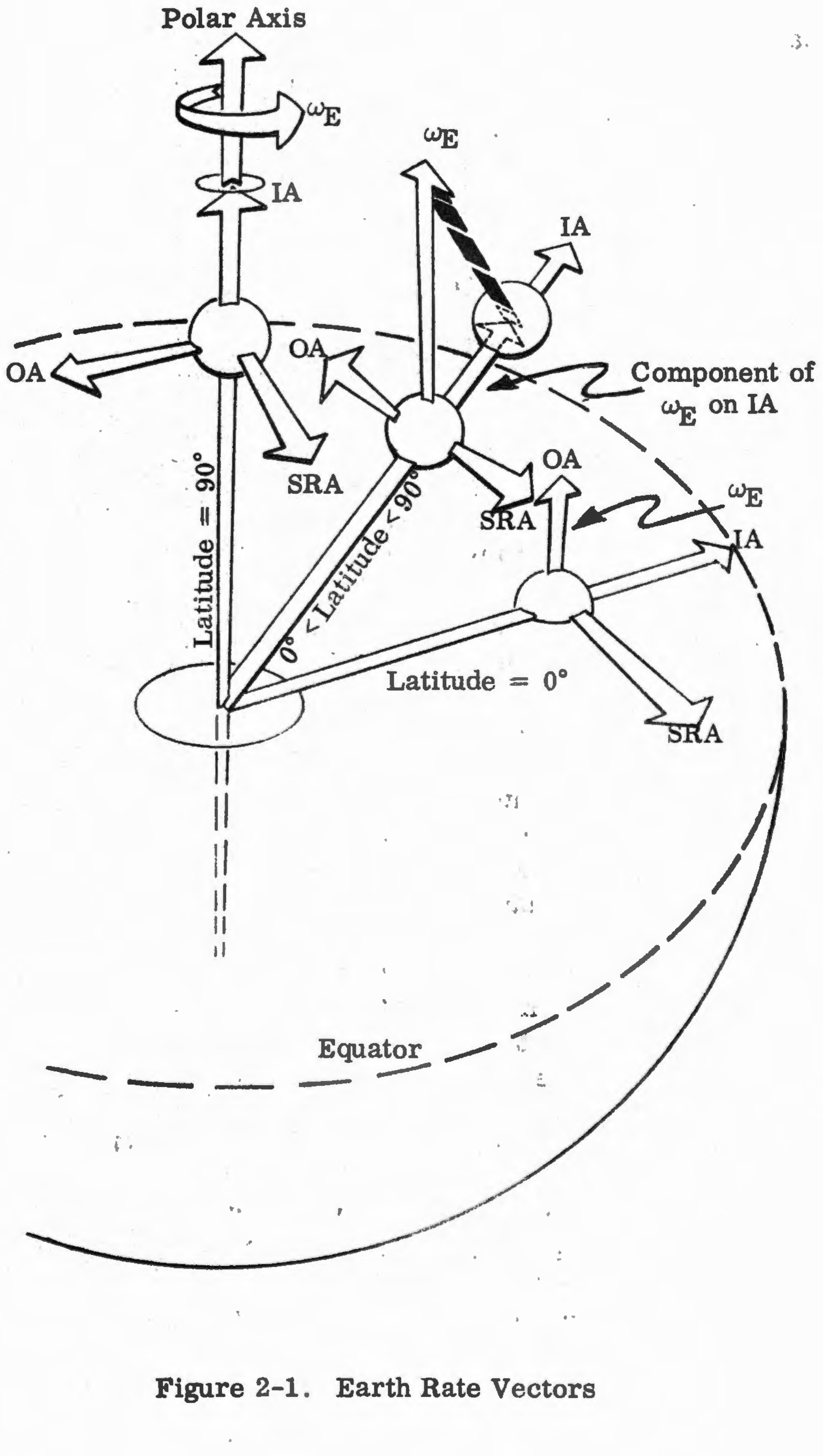


Figure 2-1. Earth Rate Vectors

function of the angle between the EPA and the gyro IA. In figure 2-1 it can be seen that when the IA is aligned parallel with EPA, the vector (ω_E) representing earth rate coincides with IA and the full effect of earth rate is sensed by the gyro. At the equator, on the other hand, the earth rate vector falls on the OA and the gyro is not sensitive to earth rate. At the intermediate latitude, the gravity vector is projected onto the IA, and a component of earth rate is experienced by the gyro. The magnitude of earth rate, correct to three figures, is 15.041 degrees/hour. This is frequently expressed as an angular velocity, 7.29×10^{-5} rad/sec. That this is a very slow rate is demonstrated by the following conversions:

$1000 \times \omega_E \cong 4$ degrees/sec

$1000 \times \omega_E \cong 2/3$ rpm

1 rpm $= 1440 \times \omega_E$

1 rps $= 86,400 \times \omega_E$.

Gyro drift rates, that are due to the extraneous torques discussed below, are still smaller rates, and are frequently expressed in milli earth rate units (MERU). This unit is one-thousandth of earth rate, or 7.29×10^{-8} rad/sec.

B. DAMPING TORQUE $C_D\ \omega_{OA}$

Damping torque, $C_D\ \omega_{OA}$, is due to the action of the viscous damping fluid on the gyro float whenever the float experiences an angular velocity about OA. The damping coefficient, C_D, is equal to H divided by the gain of the gyro. The damping coefficient can be measured by applying a known torque to the float (through the torque microsyn) and measuring the rate about OA. Hence, the convenient unit for measuring damping is dyne-cm/rad/sec. Note that gyro gain is simply a ratio (milliradians/milliradian) and so has no units. Therefore, dividing H by the gyro gain to obtain C_D produces the same unit as for H: dyne-cm-sec, which is the same as dyne-cm/rad/sec.

C. UNBALANCE TORQUES

The U, K, and R terms in equation 2-1 represent unbalances, due to unavoidable imperfection in manufacturing, that act as torques on the gyro float. These torques result from: (1) fixed mass unbalance along the input axis (U_{IA}) and along the spin reference axis (U_{SRA}), (2) compliance unbalances (K_{IA} and K_{SRA}), and (3) residual unbalance. Each of these unbalances will be discussed in the following paragraphs, and the equations for mass unbalance and compliance unbalance will be developed.

1. MASS UNBALANCE TORQUE

Mass unbalance exists in gyros because parts cannot be machined or assembled to zero tolerances. Also, the parts materials are not homogeneous. Even these very small mass unbalances are reflected in the performance of precision gyros. For example, a 0.0000022-pound mass at a 0.4-inch lever arm would produce an error torque of 1 dyne-cm. In one of the rate-integrating gyros built at AC Spark Plug, a one-dyne-cm torque produces a drift rate of 0.021 degrees/hour. Illustrating the effect on guidance, an airplane drifting off course at this rate on a flight between Los Angeles and New York would miss its destination by 11 miles. Consequently, extreme care is taken to control the material quality and the mechanical tolerances, but despite close control, floats exhibit some mass unbalance. During final test, the resultant mass unbalance is determined and resolved into components along IA and SRA. The balance devices on the float are adjusted to bring the total mass unbalance to a minimum. After adjustment, the remaining unbalance is measured very accurately, and this data becomes a part of the gyro's operating characteristics (in some applications, a further portion of the unbalance is eliminated by programming an opposite torque into the torque microsyn). Mass unbalance is dependent upon gyro orientation; that is specifically, upon the angles the gravity vector (g) makes with the unbalance masses. The equation for the torque about the OA due to the unbalances along IA and SRA will be developed for the general case where the gyro is the sensing component of some control servo (missile system, turntable, and so on) and the gyro is rotated about its IA. Other orientations of the gyro give rise to specific cases of this general example. Figure 2-2a simply shows the horizontal plane and the gravity vector perpendicular to it. In figure 2-2b the three gyro axes are shown, with the plane of the OA and SRA sketched in. Figure 2-2c shows figures 2-2a and 2-2b superimposed such that IA makes an angle (θ) with the horizontal, and the intersection of the horizontal and OA-SRA planes makes an angle (ϕ) with OA.

First, the gravity vector is resolved into components on the IA and SRA. Projecting g onto the IA produces

$$g_{IA} = g \sin \theta. \tag{2-2}$$

The projection of g onto SRA yields

$$g_{SRA} = g \cos \theta \cos \phi$$

since SRA is not in the same plane as g and IA (it is displaced from that plane by the angle ϕ).

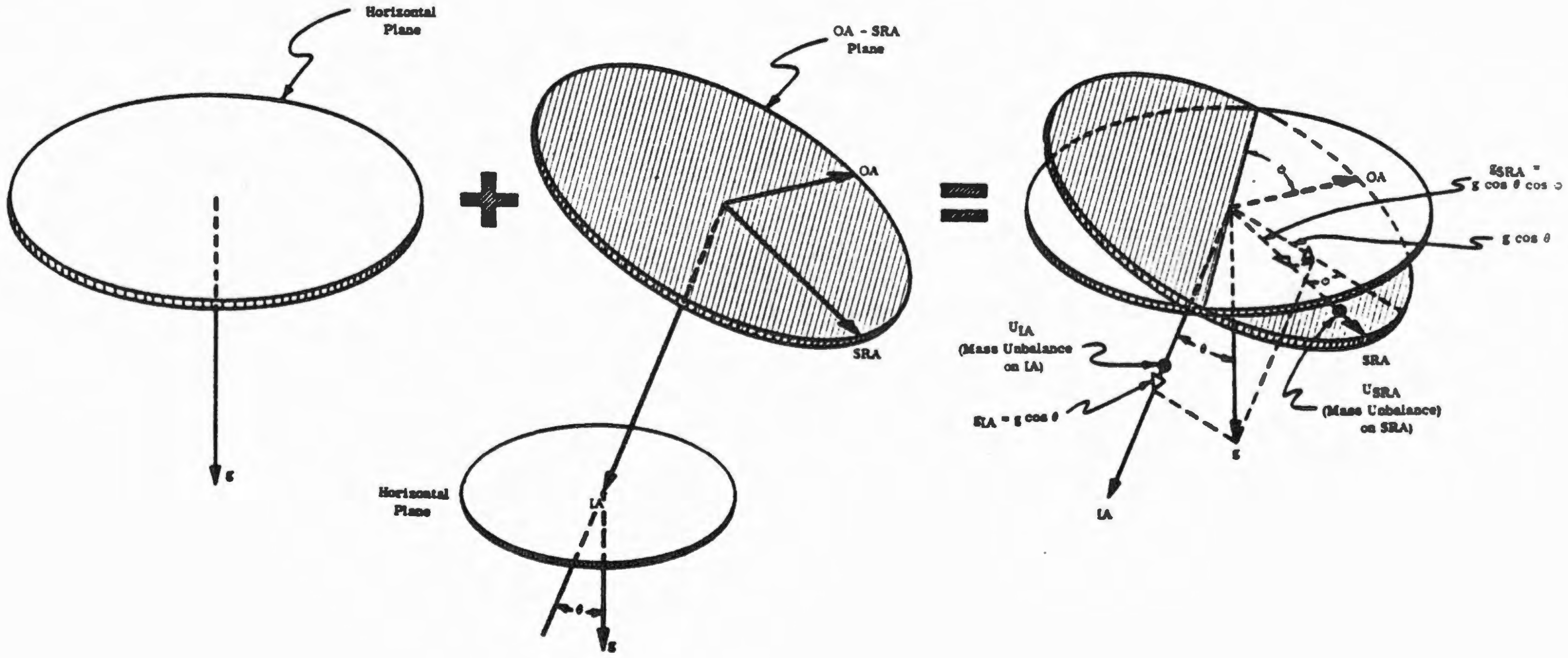


Figure 2-2. Mass Unbalance Diagram

It can be seen that the effect of the g_{SRA} component acting on the mass unbalance on IA will be to produce a negative torque about OA (as defined by the right hand rule). Similarly, the effect of the g_{IA} component acting on the mass unbalance on SRA will be to produce a positive torque about OA. Therefore, the two unbalances tend to cancel, and must be subtracted. If the magnitude of the unbalance on IA is designated U_{IA} and that on SRA is called U_{SRA}, and U_{SRA} is taken as the larger unbalance, the mass unbalance torque about the gyro output axis then becomes

$$T_{OA} = U_{SRA}\, g \sin\theta - U_{IA}\, g \cos\theta \cos\phi. \qquad (2\text{-}4)$$

It should be understood that in equation 2-4 the SRA unbalance term (U_{SRA}) is acted upon by the gravity component acting along the IA ($g \sin\theta$), and that U_{IA} is acted upon by the gravity vector along SRA ($g \cos\theta \cos\phi$).

2. COMPLIANCE UNBALANCE TORQUE

Compliance torque stems from spring-like deflections within the gyro float. Because it is impossible to build an absolutely rigid float, the design aim is to make it equally stiff in all directions about OA. When this is accomplished, the float mass still deflects, but always along the gravity vector and no torque is developed. The mechanism of compliance can be better understood by considering a mass (representing the gyro assembly) suspended by springs within a container (representing the gyro float), as shown in figure 2-3.

In figure 2-3,

M = suspended mass (wheel assembly)
a = distance M is displaced from SRA
b = distance M is displaced from IA
k_{IA} = spring constant (of the float) along IA (dynes/cm)
k_{SRA} = spring constant along SRA (dynes/cm).

It can be seen that no error will result if $k_{IA} = k_{SRA}$ (M is midway between IA and SRA), for then g will be along OA, causing no torque about OA. In the case shown, however, the component of g along SRA ($g \sin\theta$) acts on the mass M at a distance a, so that a torque is produced about OA (CCW looking into the paper) that is equal to $M g \sin\theta\, a$. Similarly, the torque about OA (CW) produced by the component of g along IA acting upon the mass M at the distance b is: $M g \cos\theta\, b$. Since the former torque is CCW and the latter is CW, they tend to cancel and must be subtracted. Hence, the torque about the output axis due to compliance is

$$T_{OA} = M g \sin\theta\, a - M g \cos\theta\, b. \qquad (2\text{-}5)$$

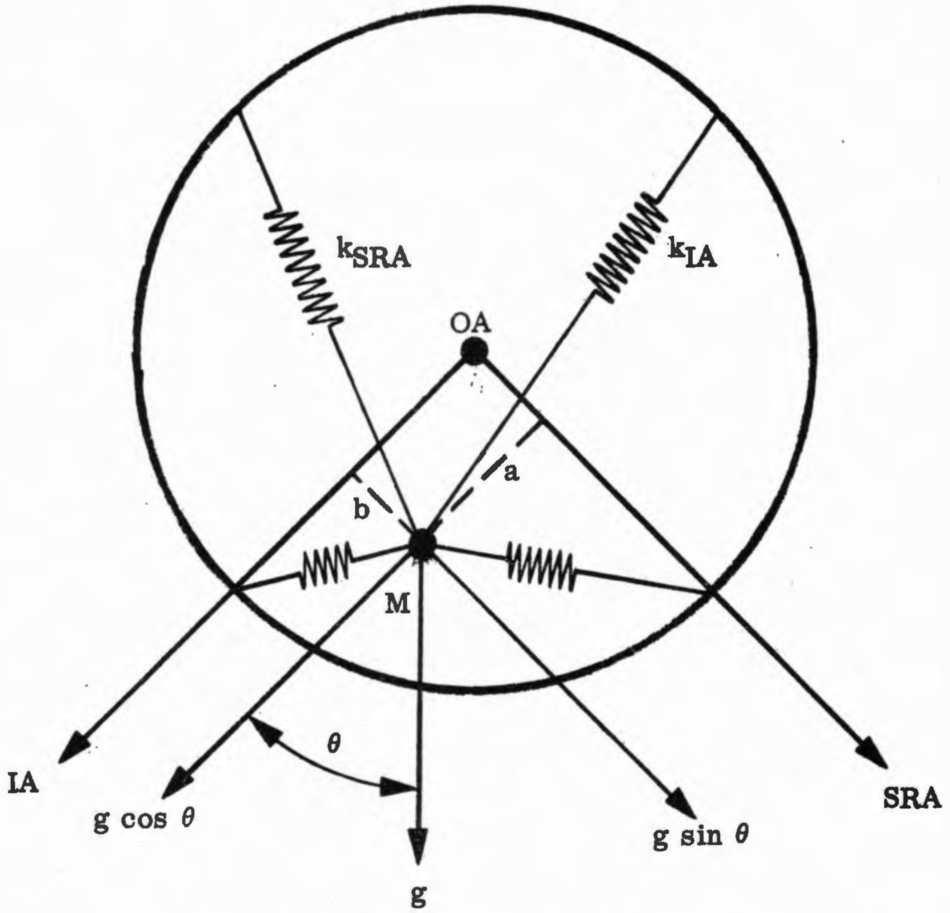


Figure 2-3. Compliance Unbalance Diagram

The displacements a and b of mass M (by Hooke's law relating to springs) are directly proportional to the forces causing the displacements, and indirectly proportional to the spring constants. Thus,

$$a = \frac{M\,g\cos\theta}{k_{IA}}, \text{ and } b = \frac{M\,g\sin\theta}{k_{SRA}}. \tag{2-6}$$

Substituting these quantities into equation 2-5 gives

$$T_{OA} = \frac{M^2 g^2 \sin\theta\cos\theta}{k_{IA}} - \frac{M^2 g^2 \sin\theta\cos\theta}{k_{SRA}}. \tag{2-7}$$

Since $2\sin\theta\cos\theta = \sin 2\theta$, equation 2-7 can be simplified to

$$T_{OA} = \frac{M^2 g^2}{2}\left(\frac{\sin 2\theta}{k_{IA}} - \frac{\sin 2\theta}{k_{SRA}}\right). \tag{2-8}$$

Or

$$T_{OA} = \frac{g^2 \sin 2\theta}{2} \left(\frac{M^2}{k_{IA}} - \frac{M^2}{k_{SRA}} \right) \quad (2\text{-}9)$$

Letting $K_{IA} = \frac{M^2}{k_{IA}}$ and $K_{SRA} = \frac{M^2}{k_{SRA}}$,

euqation 2-9 becomes

$$T_{OA} = \left(\frac{K_{IA}}{2} - \frac{K_{SRA}}{2} \right) g^2 \sin 2\theta. \quad (2\text{-}10)$$

In this derivation it has been assumed that the angle ϕ is 0 (and $\cos \phi = 1$). If ϕ is not zero, it is necessary to multiply equation 2-10 by $\cos \phi$. Again, note that the effects of compliance are dependent upon gyro orientation (the angles θ and ϕ) which may change continually in missile flight.

Conditions that produce compliance torque in the manner described above also make a gyro very sensitive to vibration. To illustrate, assume that such a gyro is being subjected to vibration, ±1g, along an axis between IA and SRA, as shown in figure 2-4. As in figure 2-3, the gravity will act upon k_{IA} and k_{SRA} and displace the float mass from OA. In this case, however, the direction of the gravity vector representing the vibration alternates. When the vector points downward the mass centers below and left of OA, according to the ratio of k_{SRA} to k_{IA}, and a CCW torque is developed. When the gravity vector points upward, the mass centers above and right of OA and again there is CCW torque. The torque curve in the figure was plotted from relationship 2-8, using $M = 1$ and maximum acceleration due to vibration = 1. Note that despite the alternating direction of g, the resultant torque is unidirectional, changing sinusoidally at twice the vibration frequency. The average level of torque from vibration is half the peak-to-peak value.

Another dynamic consideration is magnification of compliance torques by wheel assembly resonances.

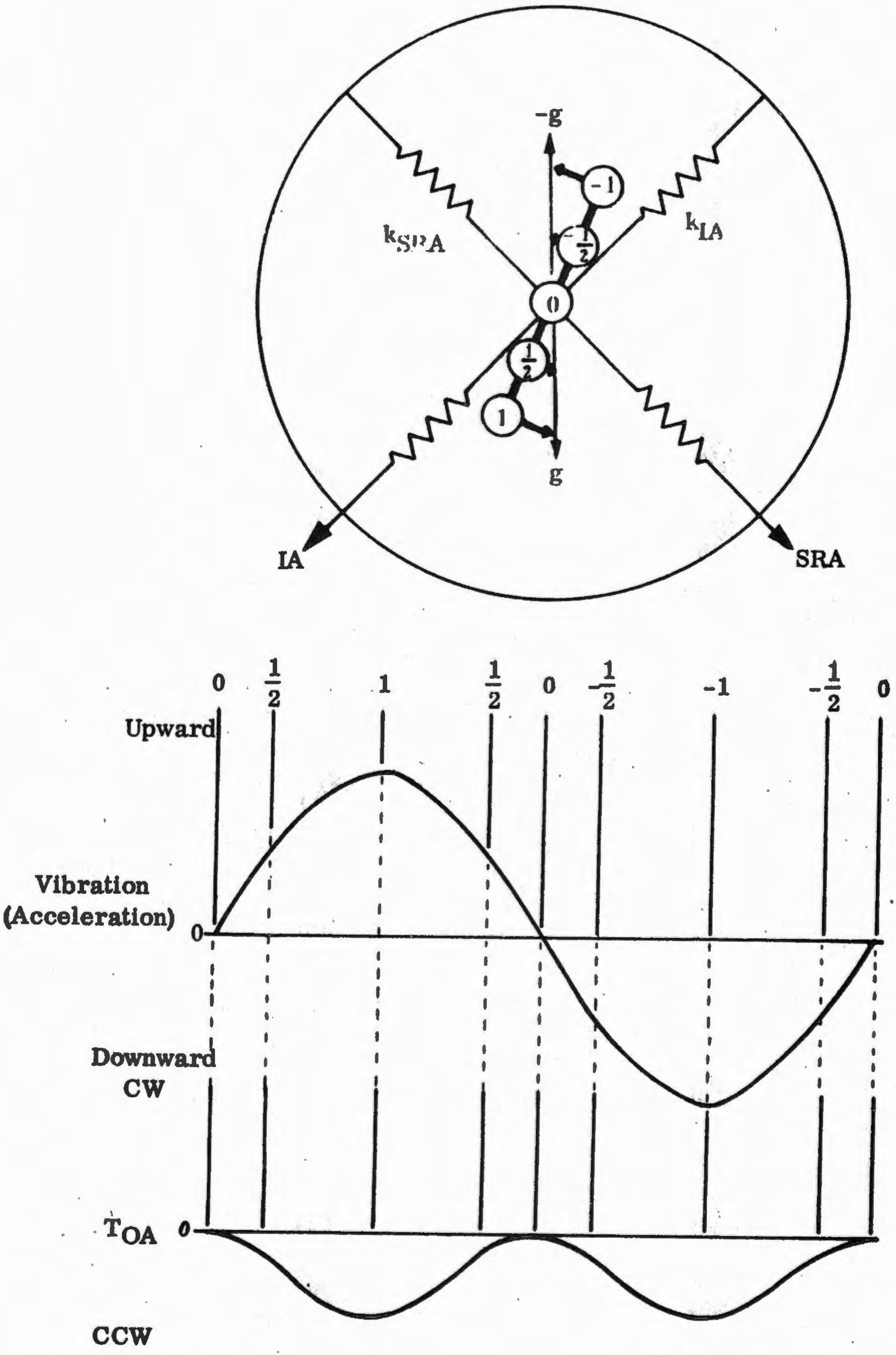


Figure 2-4. Compliance Torque from Vibration

3. RESIDUAL UNBALANCE TORQUE

Residual unbalance consists chiefly of two unbalances, one due to power lead unbalance and one due to microsyn reaction torque. Since these torques are constant for any given gyro (as opposed to mass unbalances and compliances that vary with gyro orientation), they are combined as R.

Power lead torque arises because the electrical leads to the gyro wheel motor are not perfectly positioned, so that the residual torques of opposing leads do not cancel. To attempt to overcome this unbalance, the motor power leads are made of fine ribbon, curved for flexibility. Microsyn reaction torque is due to unbalances of magnetic forces acting on the microsyn rotors. These two torques are independent of gyro orientation, and are constant when the gyro is operating at null with steady microsyn excitation currents.

D. FLOAT INERTIA TORQUE $I_{OA}\alpha_{OA}$

As is the case with damping torque, this is a dynamic torque produced whenever the float is accelerated about OA.

E. ELASTIC RESTRAINT TORQUE $k\theta_{OA}$

This torque is dependent upon float position, with respect to the outer case, as though there were a spring attached between the float and the stationary outer housing. Elastic restraint torque results from changes in microsyn reaction torque and flex lead torque with float displacement from null.

F. TORQUE GENERATOR TORQUE T_{TG}

This is a control input which may or may not be applied. When used, its functions are to compensate for unbalances, produce float rotations for test purposes, and to produce servo controlled motions about IA.

G. OTHER TORQUES

Only the most significant torques have been discussed; the performance of any practical gyro is affected by numerous other second order torques, including byoyant pendulosity torque, fluid motion torque, and uncertainty and friction torques.

SECTION III

GYROSCOPE CONSTRUCTION

A. WHEEL ASSEMBLY

1. WHEEL

AC Spark Plug gyro wheels are usually made of stainless steel or Inconel. A composite wheel, consisting of a beryllium web and a Graphmo steel rim, has also been used. The wheel shafts are usually made of 52100 steel or Invar. The most important consideration in the design of a wheel assembly is to combine thermal expansion characteristics of the materials so that center of gravity shifts with temperature are eliminated. Other desirable characteristics are high density and structural rigidity.

The wheel cross section may vary in different gyros, but the general design aim is to provide the greatest moment of inertia consistent with adequate strength and sufficient heat dissipation. The purpose of the composite wheel, as well as of the wheel cross section shown in figure 3-1, is to concentrate as much weight as possible in the rim (since $I = \Sigma m r^2$).

Hysteresis ring, synchronous motors drive the gyro wheels at high angular velocities. The angular velocity of the 10^7 and 2×10^5 gyro wheels is 12,000 rpm, while that of the 25 PIG and 25 IRIG wheels is 16,000 rpm. The velocity of the 10^4 accelerometer gyro, on the other hand, is only 8,000 rpm.

2. BEARINGS

As shown in figure 3-1, the gyro is assembled to the shaft with a matched pair of ball bearing assemblies. Each assembly consists of an inner and outer race, a lubricant impregnated ball retainer, and steel balls. An inner and outer spacer (figure 3-2) separate the races of the two bearings and provide the proper amount of preload. Preloading is achieved and controlled by the use of spacers of different thicknesses between the bearings. The magnitude of the preload is such as to constrain the axial movement of the wheel to a rotational plane at right angles to the shaft. At the same time the amount of preload cannot be so high as to introduce excessive bearing friction that would limit bearing life. (At the present time bearing life is the major limiting factor in useful gyro life at AC Spark Plug.) The importance of correct preload can be demonstrated by a numerical example. Suppose that the gyro wheel shaft is horizontal, so that the full effect of gravity can act on any unbalance. Suppose further than the gyro wheel is displaced one millionth of an inch (10^{-6} in) from

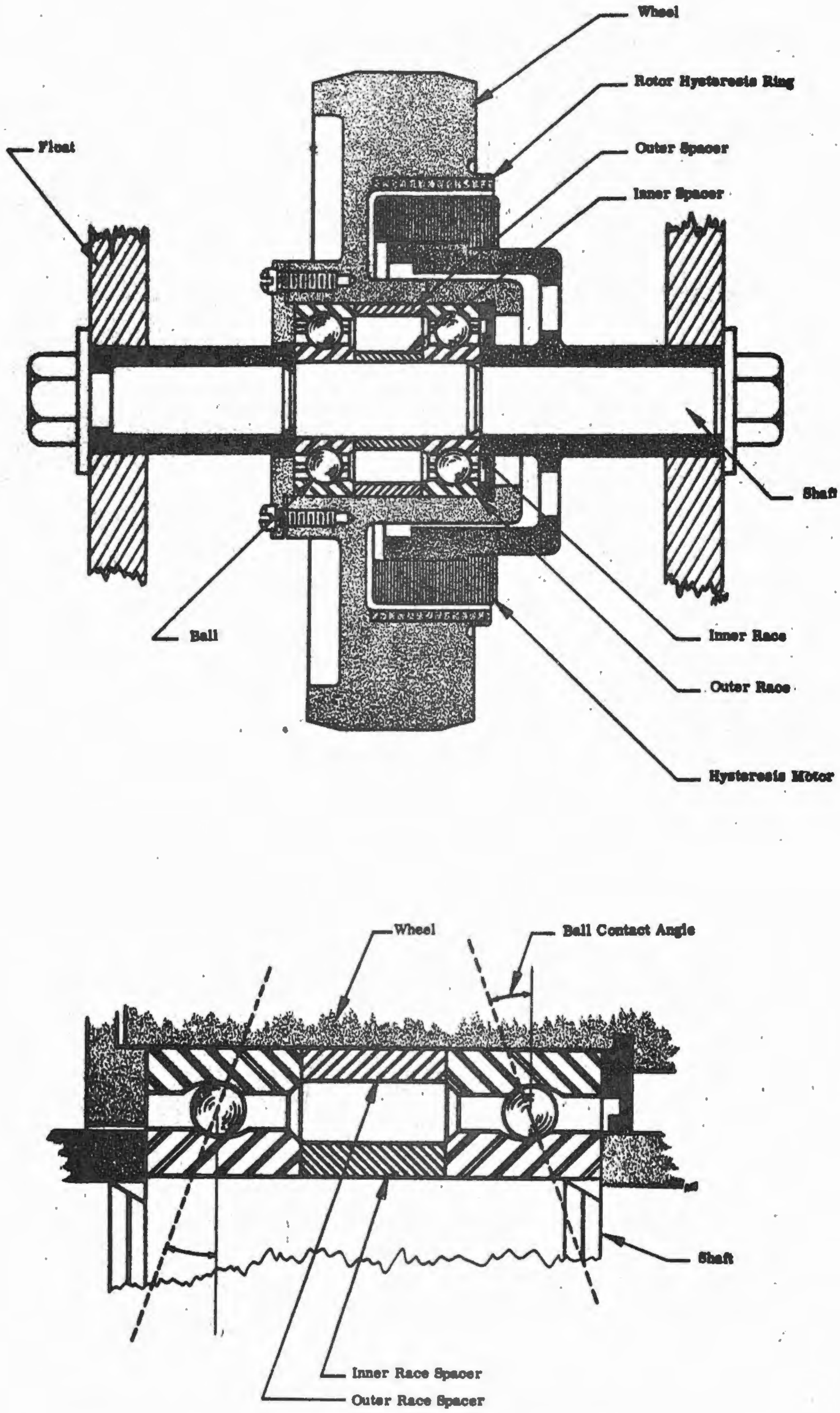


Figure 3-1. Cross Section of Gyro Wheel Assembly

its original rotational plane (thus causing an unbalance). Now the torque on the float of a 10^7 gyro can be computed as follows:

$$T_{OA} = mad$$

where

m (mass of gyro wheel) = 700 gms
a (accel. due to gravity) = 980 cm/sec^2
d (displacement of wheel) = 10^{-6} in
= 2.54×10^{-6} cm.

$$T_{OA} = 700 \times 980 \times (2.54 \times 10^{-6}) \text{ gm cm}^2/\text{sec}^2$$
$$= 1.74 \text{ dyne-cm.}$$

Or, this torque can be converted into an equivalent precessional input due to earth rotation (in MERU) by rearranging the equation for precessional torque ($T_{OA} = H\omega_{IA}$) to solve for input rate,

$$\omega_{IA} = \frac{T_{OA}}{H},$$

and substituting in the appropriate values

$$\omega_{IA} = \frac{1.74 \text{ dyne-cm}}{10^7 \text{ dyne-cm-sec}}$$

$$\omega_{IA} = 17.4 \times 10^{-8} \text{ rad/sec.}$$

Now, since

$$1 \text{ MERU} = 7.29 \times 10^{-8} \text{ rad/sec,}$$

$$\omega_{IA} = \frac{17.4 \times 10^{-8} \text{ rad/sec}}{7.29 \times 10^{-8} \text{ rad/sec}}$$
$$= 2.4 \text{ MERU.}$$

The techniques of measuring preload are indirect, most methods depending upon the known relationship between preload and wheel run-down (deceleration) time. The common method of establishing preload in a 10^7 wheel during assembly is as follows. The partial wheel assembly is put into a fixture without an inner race spacer. The desired amount of preload (in pounds) is then applied to one inner bearing race by means of a spring or by weights. The wheel run-down time and deceleration rate are then noted for this setup, and an inner race spacer is selected that will just duplicate this run-down time and deceleration.

To measure preload on the 25 PIG and IRIG gyros, on the other hand, the amount of breakaway torque is measured (the amount of torque required to accelerate the wheel from a dead stop). On the 25 PIG and IRIG gyros, the wheel package, after assembly, is vibrated translationally along the SRA and then again at 90 degrees to this axis (corresponding to the IA). The resonant frequencies of the wheel package in the two modes of vibration should be very close to each other. While this method, of course, does not measure preload in any absolute sense, it does attempt to make the compliances along SRA and IA equal.

3. WHEEL/BEARING BALANCING

Before a wheel and bearing assembly is installed, it is balanced to prevent forced vibrations in the gyro. The balancing operation equalizes centrifugal force on either side of two mutually-perpendicular planes that bisect the wheel. These are shown in figure 3-2a. Rather than equalize the mass to achieve balance, the mass distribution is adjusted so the two halves of the wheel develop canceling centrifugal forces. Centrifugal force is developed according to the following relationships.

$$Fc = \Sigma Fi, \text{ and}$$

$$Fi = mi\, r\omega^2$$

where

Fc is the net centrifugal force

Fi is the force on individual wheel particles

mi is the mass of the individual wheel particles

ω is the wheel angular velocity

Thus, a nonhomogeneous wheel having twice as much mass on one half as on the other half would be balanced — that is, centrifugal forces on both halves would be equal, if the greater mass were arranged at half the radius of the other. That is the principle followed in balancing gyro wheels. Despite the variety of conditions that cause unbalance, mass is removed from the outer rim only. There are two reasons for doing so:

a. Less material need be removed from the rim to effect the necessary change in Fi because of its greater distance from center $F = m r \omega^2$,

b. The rim, being thicker than the rest of the wheel, is not seriously weakened by the drilling away of material.

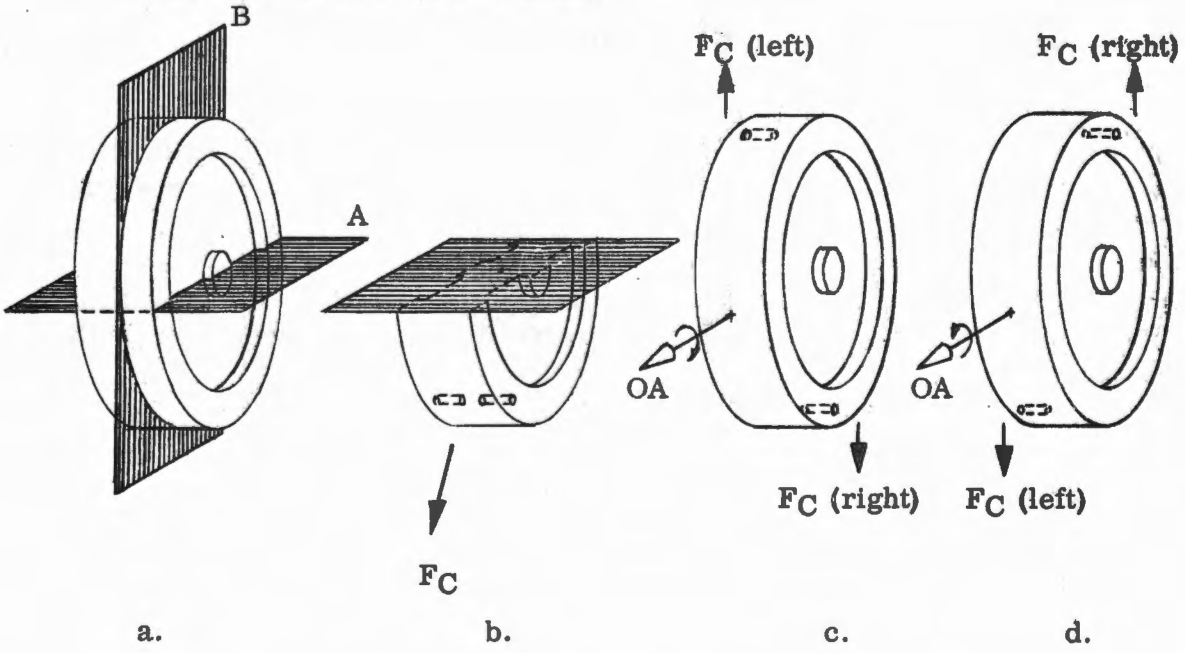


Figure 3-2. Wheel Assembly Balancing

Unbalance is detected through the forced vibrations created by the rotating wheel. In the unbalance detector, the wheel shaft is suspended by springs. At either end of the shaft are the armatures for electromagnetic pickoffs. An unbalance of centrifugal force moves the entire assembly. This movement, sensed by the pickoffs, indicates the amount and location of material that should be removed. For example, a radial motion of the wheel assembly indicates the summations of Fi developed above and below the A plane are not equal. In case the assembly is drawn outward with the lower half of the wheel, material is removed from the lower half as shown in figure 3-2b. The place on the wheel circumference from which material should be removed is pinpointed by interpreting the phase of the pickoff signal.

The condition causing the radial motion could also have been detected by suspending the wheel and observing its reaction to gravity. This is a static check and unbalances that can be sensed in such a manner are static unbalances. There are other unbalances, of the type discussed below, that register only during a dynamic check. In order to complete balancing with a single setup of equipment, AC Spark Plug employs the dynamic check being described. As an example of dynamic unbalance, a twisting motion of the wheel assembly indicates the summations of Fi developed to the left and right of the B plane are unequal. In case the pickoff signals denote a clockwise motion of the wheel in figure 3-2a, the centrifugal force on the upper left quarter of the wheel exceeds that on the lower left quarter; and the force on the lower right quarter exceeds that on the upper right quarter. The difference in force for both halves of the wheel can be represented by vectors as in figure 3-2c, which have components that tend to twist the wheel — in a clockwise direction in the orientation shown in figure 3-2c and in a counterclockwise direction 180 degrees later, when the wheel is oriented as in figure 3-2d. Drilling away material in the manner shown balances the centrifugal forces and the wheel operates smoothly.

If an unbalanced wheel were installed in a gyro, its performance and reliability would be seriously affected. The radial forces developed by any unbalance cause the bearing to wear excessively. The twisting forces resulting from dynamic unbalance would modulate the gyro output at the wheel rate, as though there were high-frequency alternations about the gyro IA. This condition has an undesirable effect on servo loop performance, loading the amplifiers and in some cases setting up oscillations in the gyro or its mount.

4. MOTOR

The gyro wheel spin motor consists of:

a. A wound pole stator rigidly affixed to the gyro float,

b. A magnetic hysteresis ring attached to the gyro wheel,

c. The gyro wheel which forms the rotor of the hysteresis motor.

The hysteresis motors used in AC Spark Plug gyros have either four poles per phase or six poles per phase, and all operate from two-phase power. The speed of the motor is a function of the frequency of the excitation voltage, as shown by the formulae.

$$\text{revolutions per second} = \frac{2\phi}{p} \times f \qquad (3\text{-}1)$$

where

ϕ = number of phases
p = total number of poles
f = frequency of excitation voltage in cycles per second.

Note that frequency is the only variable in equation 3-1. In most AC Spark Plug gyros, the wheel motors produce speeds in excess of 10,000 rpm and consume less than 10 watts of power at voltages up to 45 vac. The only load imposed on gyro wheel motors is the bearing friction (a function of preload) and windage. The ratio of this load to input power is the efficiency of the motor, which is typically about 45 percent. The hysteresis motor has the property of maintaining at synchronous speed any load

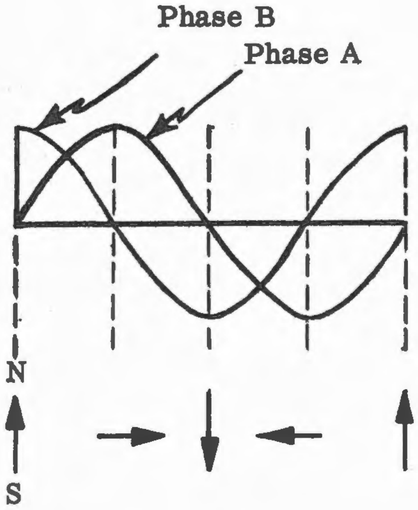


Figure 3-5. Flux Vectors in Stator

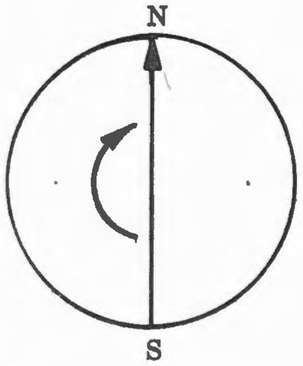


Figure 3-6. Rotating Magnetic Field in Stator

The particles of a magnetic substance have both "north" and "south" poles. In an unmagnetized sample of this material the orientation of the north and south poles is random. If the north pole of a bar magnet is moved transversely along the material; however, some of the particles align their south poles in the direction of the magnet's north pole. Some of the particles that were aligned retain their south pole alignment when the magnet is withdrawn, others do not. If a sufficient number of the particles retain their induced south pole alignment, the material is magnetized, and becomes a "permanent" magnet with its south pole in the direction described.

Two quantitative measurements are applied to the magnetizing process described: magnetic intensity (H), measured in oersteds, and magnetic induction, or flux density, measured in gausses. These quantities will be related to the example given. Magnetic intensity is a measure of the force that the north pole of the magnet exerts on the south poles of the particles. This force is defined as follows: if two poles of equal strength exert a force (either attractive or repulsive) of one dyne when placed one centimeter apart, each pole is a unit pole (has a magnetic intensity of one oersted). Once the pole strength of a magnet is known, it can then be placed in any magnetic field and the intensity of that field measured by determining the force exerted on the magnet by the field.

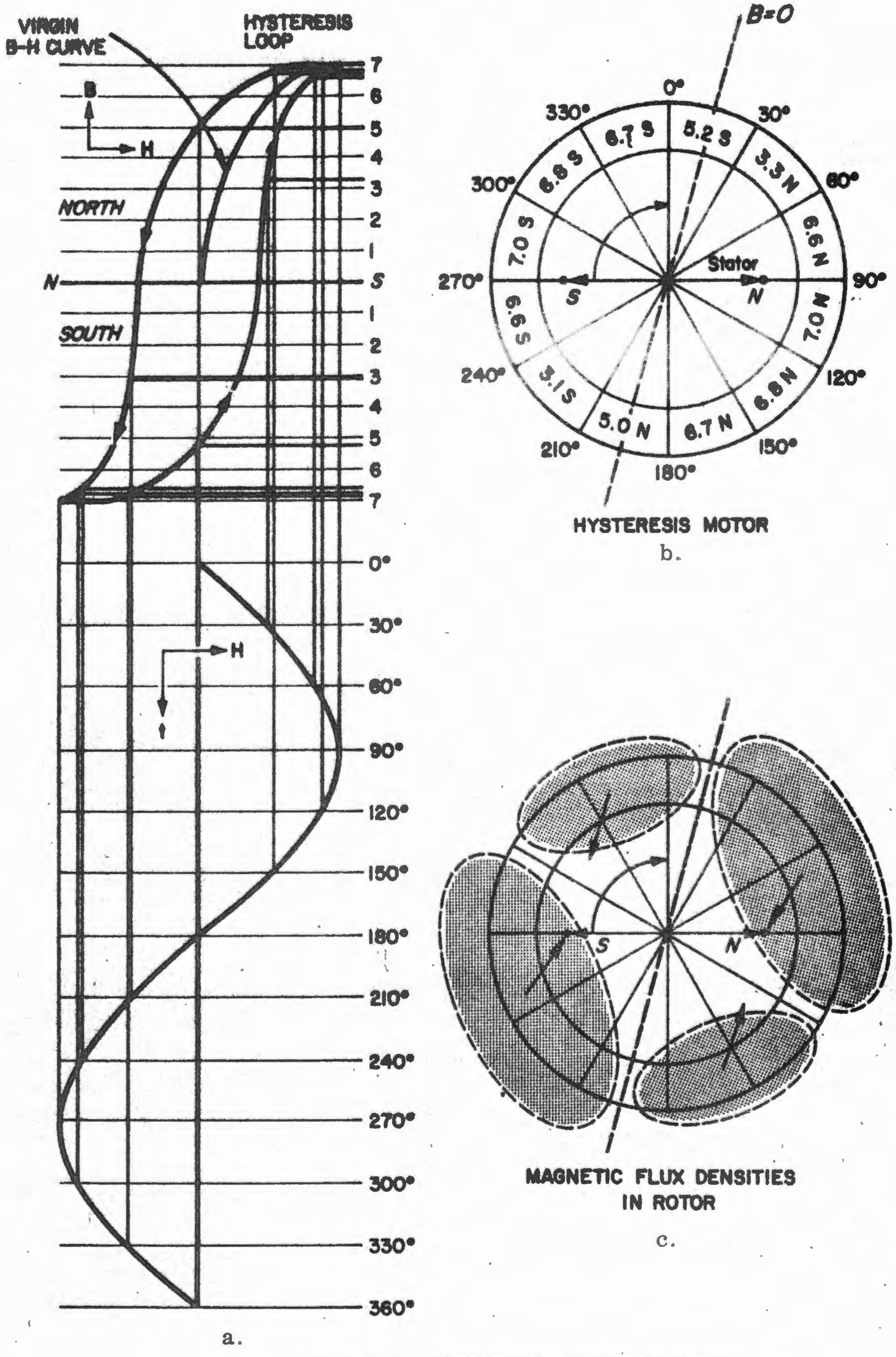
In an electromagnet (stator pole) the magnetic intensity is dependent upon the current producing the magnetic flux in the coil. It is evident from the foregoing that the force exerted on a particle is dependent upon the distance of the magnet from the particle. Thus, the particles closest to the magnet experience a maximum force, while those farther from the magnet (both ahead of and behind it) experience a lesser force. In the gyro wheel then, the particles are subjected to the magnetic intensity of the rotating magnetic field in the stator. The rotating field is magnetizing the particles in the wheel, and the attraction and repulsion of these particles to the field causes rotation.

The other quantity to be defined is magnetic induction, or flux density. Again, it will be related to the example cited. It was said before that some, but not all, of the particles in the magnetic material were aligned and retained their south pole alignment. The percentage of the particles that become aligned is a measure of the flux density (B), measured in gausses. (Not all of the particles in a given material can be aligned. Flux density considers the percentage of those particles that are aligned). Flux density is a function of H and of the type of material being magnetized.

The magnetizing process can be further illustrated by plotting magnetic intensity (H) vs. magnetic induction (B). The virgin B-H curve in figure 3-7a shows that B grows larger as H increases, until a point is reached where the material saturates (all of the particles that can be aligned are aligned). However, as H is decreased B does not decrease along the virgin B-H curve, but follows the lagging course indicated by the arrows. As H reaches 0, a large value of B still remains. As H is increased in the opposite direction, B continues to fall and reaches 0; but as H is increased still more B again increases, but now in the opposite direction until saturation of the opposite magnetic polarity is reached. A large value of B remains as H is again reduced to 0, but B continues to decrease as H is again increased in the forward direction. This curve is the hysteresis loop. (In a stationary piece of magnetic material this loop is traced out at the frequency of the voltage creating the magnetic flux. In the case of the gyro wheel motor, however, this is true only at standstill; at other times the hysteresis loop is traced out at a frequency dependent upon the relative motion between the rotor and rotating magnetic field.) Hysteresis, then, is defined as the lag between B and H.

Returning to the gyro wheel motor, let us examine the effect of the rotating fields from the stator (H) as it induces a field (B) in the hysteresis ring, which is assumed to be stationary in this case. As shown in figure 3-7b the rotating field is drawn as a N - S arrow.

If we examine the effect of the field upon the iron particles at some fixed spot in the hysteresis ring, say at 0 degrees, we see the particles exposed to a magnetizing force (H) varying sinusoidally with time. (H is shown as a sine wave below the hysteresis loop drawing shown in figure 3-7a.) Therefore, in one cycle that segment of the ring experiences the various levels of induction (B) shown in one traverse of the B-H loop.



a.

HYSTERESIS MOTOR
b.

MAGNETIC FLUX DENSITIES
IN ROTOR
c.

Figure 3-7. Hysteresis Motor Operation

If we now freeze the rotating field in the position shown in the figure after it has been rotating, we are able to examine the condition of the iron in the ring at various positions in its circumference, and observe that in moving once around the ring, we see all the B levels occuring in one traverse of the B-H loop. The values of B corresponding to H at every 30 degrees of rotation are obtained by projecting lines from the H curve to the hysteresis loop at 30 degrees multiples on the H curve. These values (in thousands of oersteds) and the magnetic polarities are shown on the corresponding rotor segments in the drawing to the right of the hysteresis loop. It is important to note that the zero value of B (represented by the dotted line) does not coincide with 0 degrees on the rotor (due to the hysteresis lag) but falls between 0 degrees and 30 degrees. Summing up the flux densities to the left of the dotted line with respect to the stator south pole shows an area of induced north poles attracted to the south pole. However, the area is weak in the vicinity of 30 degrees and contains less than a 90 degree segment of the ring. In contrast, the area below the south pole from 90 degrees to the zero line is large with a strong north orientation remaining at 180 degrees. The net force therefore is such as to produce rotation of the rotor following that of the stator. A similar situation is seen to exist to the right of the dotted line, with the induced south poles attracted to the rotating north stator pole.

The magnetic field in the motor stator rotates at high speed (the exact value being determined by equation 3-1), and a hysteresis loop is traced out for every particle on the rotor for each cycle of the excitation voltage. This, in turn, means that each particle on the rotor will correspond to some point on the hysteresis loop at any given instant. Accordingly, the instantaneous values of H and B in figure 3-7b can be shown, even though these values are changing very rapidly as the field and rotor are rotating.

The foregoing describes the events occurring at standstill and during wheel runup, when the wheel is not in synchronism. Since the torque upon the hysteresis ring was considered to be a function only of the angle between the induced field in the ring and the stator field, it follows that the torque of the ideal motor is constant from zero to synchronous speed if excitation is constant.

As the wheel nears synchronism, the rate at which the field sweeps any particular spot on the ring becomes less, and that spot traverses the B-H loop slower and slower. Finally, at synchronism, the wheel locks in, and the condition is exactly that shown in figure 3-7c with fixed poles in the ring rotating at the speed of the field at the lag angle shown.

If the excitation is now switched off suddenly, the poles remain, producing a generator action that is useful in measuring deceleration of the wheel.

a. Overexciting

It is observed that some wheels, when running synchronously, run at less current after a momentary increase in excitation voltage. The reason for this is that the torque required to maintain synchronism is fixed, consisting of friction and windage.

Overexciting strengthens the fixed poles in the rotor, so the motor can develop the same torque with a weaker stator field and the current drops. If in subsequent running the stronger poles gradually weaken, the current gradually climbs.

b. Demagnetizing

Demagnetizing of the wheel consists of removing the poles "permanently" established in the rotor at synchronism. In general, demagnetizing of iron is done by forcing it to repeat B-H loops that are gradually shrinking in size, due to gradual reduction of H, ultimately to zero. It is obvious then that demagnetizing cannot be done at synchronous speed since the iron in the rotor cannot traverse the B-H loop. The procedure thus consists of dropping the wheel from synchronism, if it is at synchronous speed, raising the excitation voltage above the normal value to traverse a larger than normal B-H loop, and then gradually reducing excitation to zero.

Another graphic illustration of the hysteresis lag is shown by plotting H and B on the same time scale as shown in figure 3-8. The arrow in the figure represents the time lag between the H and B curves.

B. GYRO FLOAT

The gyro float is a thin aluminum cylinder in the 10^7 gyro, and a hollow beryllium sphere in the 25 PIG and IRIG gyros. The float houses the wheel and motor assembly. In the 10^7 gyro the float is the wheel gimbal, while on the 10^4 gyro one float end cap is the gimbal structure. In all cases, shafts that are an integral part of the float extend outward from the float to mount the microsyn rotors and float pivots. In addition, devices for balancing the float (both rotationally and endwise) are provided on the float. It is very important that the outside diameter of the float be held within close tolerances since the clearance between the float and main housing is very small. Of equal importance is the concentricity of float, pivot, and rotor diameters.

After the wheel and motor have been installed in the float and checked out, and end caps are applied, the float is evacuated, and helium allowed to flow in. The float is sealed when the helium pressure reaches atmospheric pressure (14.7 lbs/in^2) in the case of the 10^7 gyro, and at about one-half atmospheric pressure in the case of 25 PIG and IRIG units. There are several reasons for using helium in the float. The principal advantage is that the helium acts as a good conductor of heat away from the spin motor. Also, there is little windage generated with helium, and it is easily identified by leak detectors to check on the quality of float seal.

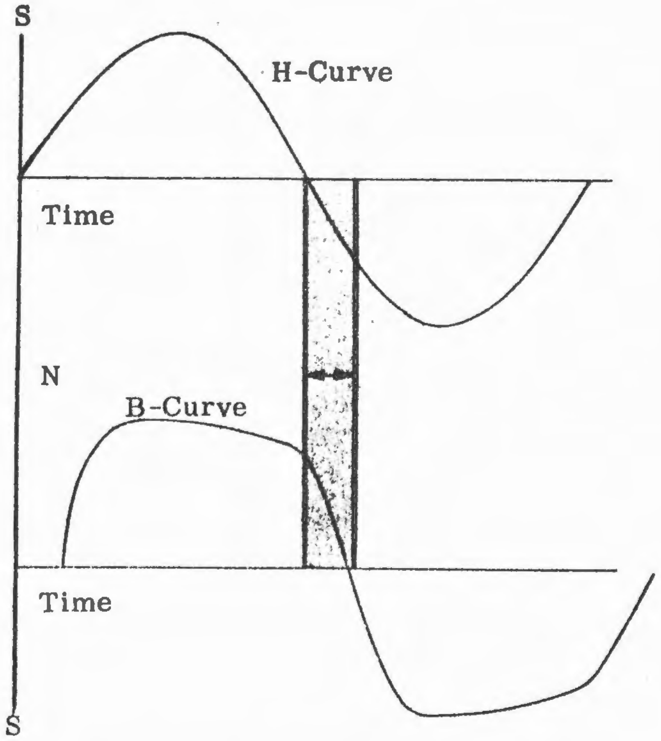


Figure 3-8. Hysteresis Time Lag

In order to better understand the buoyant action of the flotation fluid (Fluorolube) on the float, and the rotational balancing of the float which will be considered later it would be well to review the principles of buoyancy at this time.

The specific gravity of a solid, liquid, or gas is the ratio of its weight to the weight of an equal volume of water.

$$\text{Sp. Gr.} = \frac{\text{weight of object}}{\text{weight of equal volume of water}}$$

Since specific gravity is a ratio, the units in numerator and denominator cancel and it is a pure number. To illustrate this in a slightly different manner, it can be said, for example, that glycerin is 1.26 times as heavy as water (since Sp. Gr. of glycerin is 1.26).

In the metric system, water was chosen as the standard unit of mass, so that, by definition, one cubic centimeter of water weighs one gram. Because of this choice of units, the density of any substance (weight per unit volume: $D = W/V$) in the metric system is numerically equal to the specific gravity of that substance.

If a solid is placed in a liquid, the solid exerts a force downward upon the liquid equal to the weight of the solid. The liquid also exerts a buoyant force upward on the solid, equal to the mass of the fluid displaced. (This is Archimedes' principle.) The net result of the action of these two forces is related to specific gravity, as follows:

If the specific gravity of the solid is greater than the specific gravity of the liquid — the solid sinks.

If the specific gravity of the solid is less than the specific gravity of the liquid — the solid floats.

If the specific gravity of the solid is equal to the specific gravity of the liquid — the solid is suspended; i.e., remains at whatever level in the liquid that it is placed.

The latter situation is the case of AC Spark Plug "floated" gyros. The density, and hence the specific gravity, of the Fluorolube is adjusted (by means of temperature control) to just equal the specific gravity of the gyro float and contents. Hence, the float is suspended in the fluid so that the tungsten carbide pivots are centered in the jewel bearings and (at least theoretically) do not actually touch the bearings. The advantages of this "flotation" are: no loading on the pivots, viscous damping (and hence integrating action), and cushioning effect against shock. The drawback of flotation, of course, is that close temperature control must be maintained in order to realize the ideal suspended condition.

The gyro float must be balanced both longitudinally and rotationally in order to make the center of buoyancy (C_b) and the center of gravity (C_g) coincident and lying on the line of pivot centers (C_p). Note that the center of buoyancy is dependent upon the volume of the float and that the center of gravity is dependent upon the mass of the float,

Figure 3-9 illustrates these two centers in a float that has an unbalance (greatly exaggerated).

The center of gravity, C_g, is positioned so that it is the midpoint of the total mass. In the absence of other forces, an object is stable rotationally about its C_g; i.e., if suspended at its C_g the object can be rotated to any position and will remain in that position until disturbed. The center of buoyancy, C_b, on the other hand, is the midpoint of the volume of the object, which, in the case of objects that have regular shaped outer surfaces, is the geometric center of that surface.

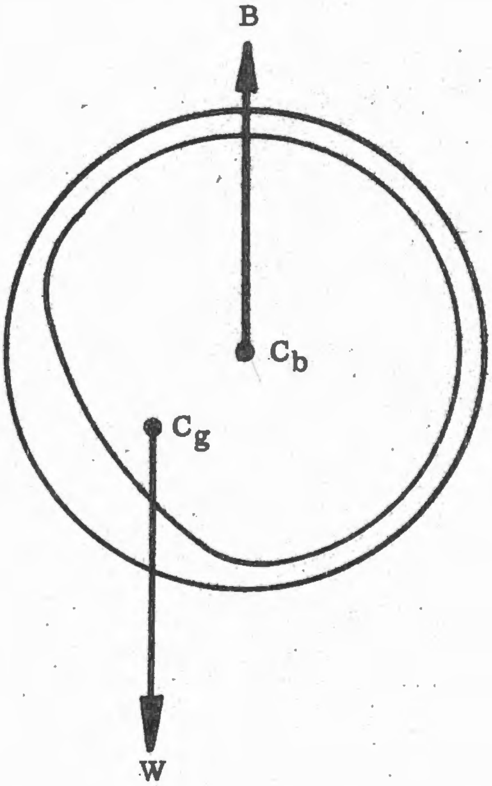


Figure 3-9. Gravitational and Buoyant Centers of the Float

1. ROTATIONAL BALANCING

Figure 3-10 illustrates the possible conditions of orientation of C_g and C_b, as viewed from the end of the float. In figure 3-10a, the float weight W acting through C_g and the buoyant force B acting through C_b are on opposite sides of a vertical line drawn through C_p. The buoyant force produces a clockwise torque Bx about the pivot centers, the float weight adds a clockwise torque, Wy and an obvious rotational unbalance is seen.

In figure 3-10b the C_g and the C_b lie on the same side of the vertical line and the clockwise torque Wy is opposed by the counterclockwise torque Bx. A special case of this condition may arise in which Bx = Wy and the float appears to be rotationally balanced in the position shown. However, rotation of the float exposes the condition.

In figure 3-10c is shown another special case of figure 3-10b where C_g and C_b are in line longitudinally and x = y. If W = B, the float appears to be balanced at any orientation. This condition is undesirable in the finished gyro, since temperature of the fluid controls its density and hence the magnitude of B, so that large torques may be produced with temperature change. During balancing this condition is eliminated by altering B, either by balancing at each of two temperatures, or in two fluids.

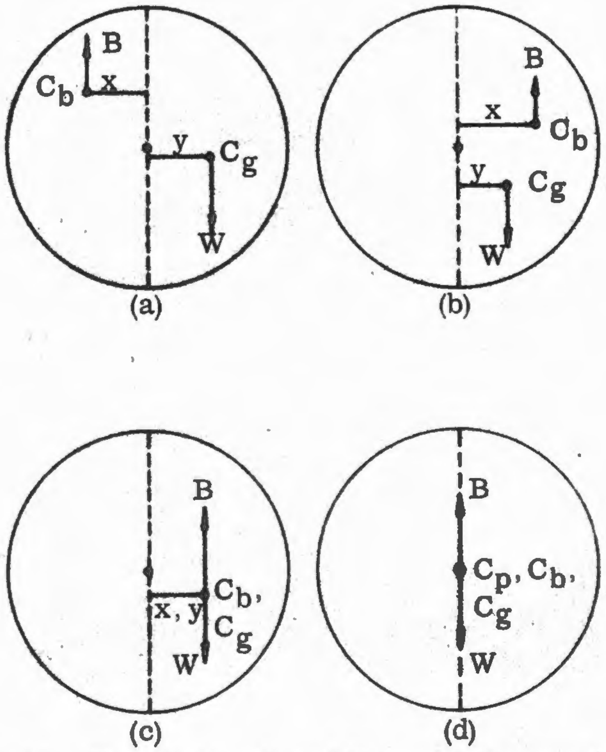


Figure 3-10. Gravitational and Buoyant Forces Acting on the Float

Figure 3-10d shows the ideal case after rotational balancing in which C_g and C_b lie on the line of pivot centers, but are not necessarily coincident.

Rotational balancing, in order to achieve figure 3-10d, consists of altering independently the locations of C_g and C_b, and the magnitudes of the gravitational and buoyant forces, W and B. This is accomplished by adding to or removing from the float ends balance weights that have a density just equal to that of the flotation fluid. The rotational balance of the 10^7 stabilization gyro is refined until a torque of 100 dyne-cm will just rotate the float in either direction.

2. LONGITUDINAL BALANCING

Figure 3-11 shows possible positions of C_g and C_b prior to longitudinal balancing. The weight of the float needed to achieve flotation at a given operating temperature is calculated, the float is then weighed, in air, and the weight adjusted, if necessary, to agree closely with the desired flotation weight.

One method of securing float longitudinal balance (in use on 10^7 gyros) will be described in general terms. Because the balancing operation is to be performed at room temperature, it is necessary to prepare a fluid that will just suspend the float.

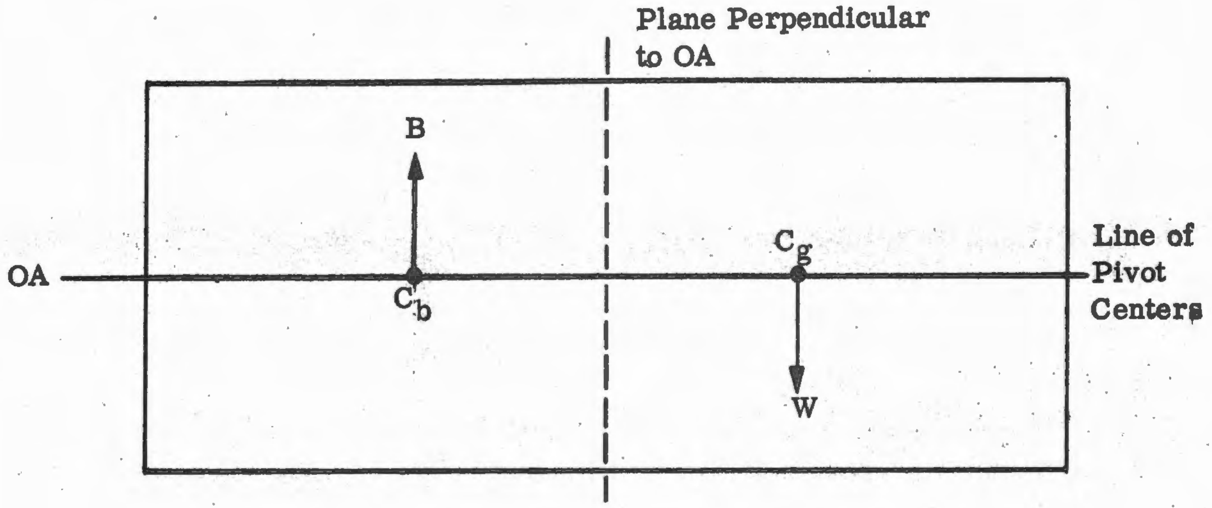


Figure 3-11. Float Longitudinal Balancing

A plummet of known density is used to obtain the desired fluid density. The weight of the plummet in any given density fluid can be calculated and that fluid density obtained by mixing two fluids, one of density greater than the plummet density and one of lesser than plummet density, until the plummet weighs the calculated weight when submersed in the mixture. Once the fluid is of desired density, balance weights are adjusted until the float is longitudinally balanced, as indicated by equal weights (within 30 milligrams) on the scale pans. The rotational balance is checked and corrected, if necessary, after completing the longitudinal balancing.

C. MICROSYNS

The microsyn is an electromagnetic device that has a wound-pole stator and an unwound rotor. Both four-pole stators with two-pole rotors and eight-pole stators with four-pole rotors are in use at AC Spark Plug. Depending upon the manner in which the windings are connected, the microsyn can be used to produce:

1. A voltage proportional to the rotational displacement of the rotor from its zero or reference position (movement of gyro float with respect to case), in which case the microsyn is called a signal generator
2. A torque that is a function of the currents through the primary and secondary windings, in which case the microsyn is used to torque the gyro float and is called a torque generator
3. Magnetic forces that will cause the rotor to remain, both axially and radially, at the geometric center of the stator bore (magnetic suspension).

At AC Spark Plug the four-pole microsyn is used in applications (1) and (2), while the eight-pole instrument is used to provide (1) and (3) together and (2) and (3) simultaneously. The signal and torque generator functions will be discussed with reference to a four-pole microsyn, it being understood that the principles are also applicable to the eight-pole device. Magnetic suspension will be explained with reference to an eight-pole microsyn.

1. SIGNAL MICROSYN

The signal microsyn converts rotations about OA into electrical signals. Its stator, containing four wound poles encapsulated in a potting compound, is rigidly affixed to the gyro case, and the unwound rotor, or slug, is attached to the gyro float and rotates between the poles, with a very slight air gap between the rotor and pole faces. (See figure 3-12.)

Each pole is wound with an input winding, excited with low voltage alternating current, and an output winding. When the rotor is at the null position (as shown in the drawing), the voltages induced in opposite secondary poles are equal in magnitude but 180 degrees out of phase with the voltages induced in the secondary poles 90 degrees away. Any rotation of the rotor causes the voltage in one pair of output poles to be greater than that in the other pair of poles, and the voltage difference is the signal output of the microsyn. This result is caused by the fact that the rotor movement presents greater rotor pole area between one set of poles and lesser rotor pole area between the other set of poles. The greater or lesser area of metal increases or decreases, respectively, the lines of magnetic flux between the poles, hence altering the voltage output. The flux paths between the poles are shown in figure 3-13. Observe that the direction of flux travel through the poles can be determined by applying the right hand rule to the direction of primary windings on the poles in figure 3-12.

The manner of connecting the windings on the signal generator can be made clearer by considering the equivalent electrical circuit shown in figure 3-14. The dots indicate the direction in which the various poles are wound with respect to each other, and hence the instantaneous polarities of the poles with respect to one another. If we assume instantaneous primary current flow into P_2 and out of P_1, we may place primary polarity dots as shown, with the dot at the top of the winding indicating flux flow toward the rotor. Polarity dots may be similarly chosen for the secondary, assuming current flow into S_2 and out of S_1. Observe that the secondary windings of poles 1 and 3 "aid" their primary windings, whereas the secondaries of poles 2 and 4 "oppose" their primaries.

The operation of the signal microsyn can be explained by means of figures 3-13 and 3-14, and by the use of vectors representing the magnitude and phase of the output

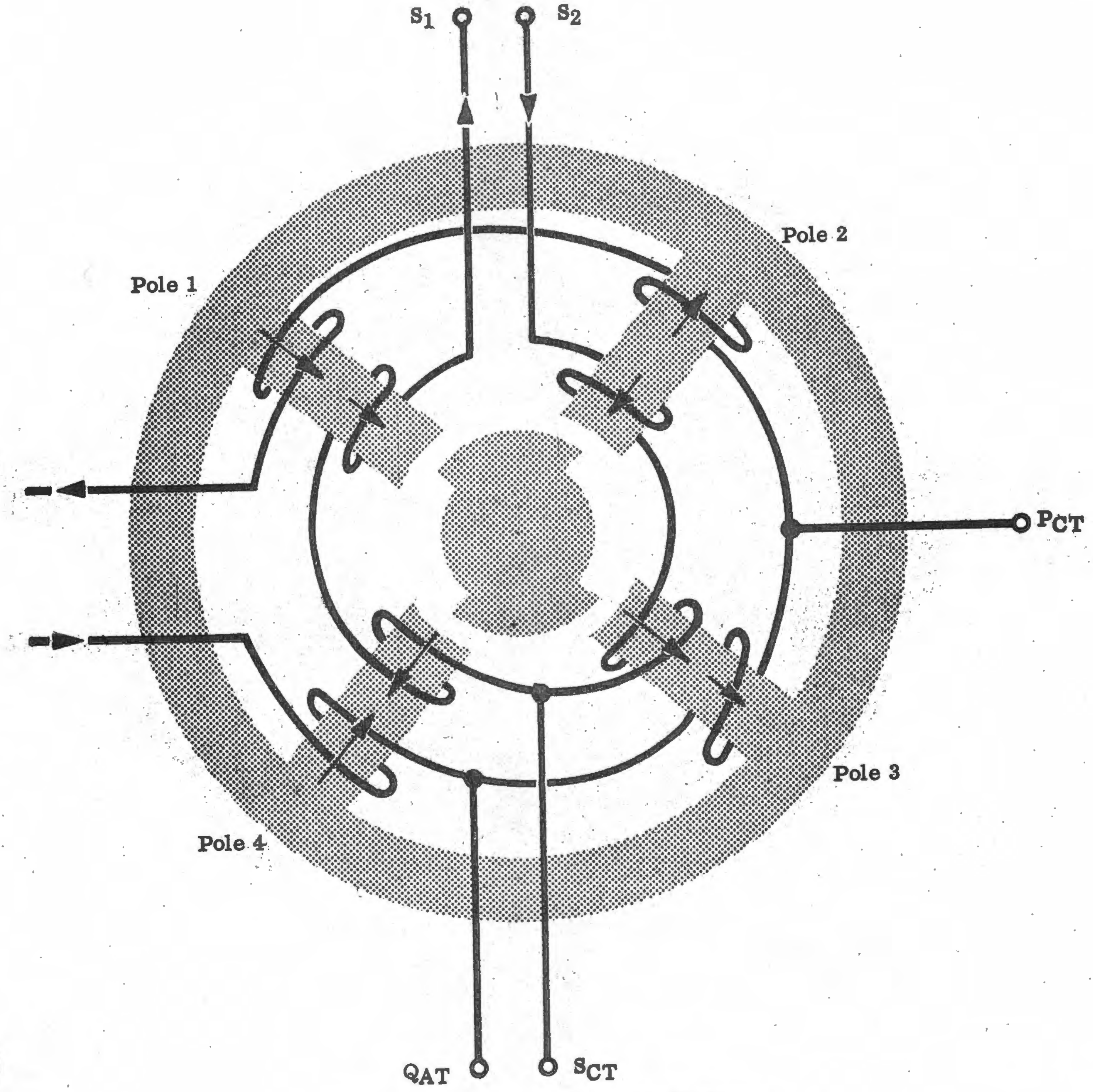


Figure 3-12. Signal Microsyn Windings

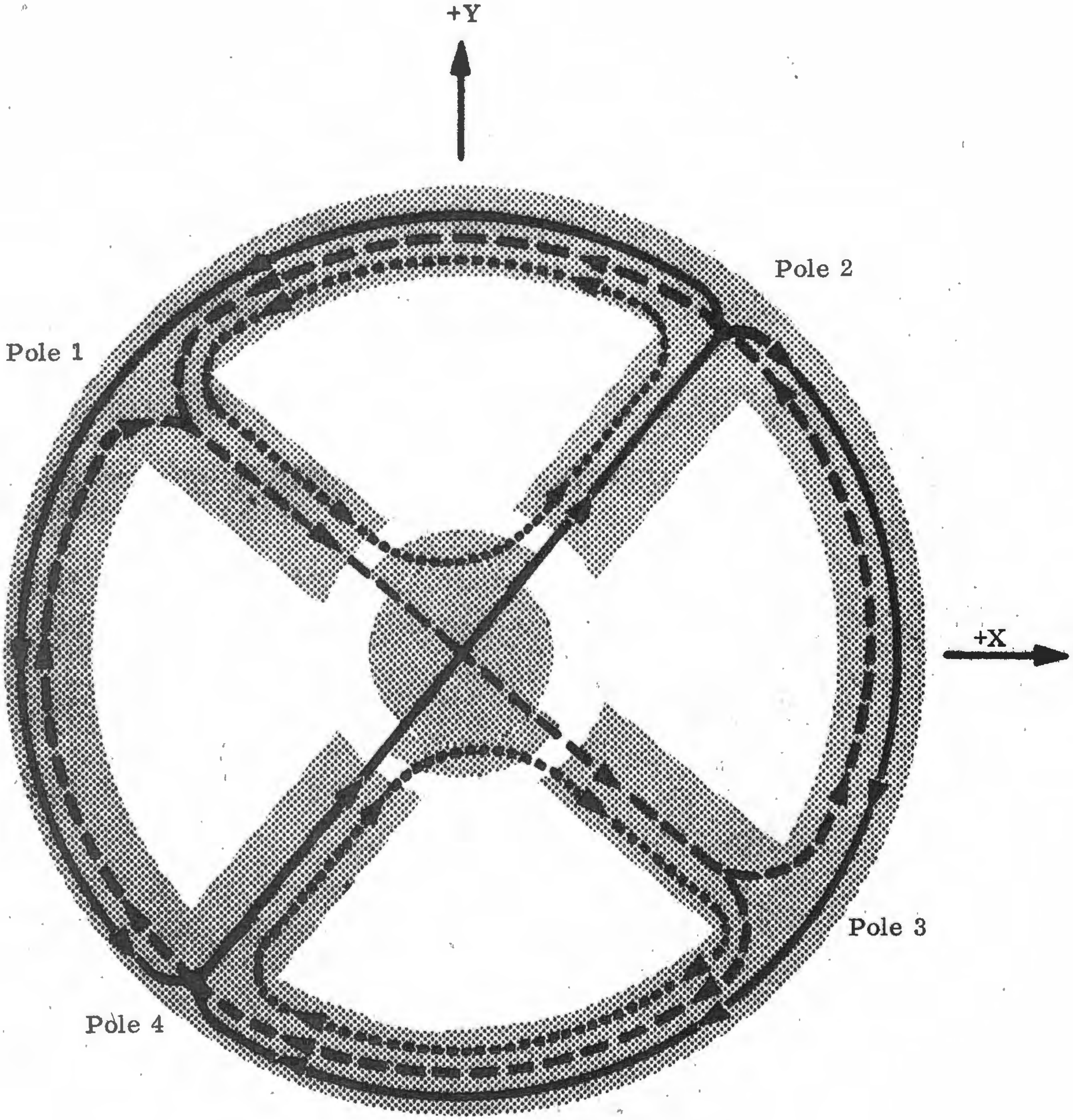


Figure 3-13. Flux Paths in Signal Microsyn

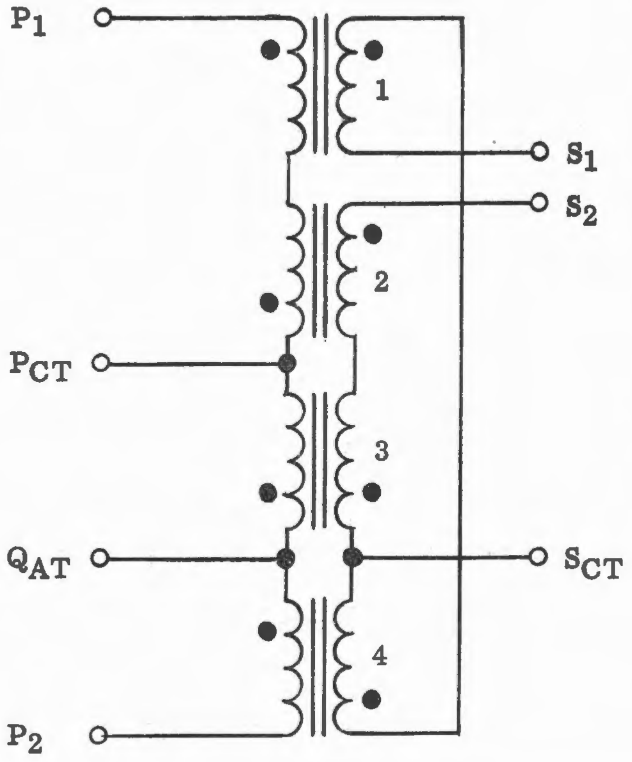


Figure 3-14. Signal Microsyn Equivalent Circuit

voltages (secondary windings) of the poles at various rotor orientations. For this purpose, let the null voltage of the microsyn be represented by vectors one inch in length, and let the phase of the voltages from poles which have their primary and secondary wound in the same direction (poles 1 and 3) be represented by vectors pointing to the right side of the page, and let the voltages of the other phase (poles 2 and 4) be represented by vectors in the opposite sense. Various cases of rotational and translational displacement of the rotor with respect to the poles will be examined in this manner. In the first five cases P_1 - P_2 are excited, and the output is measured between S_1 - S_2.

a. Case 1 — Rotor at Null Position

Referring to figure 3-13, it can be seen that with this rotor orientation the air gap between the rotor and each of the poles is the same. Therefore, the dotted line flux paths give rise to magnetic fields of equal intensity, and the dashed lined and solid lined paths will produce equally strong fields. The output vectors, then, will be

and no output voltage (actually a "null value" of output voltage) will result.

b. Case 2 — Clockwise Rotation of Rotor

Again referring to figure 3-13, the dotted line flux paths remain the same, since poles 2 and 4 gain only as much rotor area as is lost by poles 1 and 3. The solid line path, however, is strengthened (more rotor area under poles 2 and 4) while the dashed line path is weakened (less rotor area under poles 1 and 3). The vector representation is obtained by increasing the length of vectors 2 and 4 while decreasing the length of 1 and 3:

The net result is an output voltage, the magnitude and phase of which are represented by the combination of the four vectors: $\overline{V} = (2 + 4) - (1 + 3)$ or

c. Case 3 — Counterclockwise Rotation of Rotor

In this similar case, the dotted line flux paths remain unchanged, but the dashed line path is strengthened while the solid line path is weakened.

The result is the voltage vector.

d. Case 4 — Translation of the Rotor in the +X Direction (See figure 3-13)

The result is the same as in Case 1. (And the vectors are the same so will not be redrawn here.) The dotted line paths are essentially unchanged, since poles 1 and 4 "lose" as much rotor area as is "gained" by poles 2 and 3. Similarly, the dashed line path is not altered since the flux linkage between the rotor and pole 3 is strengthened, but only by the same amount that the linkage between the rotor and pole 1 is weakened. In the solid line path, pole 4 is weakened.

e. Case 5 — Translation of the Rotor in the +Y Direction

The dashed line and solid line flux paths are unaltered. However, the dotted line flux path between poles 1 and 2 is strengthened, while the dotted line path between poles 3 and 4 is weakened. The vector result is

but no net output is produced. Therefore the signal microsyn output is shown to be sensitive to rotation (cases 2 and 3) and yet insensitive to radial translation (cases 4 and 5). This feature is important since some jewel-pivot clearance exists in all gyros.

f. Case 6 — Translation of Rotor in +Y Direction; $P_1 - P_2$ Excitied; Output Measured Between S_1 and S_{CT}

This case is the same as case 5, except that only half of the output (poles 1 and 4) is measured; thus, the vector representation is

which yields the resultant vector

g. Case 7 — Rotor Centered; $P_1 - P_{CT}$ Excited; Output Measured Between $S_1 - S_2$

With only half of the primary excited (poles 1 and 2) the flux paths are as shown in figure 3-15.

Note that the two flux paths through pole 3 are traveling in different directions, and that this is also true of pole 4. Therefore, in the rotor centered case there will be zero output from these two poles. Since there are equal air gaps between all poles, the outputs from poles 1 and 2 will be equal in magnitude also but out of phase. There is, accordingly, no voltage output in this case, as shown by the vectors:

h. Case 8 — Rotor Translated in +Y Direction; $P_1 - P_{CT}$ Excited; Output Measured Between $S_1 - S_2$

The flux paths in poles 2 and 1 are strengthened and those in poles 3 and 4 weakened. However, since both the paths in pole 4 are weakened an equal amount, and both the paths in pole 3 are weakened an equal amount, there is still no output from these two poles. The vectors representing the voltages from poles 1 and 2, therefore, are enlarged, but still cancel each other so that there is no net output from the microsyn, as shown by the vectors.

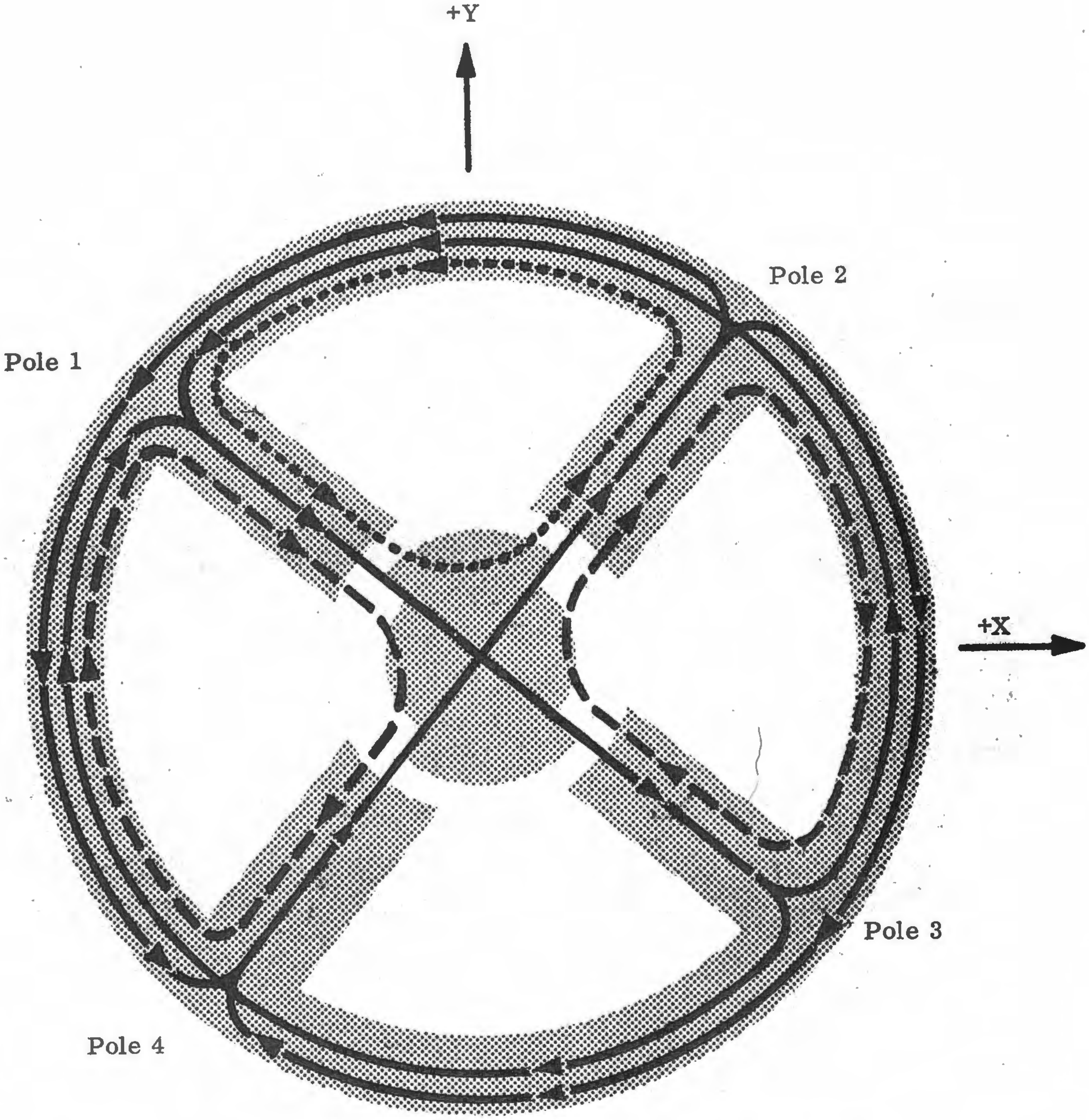


Figure 3-15. Flux Paths When P_1 - P_{CT} is Excited

i. Case 9 — Rotor Translated in +X Direction; P_1 - P_{CT} Excited, Output Measured Between S_1 - S_2

The dotted flux path between poles 1 and 2 is unaltered; but, due to the dashed line flux path between poles 2 and 3, pole 2 grows slightly larger than pole 1. Now, considering poles 3 and 4: the solid line flux linkages remain unchanged, but the dashed line path through pole 3 is increased, and the dashed line path through pole 4 is decreased. Hence, there will be an output from poles 3 and 4. Observe that the flux increase in both poles is in toward the rotor (positive increase of dashed line path in pole 3 and relative increase of solid line path in pole 4). Therefore, the voltages in 3 and 4 will be additive. In order to determine whether the phase of poles 3 and 4 is the same as that of pole 1 or pole 2, we redraw the equivalent electrical circuit of the microsyn. Since the primary excitation is across P_1 - P_{CT}, primary poles 3 and 4 are drawn in dotted lines as shown in figure 3-16. The dots assigned to all of the secondary windings remain the same, but those given to the phantom primaries 3 and 4 are drawn as if the effect seen in the secondaries of 3 and 4 (resultant flux into the rotor) was caused by primary 3 and primary 4. (In initially assigning dots to the primaries, the convention was used that a dot at the top of the winding indicated flux into the rotor; the dots on the secondaries were then placed according to whether the direction of winding was the same or opposite that of the primary.) Having assigned the dots to the phantom primaries of windings 3 and 4, we see that their relation to their secondaries is the same as that for pole 2 (opposite). Therefore, the vectors are as follows:

The net output is then: 

Cases 6, 7, and 9 are used in microsyn centering.

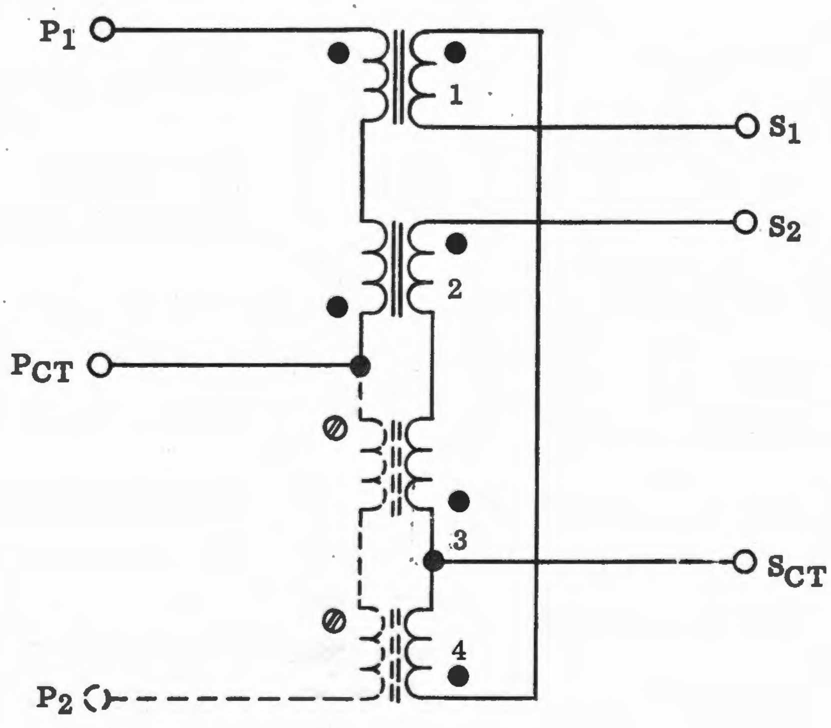


Figure 3-16. Transformer Equivalent of Microsyn When P_1 - P_{CT} is Excited

This completes the explanation of the rotational and translational sensitivity of the signal microsyn. Freedom from the effects of axial movement of the rotor is secured by making the rotor thicker than the stator poles.

The operation of the quadrature adjust tap has yet to be discussed. For purposes of simplifying the foregoing explanation, the vectors representing signal outputs were assumed to lie along a straight line; i.e., vectors 1 and 3 in-phase with the reference voltage and vectors 2 and 4 180 degrees out-of-phase. In actual practice, however, due to small imperfections in manufacture, lack of homogenity in materials, etc., some or all of the vectors might make some small angle with the line representing the reference voltage and also be of different lengths. This line itself lags the primary excitation voltage (by 30 degrees in the case of the 10^7 gyro). Such vectors are customarily resolved into two right angled components: signal voltage (lying along the reference voltage line in figure 3-17 and quadrature voltage (at right angles to the reference voltage line shown as dotted lines in figure 3-17).

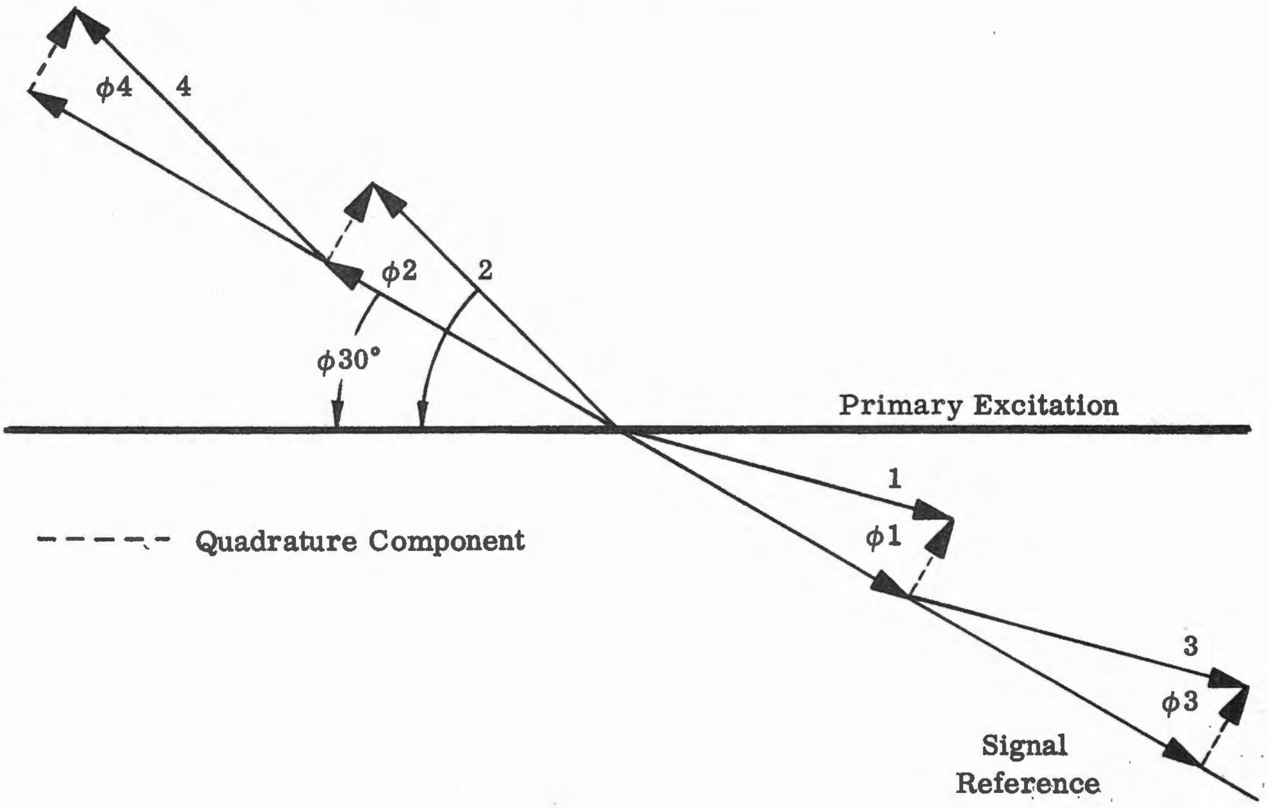


Figure 3-17. Signal and Quadrature Components of Microsyn Output Voltage

It can be seen that, if the original vectors were added by the polygon method, some resultant vector would be produced (due to the phase angles) although a null (0 resultant) should occur. (See figure 3-18.) In order to correct this situation, a resistor (the resistance of which is determined experimentally) is connected to the quadrature adjust tap and across either pole 3 or pole 4.

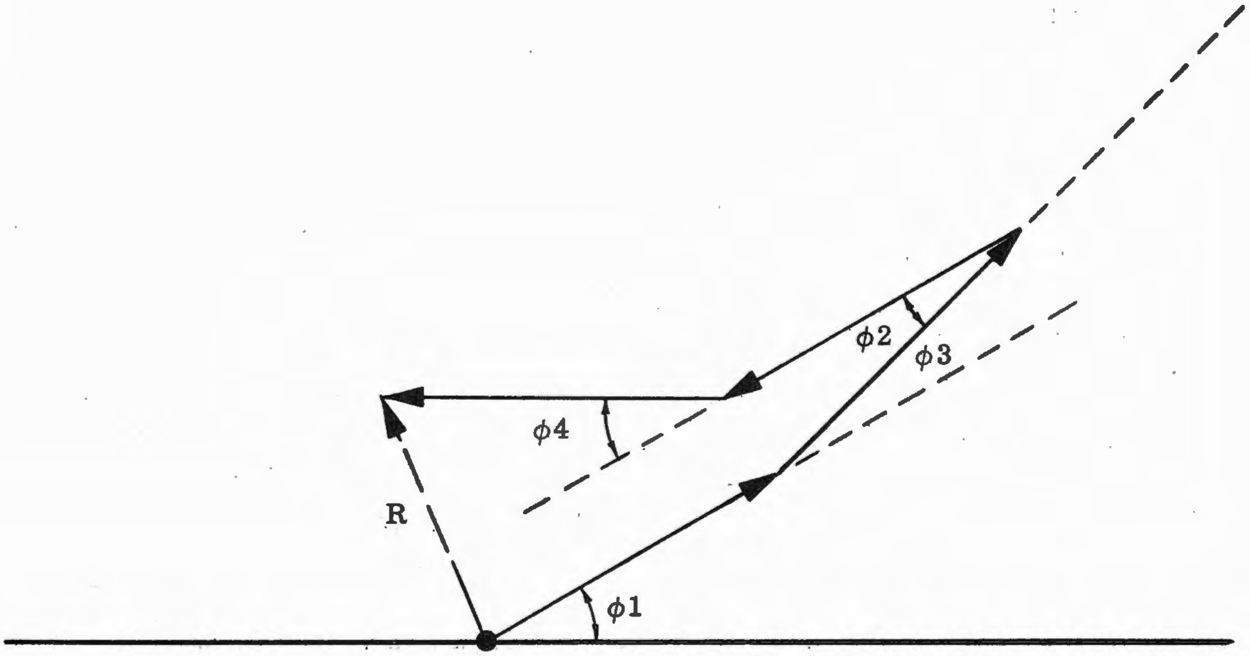


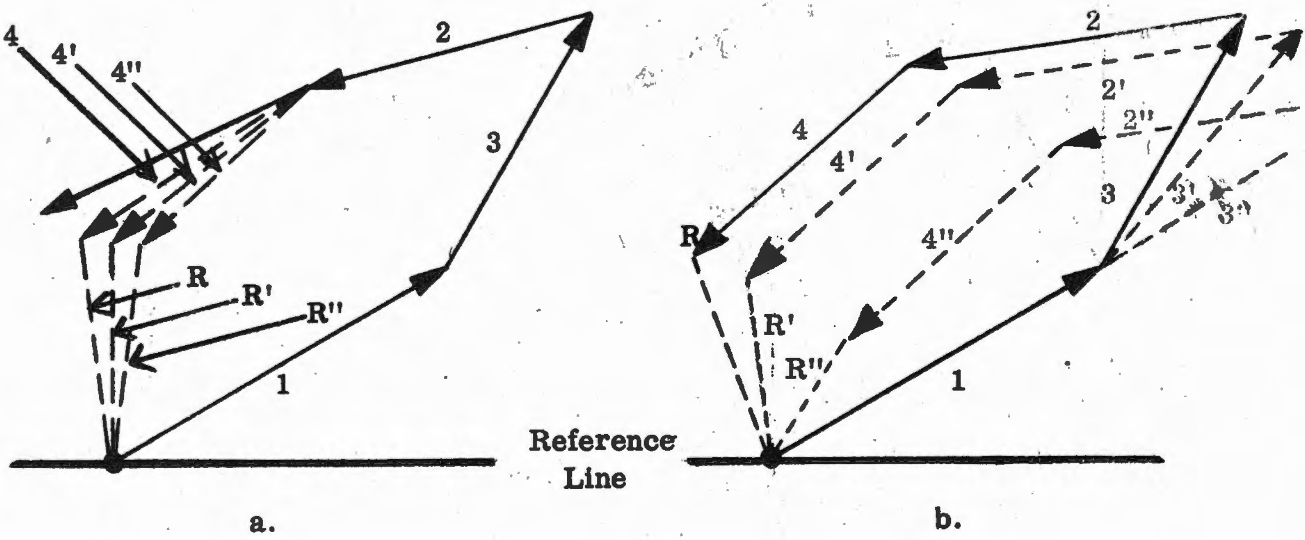
Figure 3-18. Microsyn Error Voltage Due to Quadrature

If connected across pole 4, the effect is to make pole 4 voltage less inductive and more resistive, thereby changing its phase angle. This amounts to rotating vector 4 counterclockwise about the junction between vectors 2 and 4. The resultant vector would be shortened somewhat and rotated clockwise, as shown in figure 3-19a. If the resistor were connected across primary winding 3, that voltage would become more resistive and vector 3, and vectors 2 and 4 connected to it in their same relative positions, would be rotated counterclockwise about the junction of vectors 1 and 3. The end result would be as shown in figure 3-19b. It is likely that connecting the resistor across neither pole will eliminate all of the unwanted vector; in which case the connection is made that will make the resultant as small as possible, and the rotor is rotated slightly (in either direction) and the resistance value trimmed to further reduce the error. By alternately adjusting the resistance value and moving the rotor, the resultant vector is completely eliminated, and the null of the microsyn is determined.

The excitation voltage for the signal microsyn varies from 1-10 vac at 25-125 ma. The sensitivities range up to about 150 mv/mrad.

2. TORQUE MICROSYN

The construction of the torque microsyn is the same as that of the signal microsyn, except for the number of turns in the primary and secondary windings, which are called reference and control windings, respectively. The value of voltage and current



a.

b.

Figure 3-19. Quadrature Adjust Procedure

in the reference winding varies with the specific microsyn application. With current in the reference winding only, the four poles exert equal magnetic forces attracting the rotor and no torque is produced. When the control winding is also energized, a pair of opposite poles strengthen their fields through aiding winding directions, and the remaining pole pair fields weaken through opposing winding directions. Thus a torque is produced. The torque is proportional to the product of the currents in the reference and control windings and is in a direction dependent upon the phase of the currents. From this it can be seen that the sensitivity of the torque generator is measured in dyne-cm/ma^2, and values range from a fraction of one to 150 dyne-cm/ma^2. A method of measuring this sensitivity when the microsyn is installed on a gyro is to let that gyro precess in response to a known earth rate, but to restrain that precession by applying torque to the float through the torque microsyn. Since both the torque and the current are known, the sensitivity of the microsyn can be found simply by forming the ratio. The various rotational and translational cases discussed for the signal generator all have close equivalents in the torque generator and will not be repeated here. The principal difference lies in the application of voltage and the measuring of output. It should be noted that, since the torque microsyn action in producing a torque does not depend upon transformer action, the microsyn may be excited with either ac or dc, whereas the signal generator is an ac instrument only.

3. MAGNETIC SUSPENSION — EIGHT-POLE MICROSYN

Figure 3-20 shows the manner in which the eight-pole microsyn is wound, and the associated flux paths. Note that there are four types of flux linkages shown and there are four of each type. The electrical equivalent circuit and the external connections, are shown in figure 3-21 and 3-22. Note that a capacitor is connected in series with each pair of poles.

The signal and torque generator functions of this microsyn are accomplished in the same manner as they are in the four pole instrument. The secondary windings on poles 1, 3, 5, 7 are wound in phase and the secondaries on poles 2, 4, 6, 8, out of phase with their respective primaries. If the rotor is in its null position, the flux through all poles is equal, and therefore the voltages induced in the series connected secondary windings are equal and cancelling and produce an output of zero. A rotation of the rotor in the clockwise direction (See figure 3-20) will not affect the flux paths of the 8-1 or 6-3 type, but will decrease the reluctance of the 2-4 type, while increasing reluctance of the 7-5 type path. Thus an out of phase voltage results from the stronger, even numbered poles 2, 4, 6, 8.

As in the four pole microsyn it is desired that rotor translation produce no secondary output. Because of the microsyn symmetry, voltages induced cancel each other. For example, if the rotor is moved in the +X direction, flux path 8-1 is strengthened, and path 5-4 weakened. However, secondaries of poles 8 and 1 are opposingly wound, as are secondaries of poles 5 and 4. A similar situation is seen to exist for the other types of flux paths and for translation in any direction.

Radial movement of the rotor is indicated by comparing voltages across the primary coil pairs, as shown by the terminals X and Y on the external circuit diagram of figure 3-22. As shown previously, rotor movement in the X direction increases the flux and hence the primary voltage drop of poles 8 and 1, while decreasing primary voltage drop of poles 5 and 4.

When used as a torque microsyn, a voltage is applied to the secondary windings in order to strengthen or weaken the magnetic fields through certain poles, thus creating a force that tends to rotate the rotor. If a signal in phase with the primary voltage is applied to S_1, the motion will be counterclockwise. An out of phase voltage on S_1 will produce the opposite effect.

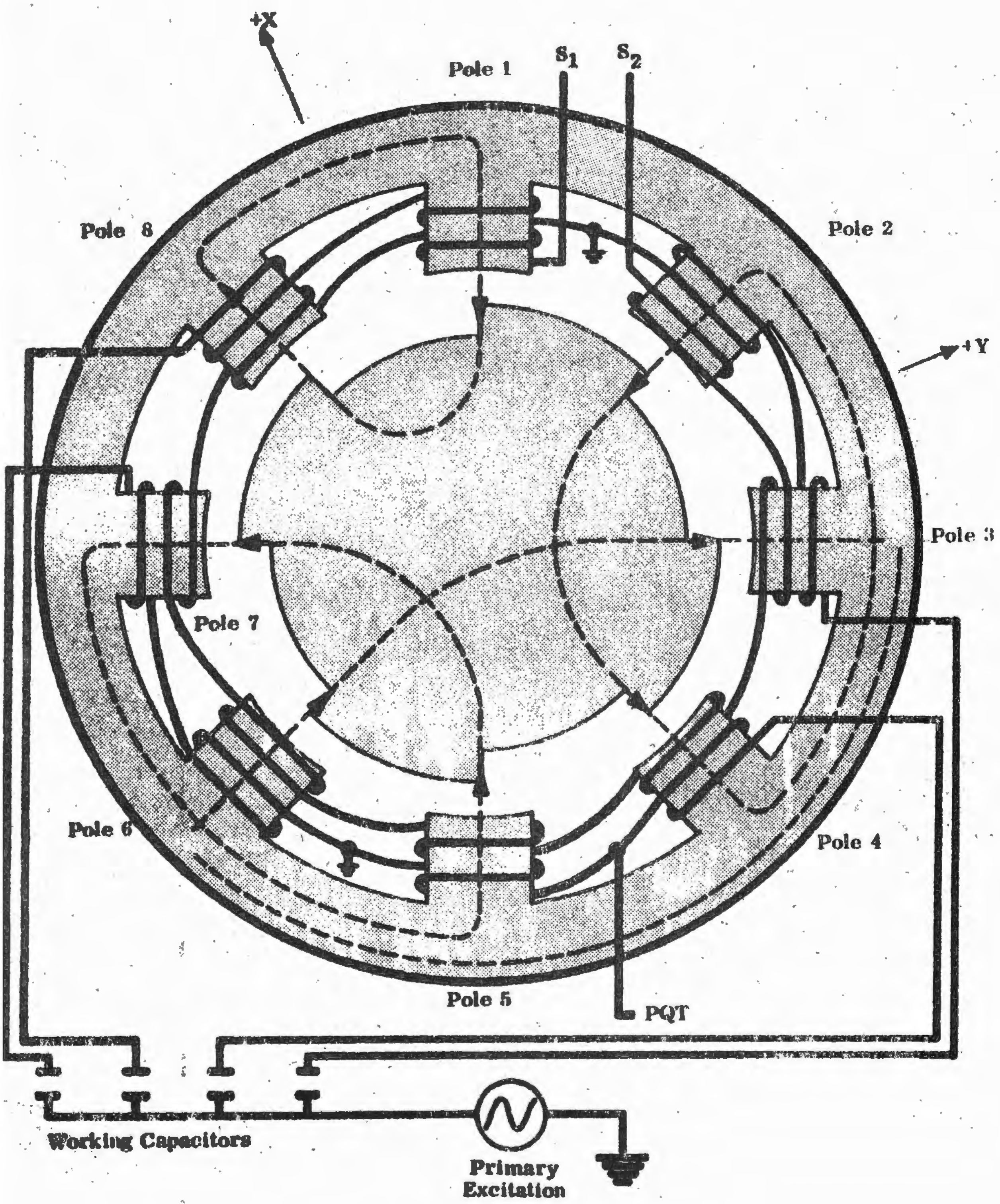


Figure 3-20. Eight-Pole Microsyn

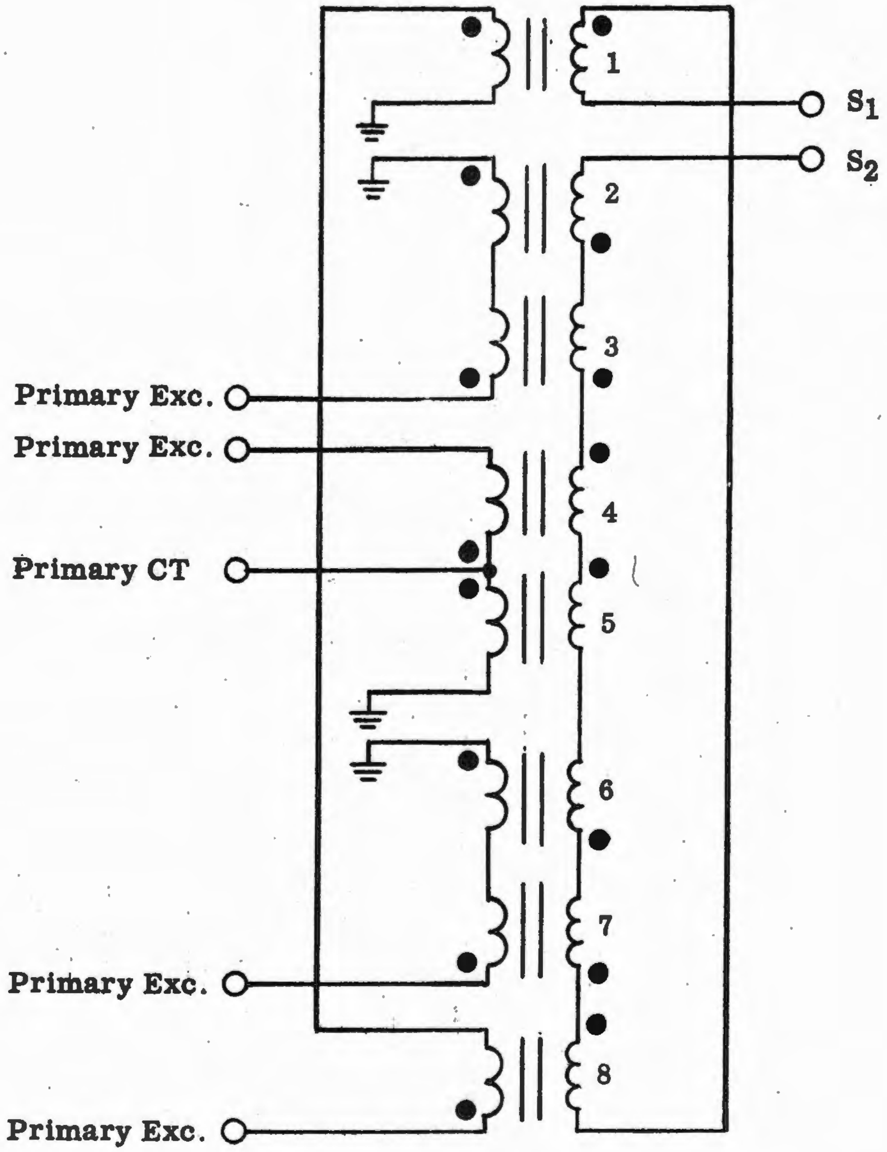


Figure 3-21. Eight-Pole Microsyn Equivalent Circuit

The magnetic suspension property of the microsyn is obtained from the primary windings only. Since the stator windings have inductance (L), there is a restriction to the flow of current through them that is called inductive reactance (X_L); and since pairs of primary windings are connected in series with capacitors, there is within the circuit another restriction to the flow of current called capacitive reactance (X_C). There is also resistance (R) in the circuit (due to the core losses, coil windings, wiring, etc.) which together with the vector sum of inductive and capacitive reactance constitutes impedance (Z).

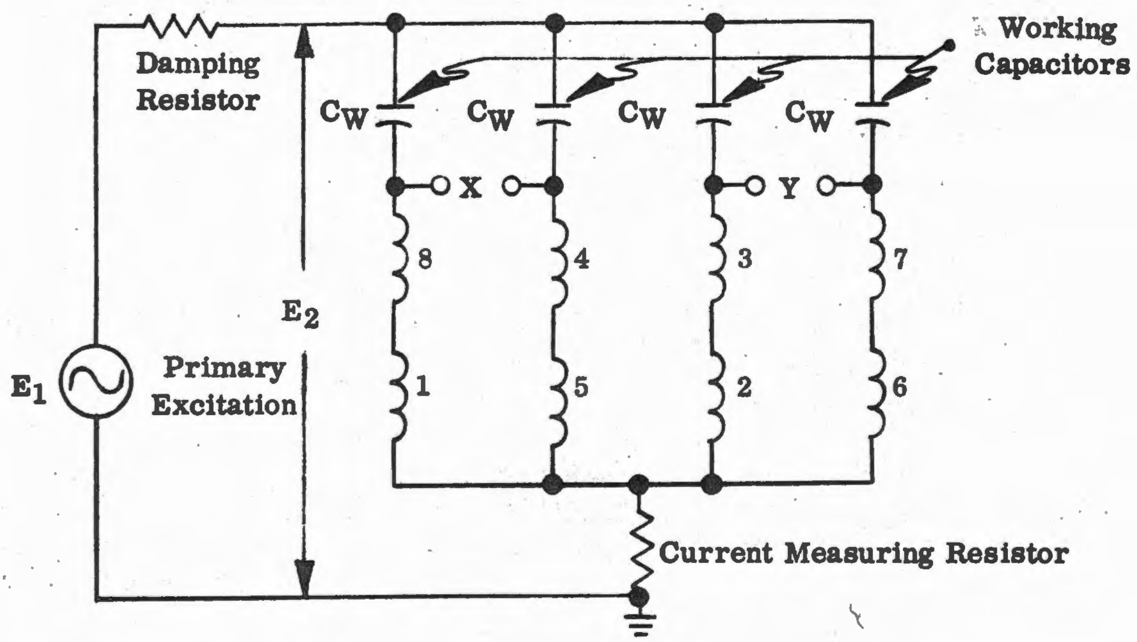


Figure 3-22. External Circuit for Eight-Pole Microsyn

Impedance is a function of frequency (f) and will be a minimum at some frequency called the resonant frequency. When the impedance is a minimum (at the resonant frequency) the current flow will be at a maximum. Since magnetic suspension operates on the principles of reactance, impedance, and resonance (RES), these phenomena will be reviewed in some detail.

a. Capacitive Reactance

With the switch in position 1 in the simple circuit shown in figure 3-23, electrons flow from the negative terminal of the battery to the negative plate of the capacitor, building up a negative charge on that plate; electrons also leave the positive plate of the capacitor and travel to the positive terminal of the battery, thus leaving that plate of the capacitor with a deficiency of electrons, or a positive charge. As the number of charges accumulated on the plates of the capacitor reach a maximum (depending upon the capacitance of the capacitor), those charges begin to repel new charges just arriving at the plates. The current flow decreases and finally comes to a stop, at which time we say the capacitor is charged. If the resistor R in the circuit is very large and the capacitance of C is large, a measurable length of time is required to charge the capacitor. During this time it can be observed that the ammeter reads a maximum amount of current (in the counterclockwise direction say) at the instant the switch is closed, but that this current declines to zero as the charging process is completed. Conversely, the voltmeter reads zero when the switch is closed, but increases to a maximum voltage reading as the capacitor becomes charged. Thus it begins to become apparent that voltage and current are out of phase in a capacitive circuit, with current leading the voltage.

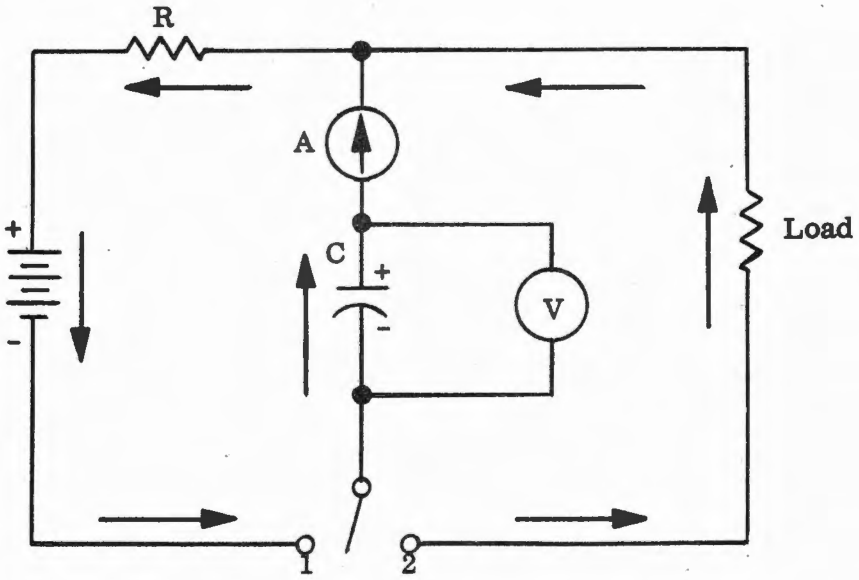


Figure 3-23. Circuit to Demonstrate Capacitance

If the switch is now placed in position 2, the electrons will leave the negative terminal of the capacitor and flow through the load in the direction indicated by the arrows. This current flow will cause the ammeter deflection to be clockwise. The current and voltage will both drop to 0 after a short time (the length of time depending upon the size of the load). This action is called discharging the capacitor. If the polarity of the battery is reversed, the same sequence of events takes place, but the current flow during the charging condition will cause a clockwise deflection of the ammeter, and a counter-clockwise rotation will result upon discharging the capacitor. Since the capacitor operates equally well with current of either polarity, the battery can be replaced with an ac source. With an ac source, the capacitor will charge and discharge once on the positive half cycle, and will also charge and discharge once on the negative half cycle, as shown in figure 3-24. In this figure, current (i) is plotted for one cycle, starting at a maximum (the condition when the switch in the preceding circuit is closed). The small figures beneath the plot show the polarities of ac source and capacitor voltage and the current flow during each quarter cycle. During the initial quarter cycle the current flows CCW and charges the capacitor plates with the polarities indicated. During the second quarter cycle the source polarities change, but those of the capacitor do not; and since the current is zero at the start of the quarter cycle the capacitor starts discharging current in the same direction as the source, thus aiding current flow. At the start of the third quarter cycle the polarity of the source is the same as it was during the second quarter cycle and, since the capacitor is completely discharged, the current starts charging it with the polarity shown. In the last quarter cycle, the source again changes polarity but the capacitor does not and starts discharging in a direction to aid the source. If it were possible to read the voltage across the capacitor throughout the entire cycle, the voltage at every instant could be plotted on the same graph with the current, and would be represented by the dotted curve in figure 3-24. Again, it can be seen that current and voltage are out of phase, with current leading the voltage (by 90 degrees in a circuit with capacitance only).

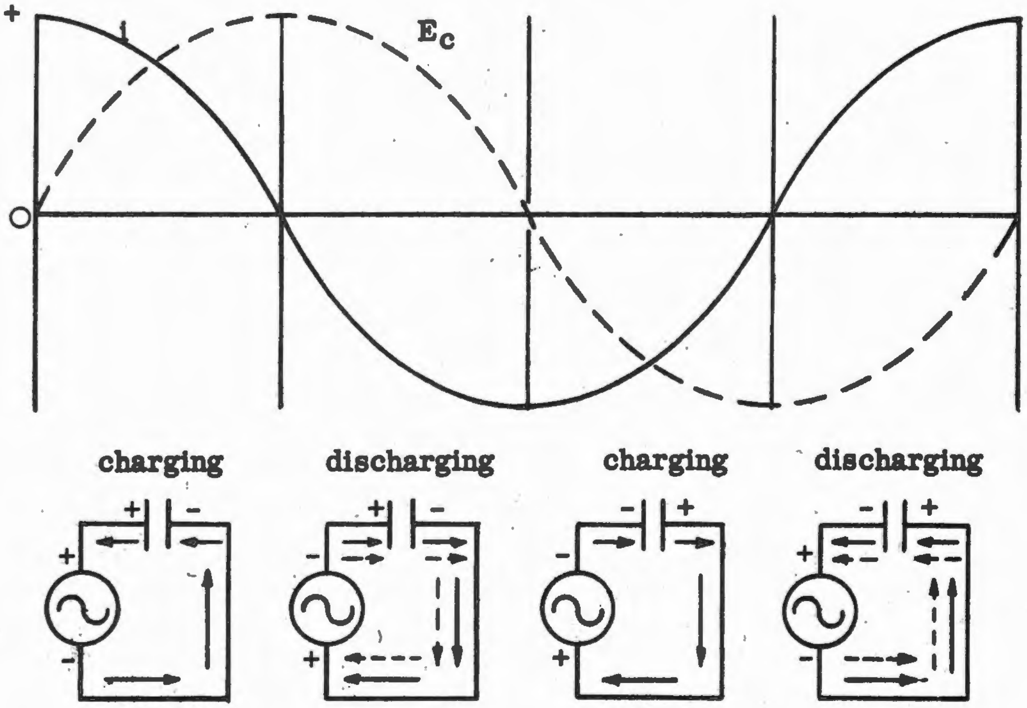


Figure 3-24. Capacitor Charge and Discharge Cycle

Another way in which the current-voltage relationship in a capacitive circuit may be developed is by considering the equation

$$Q = CE \tag{3-2}$$

where

Q = charge on the capacitor
C = capacitance of the capacitor
E = voltage across the capacitor.

Rearranging equation 3-2 gives

$$E = \frac{Q}{C} \tag{3-3}$$

or

$$E = \frac{1}{C} Q. \tag{3-4}$$

But Q is equal to the sum of the product of the current and time increments, or

$$Q = \Sigma\, i\, dt \tag{3-5}$$

$\Sigma\, i\, dt$ may be represented as the area under the current curve; i.e., the current curve is composed of many small rectangles of height i and width dt, as shown in figure 3-25. Substituting equation 3-5 into equation 3-4 gives

$$E = \frac{1}{C} \Sigma\, i\, dt. \tag{3-6}$$

The constant 1/C affects only the amplitude of E. Equation 3-6 can be used to plot the voltage across the capacitor, since the voltage at any instant is simply the total area under the current curve up to that instant. In figure 3-25 the shaded area under the current curve is zero at the start of the first one-quarter cycle but grows to a maximum by the end of that quarter cycle. Hence, the voltage curve goes from zero to a maximum in the same period. During the second quarter cycle, the area under the curve continues to increase but in a negative direction. This means that that area must be subtracted from the area in the first quarter cycle. Therefore the area, and the voltage, decreases from a maximum to 0 by the end of the second quarter cycle. The area (and voltage) have again built up in the third quarter cycle, but in a negative direction, and the positive area in the fourth quarter cycle is subtracted from that in the third portion of the cycle so that the area and voltage again go to zero.

It can be shown that the formula for capacitive reactance is

$$X_C = \frac{1}{2 \pi f C} \tag{3-7}$$

where

f = frequency of the excitation.

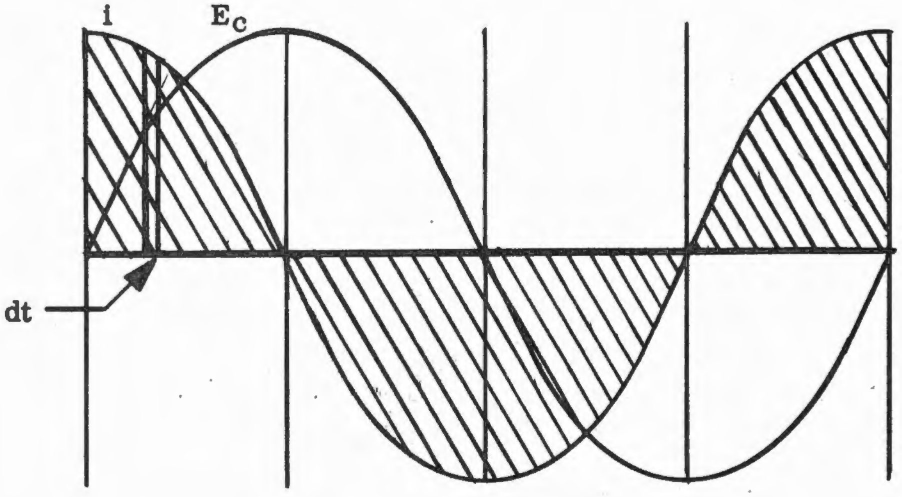


Figure 3-25. Voltage Developed in a Capacitor

It can be seen that the reactance varies inversely with the frequency. When the frequency is zero, as it is with dc, the reactance is infinite and blocks the flow of current.

b. Inductive Reactance

The simple circuit shown in figure 3-26 gives the intuitive idea that the current lags the voltage in an inductive circuit. The circuit consists of an iron core inductor connected to a battery and switch through a series resistor. Across the inductor is connected a lamp having much less inductance and much greater resistance than the inductor. At the instant the switch is closed the lamp flashes briefly, then extinguishes.

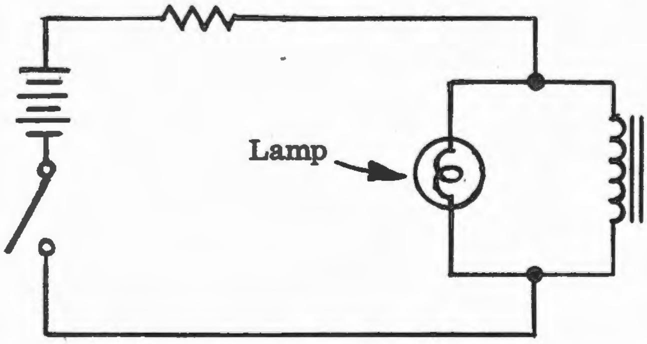


Figure 3-26. Circuit to Demonstrate Inductance

The explanation of this phenomenon is as follows: as current from the battery begins to flow through the inductor, an expanding field of magnetic flux is created together with a voltage opposing the current flow. The battery current therefore is shunted through the lamp, causing it to flicker. As the circuit current becomes stabilized, the magnetic field is maintained but stops expanding, the opposing voltage drops to zero, and the circuit current now flows mostly through the inductor since its resistance is much less than that of the lamp. When the switch is opened, the magnetic field collapses, producing a voltage and resulting current which again lights the lamp for a brief time until the field and current decay. The direction of the voltage induced from the expanding or collapsing field is such as to promote current flow which resists the change (Lenz' Law). A similar action takes place when any coil is operated with ac voltage. During the two quarter cycles when the current is rising the magnetic field expands; during the two quarter cycles when the current is decreasing the magnetic field collapses. The expanding and contracting magnetic field induces a counter voltage in the coil that opposes the change in current. (See figure 3-27.)

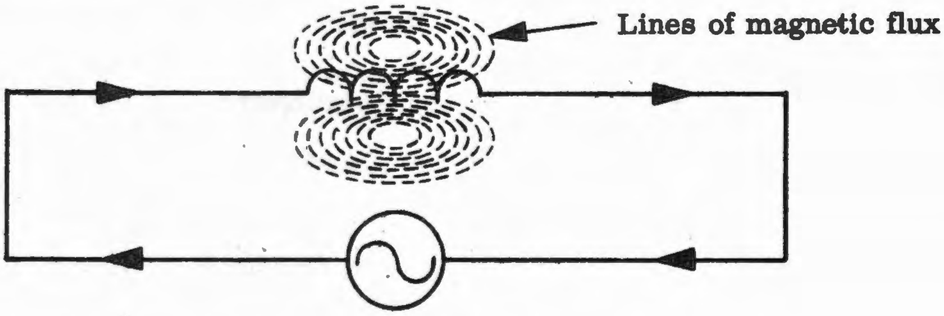


Figure 3-27. Inductive Reactance

The current-voltage relationship in an inductive circuit can be developed more rigorously by considering the equation

$$E_L = L \frac{di}{dt} \qquad (3-8)$$

where

E_L = induced voltage
L = inductance of the coil
di = small change in current
dt = small change in time.

The ratio di/dt is the instantaneous slope of the current curve. Slope of a curve at a point is the same as the slope of a tangent to the curve at that point, and the slope is a maximum if the tangent is vertical and is zero if the tangent is horizontal. In figure 3-28, di and dt are defined, and the slope is drawn at every 90 degree point. The inductive voltage curve is then drawn in dotted lines from the values of the slopes.

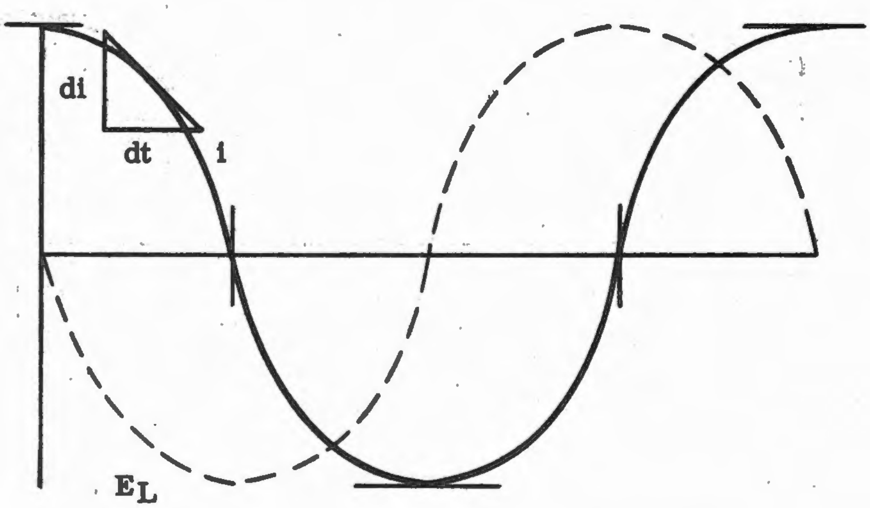


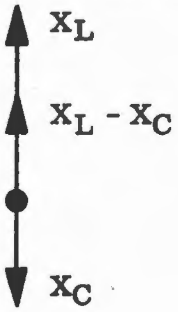
Figure 3-28. Voltage Developed in an Inductor

The current lags the voltage by 90 degrees only when there is no resistance in the circuit; this is an ideal case and never realized since any practical inductor will also have some resistance. It can be shown that the inductive reactance is

$$X_L = 2 \pi f L \tag{3-9}$$

so that the reactance is directly proportional to the frequency, and is zero for dc (where the frequency is 0).

X_C and X_L oppose each other (since for a given current flow the first causes a voltage lag while the second causes a voltage lead), but they are both vector quantities and so can be combined to obtain $X_L - X_C$ as shown in the next drawing.



c. Impedance (Series Circuit Only)

Impedance is the resultant when the resistance and ($X_L - X_C$) vectors are combined, as shown in the triangle in figure 3-29. The angle θ is the phase angle, and is the angle by which the voltage leads (or lags) the current. If the current and voltage in an ac circuit containing R, C, and L are known, the impedance Z may be found by an adaptation of Ohm's Law: $Z = E/I$.

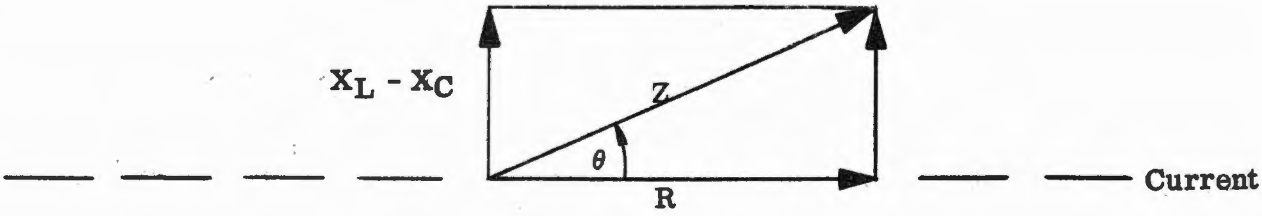


Figure 3-29. Impedance Triangle

Since Z is the hypotenuse of a right triangle,

$$Z = \sqrt{R^2 + (X_L - X_C)^2} = \frac{R}{\cos\theta} = \frac{X}{\sin\theta} \tag{3-10}$$

and θ may be found by taking any of the trigonometric functions, the one most commonly used being

$$\tan\theta = \frac{(X_L - X_C)}{R}\ . \tag{3-11}$$

d. Resonance (Series Circuit Only)

Every ac circuit that has L and C has a resonant frequency. If R, X_L, and X_C are plotted versus frequency, as in figure 3-30, it will be seen that X_L and X_C curves intersect at a common point. At this point (or resonant frequency), $X_L = X_C$ and therefore $(X_L - X_C) = 0$. By equation 3-10 we see that at this condition $Z = R$ and is thus a minimum. Since Z is a minimum, I is a maximum and is in phase with the applied voltage ($\theta = 0$). Summarizing these statements:

At resonance,

$$X_L = X_C$$

and

($\theta = 0$)
($Z = R$) (minimum)
($I = E/R$) (maximum)
(I is in phase with E).

Note that resonance can be achieved at a specific frequency by varying either L, or C, or both.

The magnetic suspension microsyn will now be discussed. As shown in figure 3-22, the eight pole microsyn has four tuned circuits in parallel. Observe that two adjacent primary coils are series connected in each leg, so that rotor rotation has no effect upon the sum of their inductances. (See figure 3-20.) In order to choose the suspension operating point, the four branches are connected together (to make the combined inductance independent of rotor translation) with a variable capacitor in series. In one setup method, the capacitor is first adjusted for resonance to obtain a reference point, then made larger (decreasing X_C), while holding the microsyn voltage E_2 constant, until the current is 0.707 times the maximum (resonant) current. This point is called the inductive half power point. When the value of the capacitance has been found experimentally, a fixed capacitor of one-fourth the value of the variable capacitor is connected in series with each leg of the circuit. In operation, translational movement of the rotor alters the inductance (the capacitance remaining fixed) to bring the system either closer to or farther from resonance in each leg.

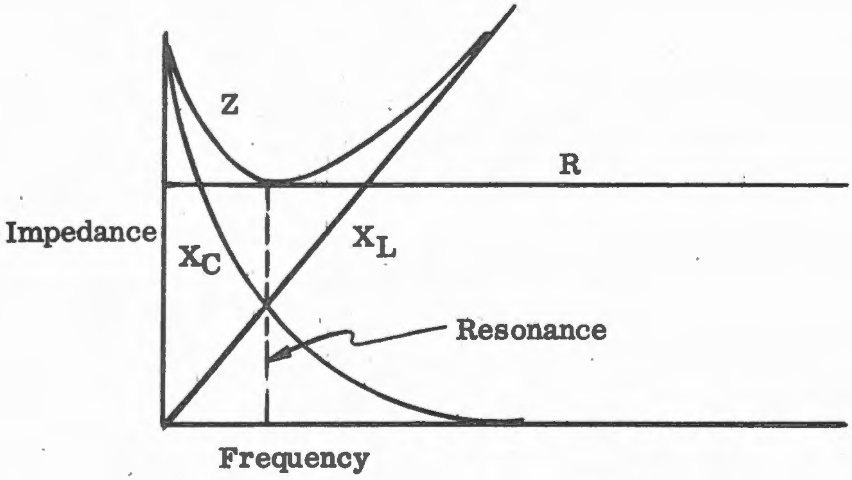


Figure 3-30. Resistance, Reactance, and Impedance at Resonance

In order to understand the magnetic suspension operation, let us examine a simplified magnetic circuit shown schematically in figure 3-31 where E is the excitation voltage, L is the inductance of the winding, A is the ferromagnetic core upon which the winding is wound, B is a movable block, also of ferromagnetic material, and x is the gap between L and B.

The inductance of L is given by the formula

$$L = \frac{c\,N\,\phi}{I} \qquad (3\text{-}12)$$

where

c = a constant
N = number of turns in the winding.

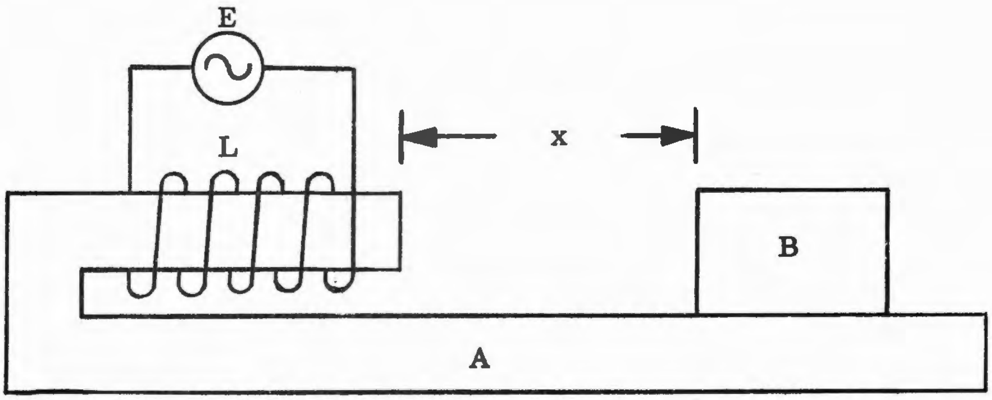


Figure 3-31. Circuit Equivalent of Eight-Pole Microsyn (One Pole)

ϕ = flux in the winding
I = current in the winding

$$\phi = \frac{\text{magnetomotive force}}{\text{reluctance}} = \frac{C\,N\,I}{\dfrac{x}{\mu A'}} = \frac{C\,N\,I\,\mu A'}{x} \tag{3-13}$$

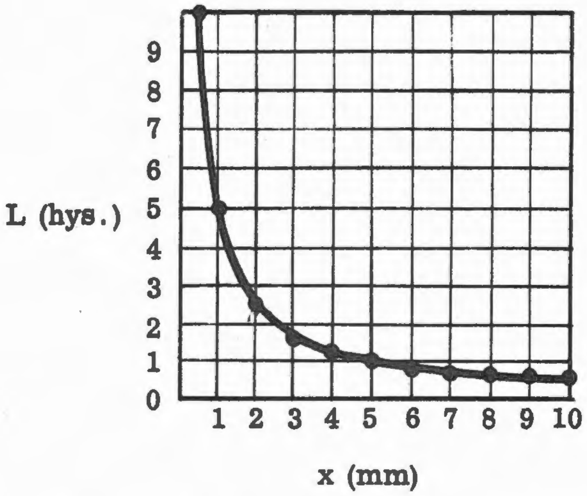
where

C = a constant
μ = permeability of the ferromagnetic material
A' = cross sectional area of the pole.

Since c and N in equation 3-12, and C, N, μ, and A' in equation 3-13 are all constant for a given pole, they can all be lumped together in another constant k. Then substituting equation 3-13 into equation 3-12 and substituting k for the constants

$$L = \frac{k\,I}{I\,x} = \frac{k}{x}. \tag{3-14}$$

Since L varies inversely with x, a plot of L versus x would look something like that of figure 3-32. The shape of the actual curve would depend upon the values of L and x, but since the rotor of the microsyn is limited mechanically to very small movements, the curve will be nearly linear in the range considered.



NOTE: Values are arbitrarily assigned.

Figure 3-32. Plot of Inductance versus Air Gap

The energy in the magnetic field surrounding the coil is given by the equation

$$W = \frac{I^2L}{2}. \qquad (3\text{-}15)$$

For an ac circuit with inductance only

$$I = \frac{E}{X_L}. \qquad (3\text{-}16)$$

By equation 3-9

$$X_L = 2\pi fL$$

so that

$$I^2 = \frac{E^2}{4\pi^2 f^2 L^2}. \qquad (3\text{-}17)$$

Substituting equation 3-17 into equation 3-15 gives

$$W = \frac{1}{2}\frac{E^2}{4\pi^2 f^2 L}. \qquad (3\text{-}18)$$

But

$L = \frac{k}{x}$ (by equation 3-14),

so

$$W = \frac{1}{2}\frac{E^2x}{4\pi^2 f^2k}. \qquad (3\text{-}19)$$

All of the terms in equation 3-19 are constant except x, so that the energy in the field varies directly with the gap between the pole and the rotor as shown in figure 3-33.

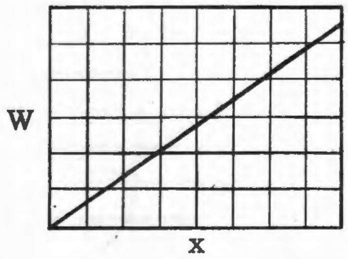


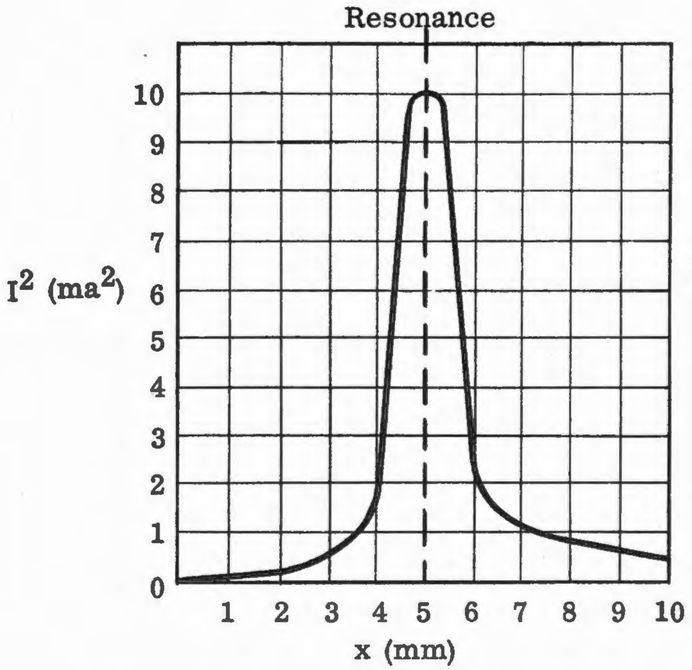
Figure 3-33. Plot of Energy in Microsyn versus Air Gap

This simplified case is analogous to potential energy of an object in the gravitational field, where energy is increased in proportion to the height an object is raised. Observe that the force with which B is attracted to the pole is constant regardless of distance, since force is the slope of the W versus x curve. Consequently the force necessary to move B away from the pole is equal and opposite to the attractive force, as it is in the gravitational system.

It is obvious that magnetic suspension cannot be achieved with this circuit, and that some arrangement is needed whereby the force upon the block B decreases sharply as B approaches the pole. Addition of a capacitor to the schematic drawing, figure 3-31, achieves this effect. A resistor representing coil and iron losses is also added. The complete microsyn then is composed of R, L and C components so that 4 series resonant circuits are formed. (Figure 3-37 shows one set of opposing pole pairs with their associated resistors and capacitors.)

As the forces acting upon the rotor to achieve suspension are dependent upon the energy fields, it is important to know the shape of the energy versus gap curve with the tuned circuit. We already have the L versus x curve (figure 3-32). We will draw the curve for I^2 versus x, and will then combine the two curves to show $1/2\ I^2L$ versus x, or W versus x.

In figure 3-37, there will be some position of the rotor (or value of x) at which the value of L will be such as to make $X_L = X_C$ and the circuit will be at resonance. At this point the impedance will be a minimum and the current (and I^2) will be a maximum (see III.C.3.c.) As the rotor moves in either direction (x gets larger or smaller) the current falls off sharply, since the value of L (and X_L) changes such as to make the circuit impedance greater. The curve of I^2 versus x then must look like figure 3-34.



NOTE: Values are arbitrarily assigned.

Figure 3-34. Plot of Current versus Air Gap

To get the graph of W versus x, we make table 3-1 from figures 3-33 and 3-34 in order to plot values.

x	L	I^2	$\frac{I^2L}{2}$
1	5.00	0.007	0.017
2	2.50	0.045	0.057
3	1.70	0.20	0.17
4	1.25	1.44	0.90
5	1.00	10.00	5.00
6	0.81	2.26	0.92
7	0.70	1.00	0.35
8	0.63	0.67	0.21
9	0.56	0.50	0.14
10	0.50	0.39	0.097

Table 3-1. Tabulation of Magnetic Energy Level with Rotor Position

NOTE: Values are arbitrarily assigned.

The energy curve has nearly the same shape as the I^2 curve. Both curves are somewhat skewed because of the hyperbolic shape of the inductance curve. Since work equals force times distance, and the change in work equals force times the change in distance, then force equals change in work divided by the change in distance, or

$$F = \frac{\Delta W}{\Delta x}.$$

In other words, force is the slope of the W versus x plot. (See figure 3-35.) In contrast to the untuned circuit previously examined, where the energy slope and force were constant, the tuned circuit yields a rising attractive force as the block is moved from the pole, then a force decreasing sharply to zero where the curve has zero slope at resonance, and repelling the block at a spacing greater than resonance. The plot of this force from one pole is seen in figure 3-36.

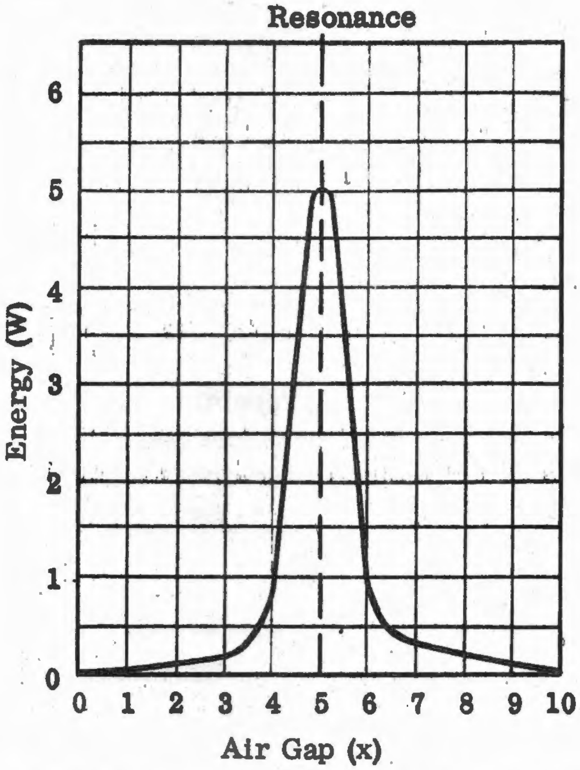


Figure 3-35. Plot of Energy versus Air Gap with Working Capacitors Added to Microsyn

As was mentioned previously, the microsyn is initially set to operate at the half power point. Therefore the position of the rotor B at null is as shown in figure 3-36. A displacement to the left (decreasing gap) decreases the force (ultimately to zero), while a slight movement to the right increases the force. Further displacement to the right would cause the force to decrease to 0, and an even greater displacement would result

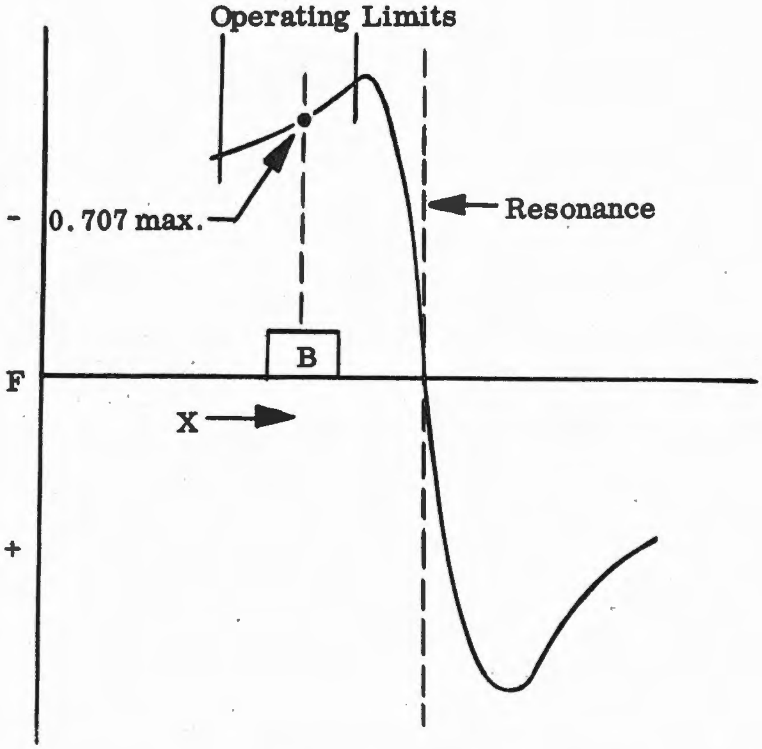


Figure 3-36. Forces on Microsyn Rotor at One Pole

in the force changing direction (becoming repulsive instead of attractive). However, the motion of the rotor is limited to a very short distance so that operation is between the two limits shown. Thus far we have been considering the action of one pole on the rotor. Now let us examine the action of opposing poles upon the rotor as shown in figure 3-37.

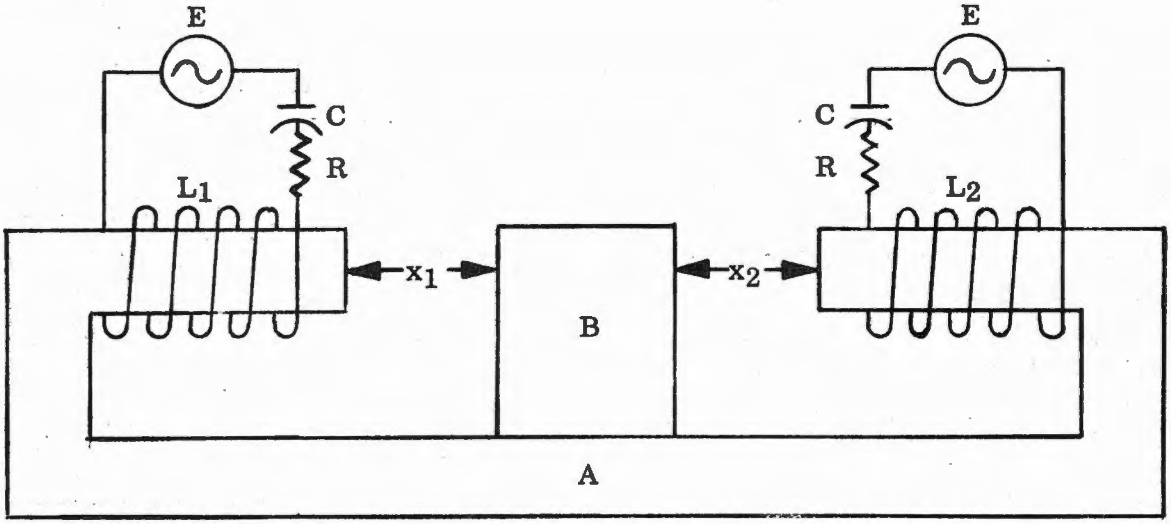


Figure 3-37. Circuit Equivalent of Eight-Pole Microsyn (Two Poles)

Obviously if B moves to the left x_1 decreases and x_2 increases and vice-versa. Therefore the force curve associated with one pole is upside down with respect to the other pole of the pair, as shown in figure 3-38. Then if the rotor is displaced from its null point (where the forces on it from both poles are equal), the force from the pole the rotor is approaching decreases, and that of the opposite pole increases. This action magnetically clamps B between the operating limits, and as the four pairs of poles are arranged in a circle around B, the rotor is effectively suspended.

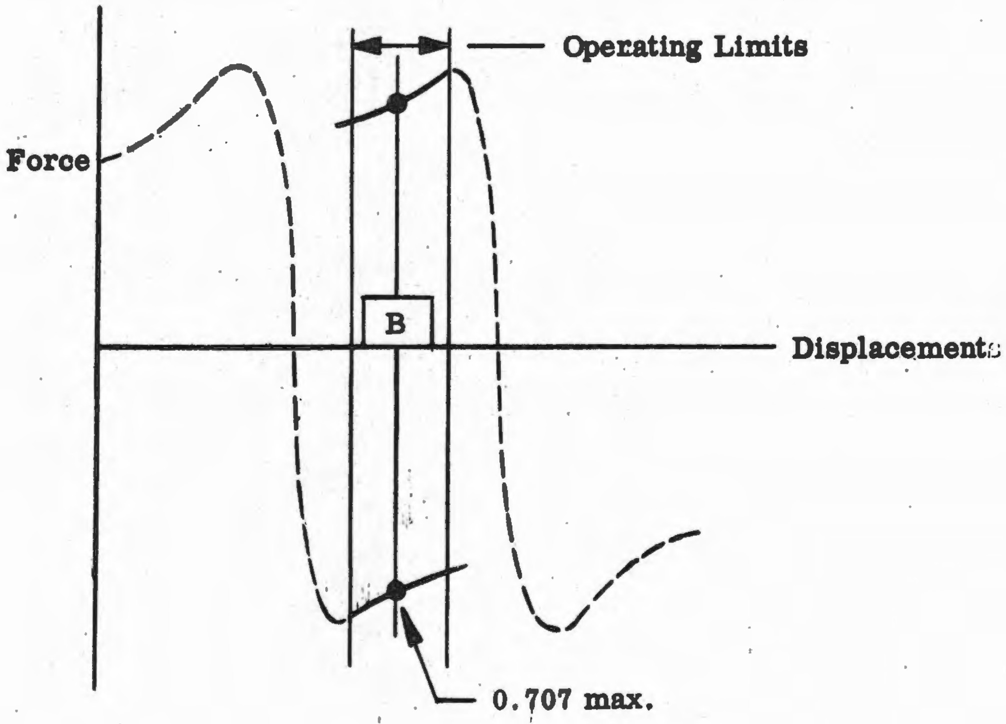


Figure 3-38. Forces on Microsyn Rotor Between Two Poles

It is desired that the magnetic suspension system be insensitive to rotational movement, but if B rotates, the inductance of the coils closest to B will change since the flux changes. To overcome this change in inductance, adjacent poles are connected in series so that an increase in the inductance of one is compensated for by a decrease in the inductance of the other, thus causing the suspension to be independent of rotation.

D. TYPICAL GYROSCOPE CONSTRUCTION

Figures 3-39 and 3-40 are examples of typical gyro construction, the former being a cutaway view of a 10^7 stabilization gyro, and the latter being a schematic of a gyro containing a spherical float. Between them is a set of illustrations showing various constructional features of the 10^7 design.

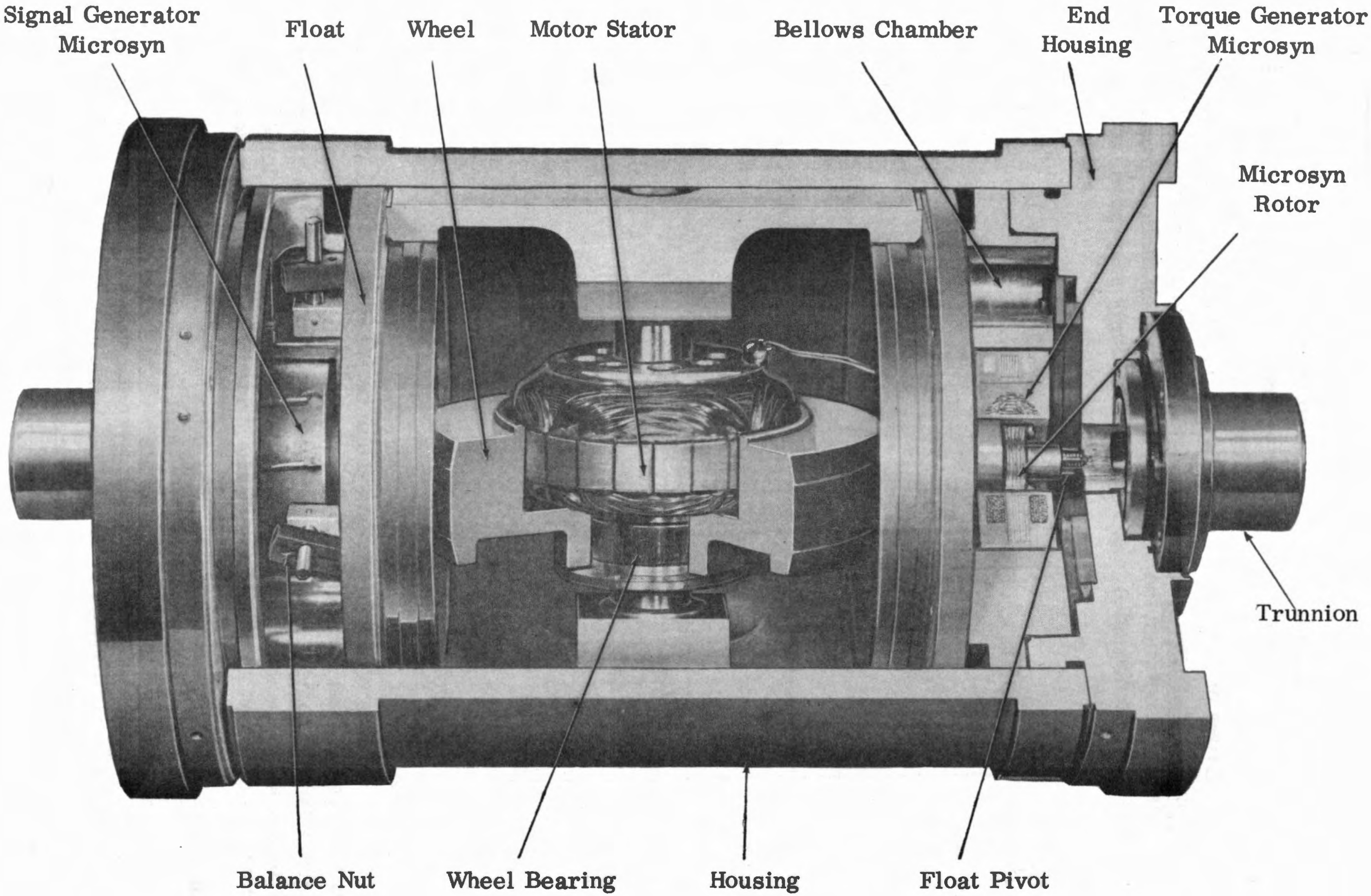


Figure 3-39. Cutaway View of 10^7 Stabilization Gyro

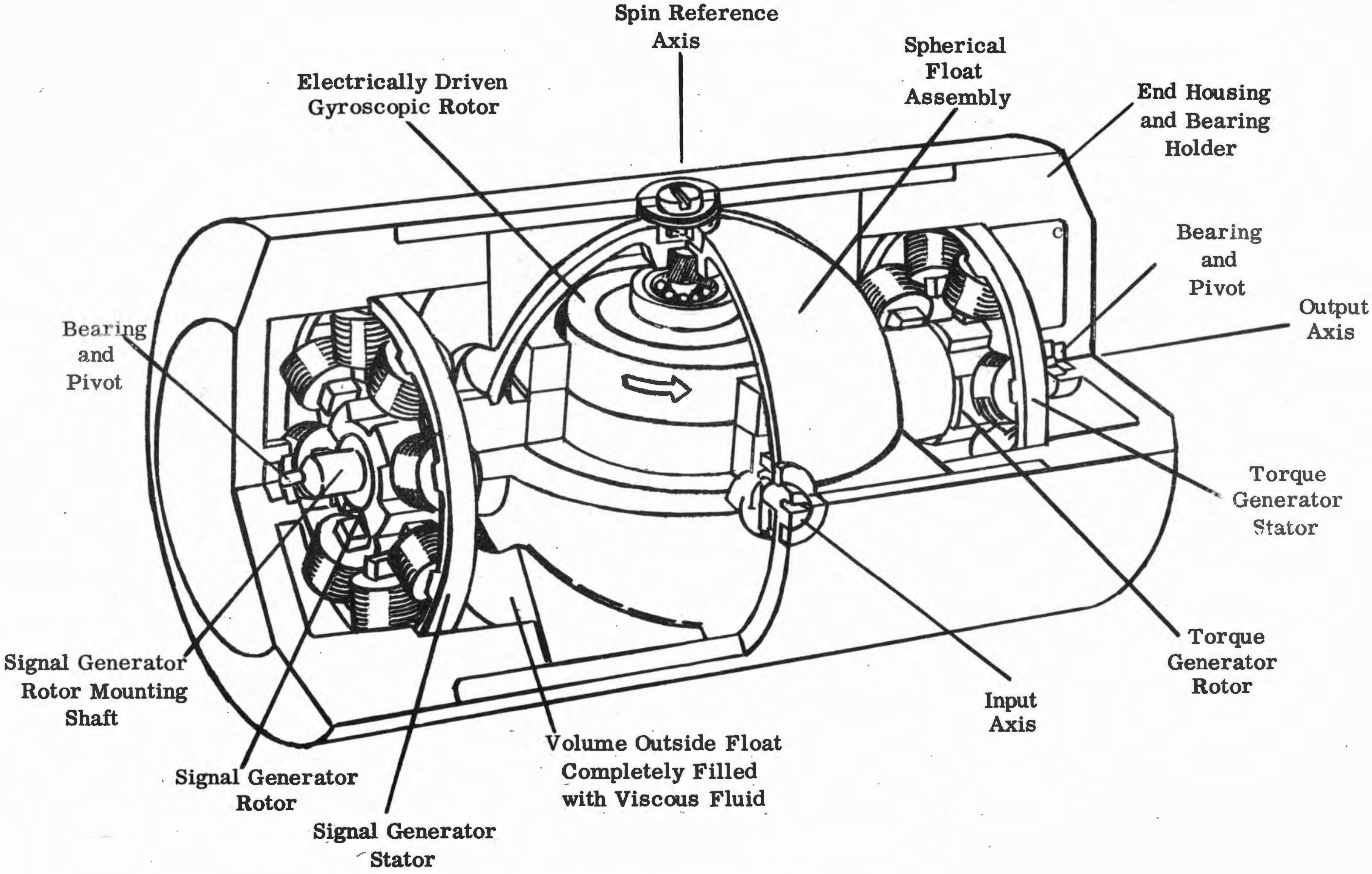
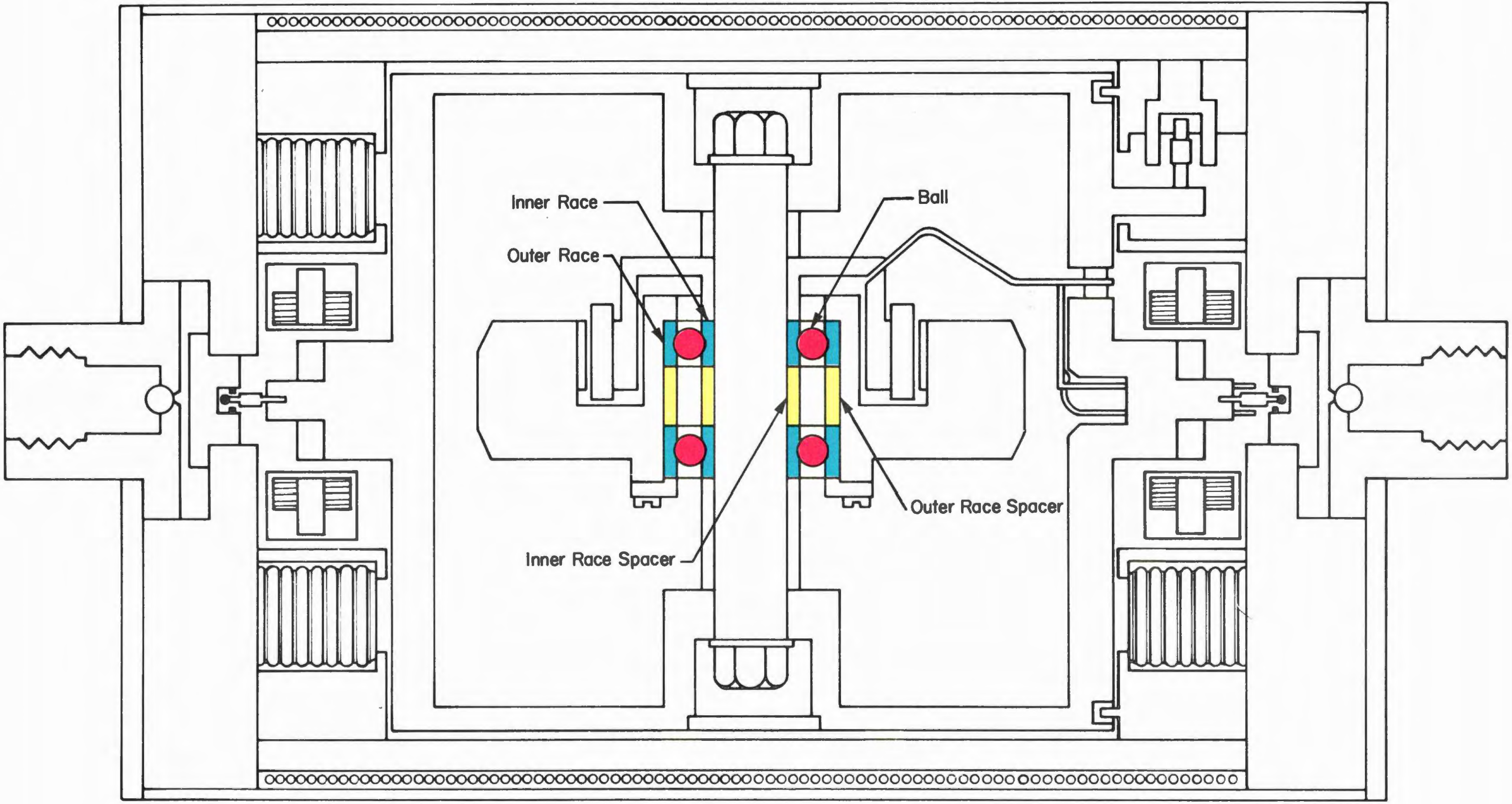
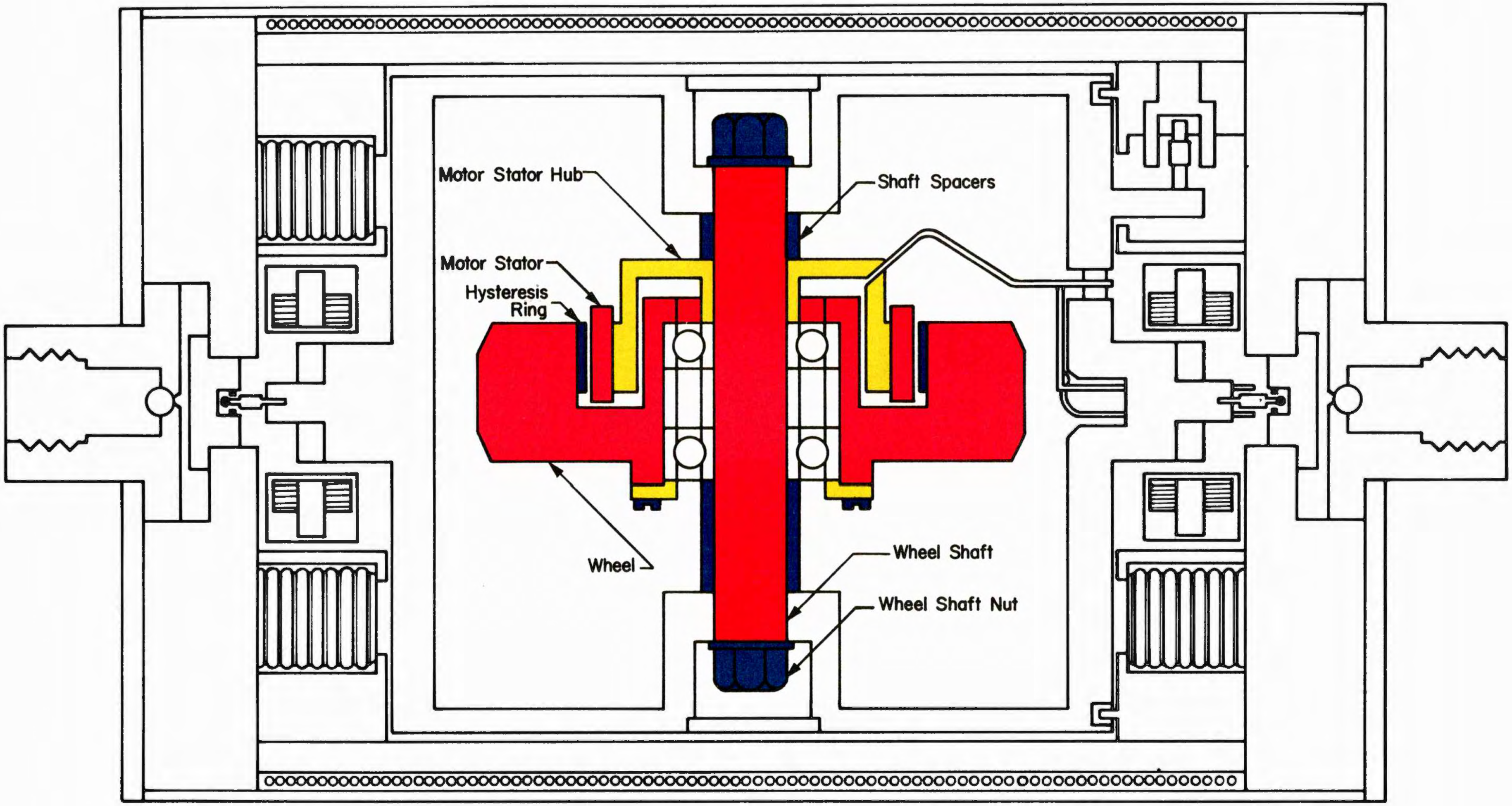


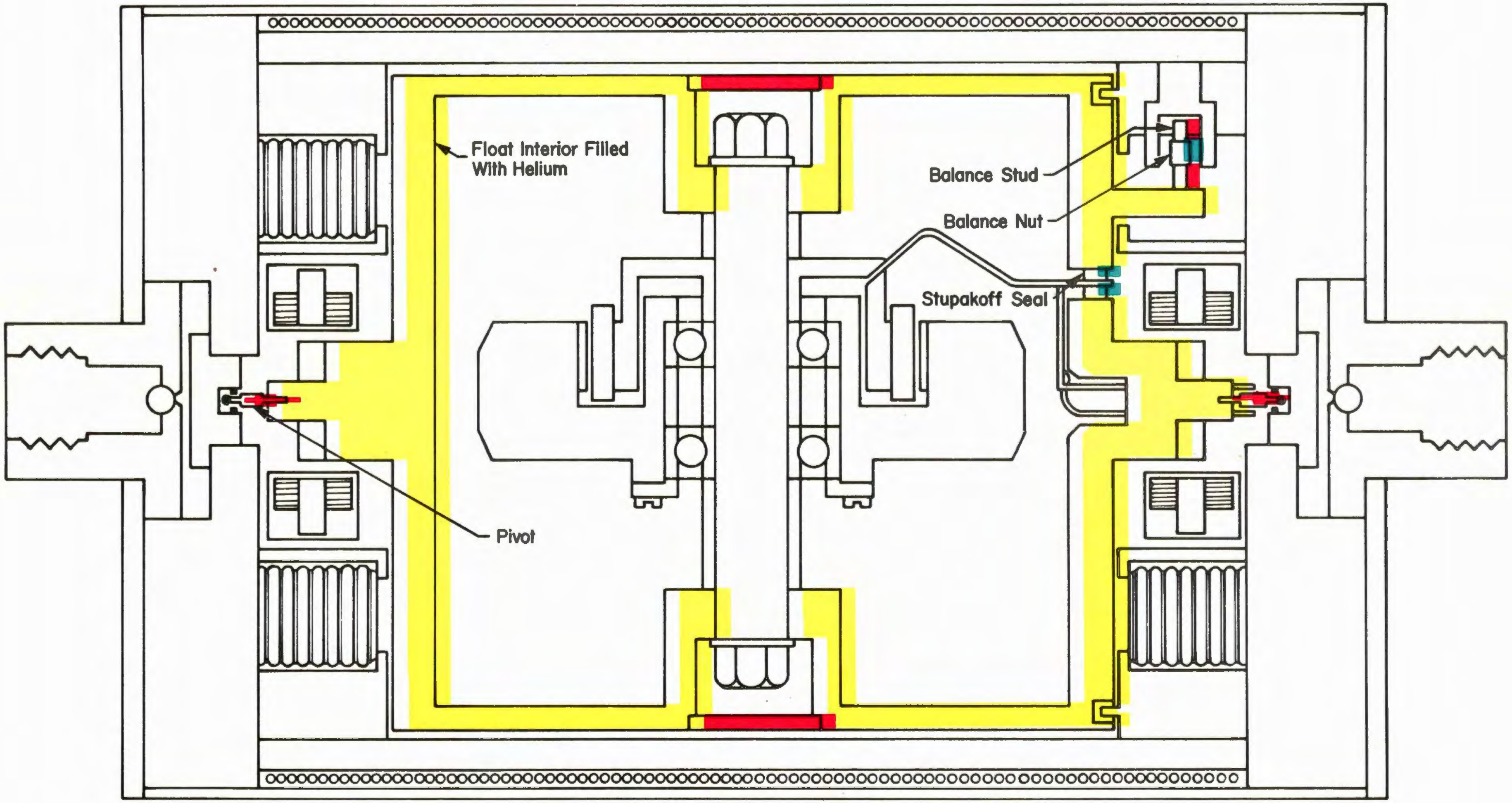
Figure 3-40. Generalized Pictorial Schematic Drawing of Gyro with Spherical Float



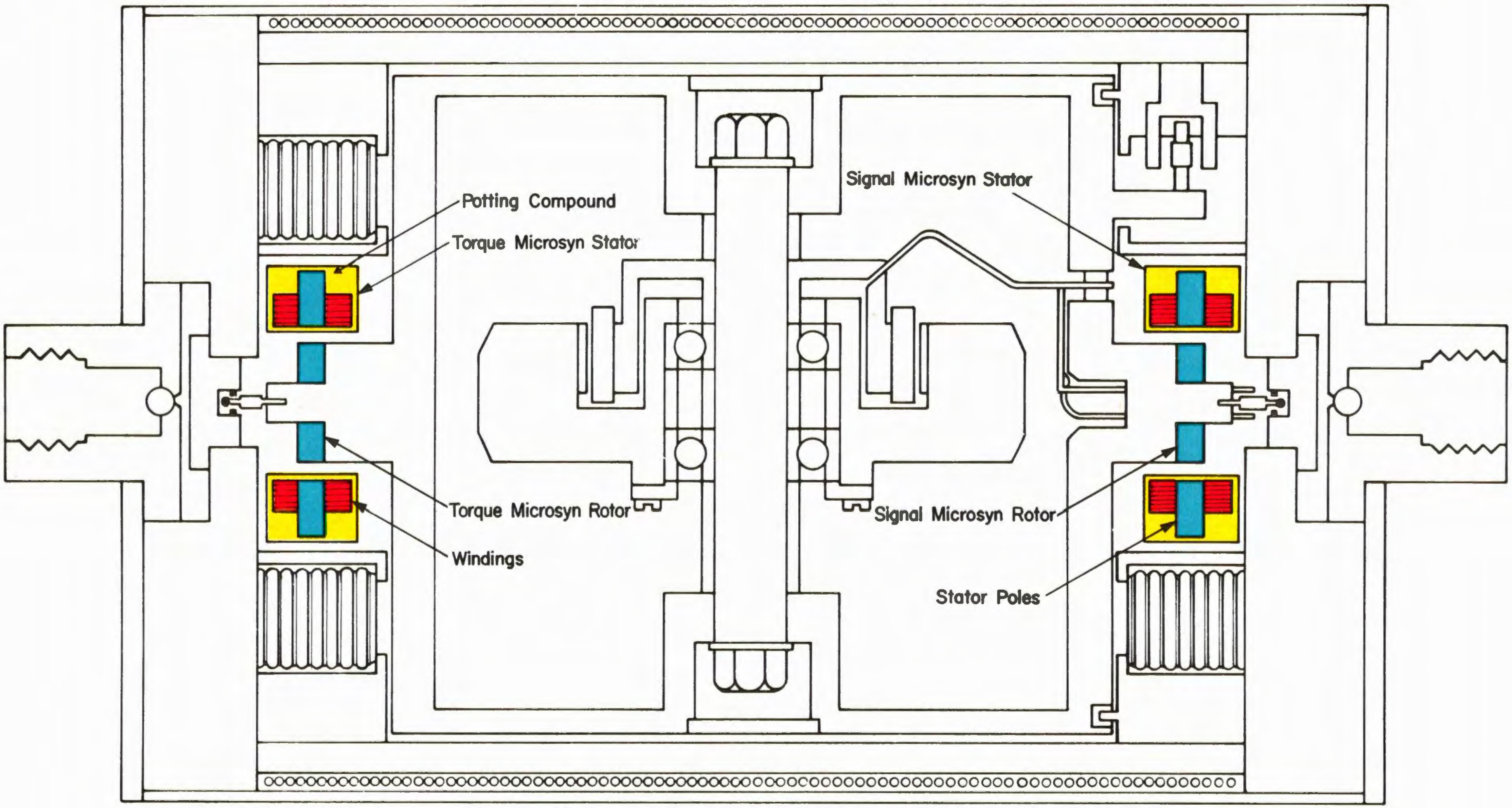
Gyro Wheel Bearing Assembly



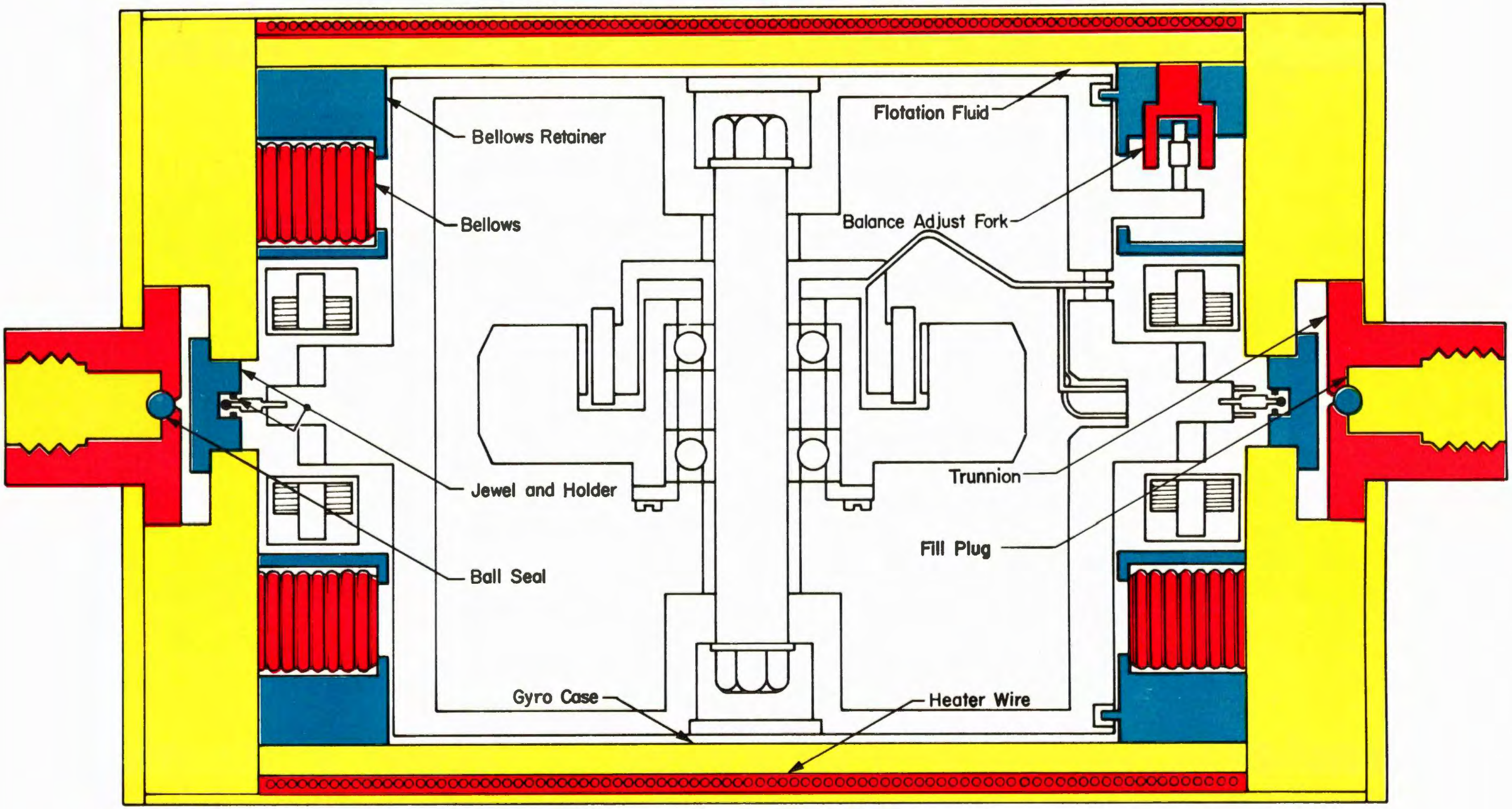
Gyro Wheel and Motor Assembly


Float Interior Filled With Helium
Balance Stud
Balance Nut
Stupakoff Seal
Pivot

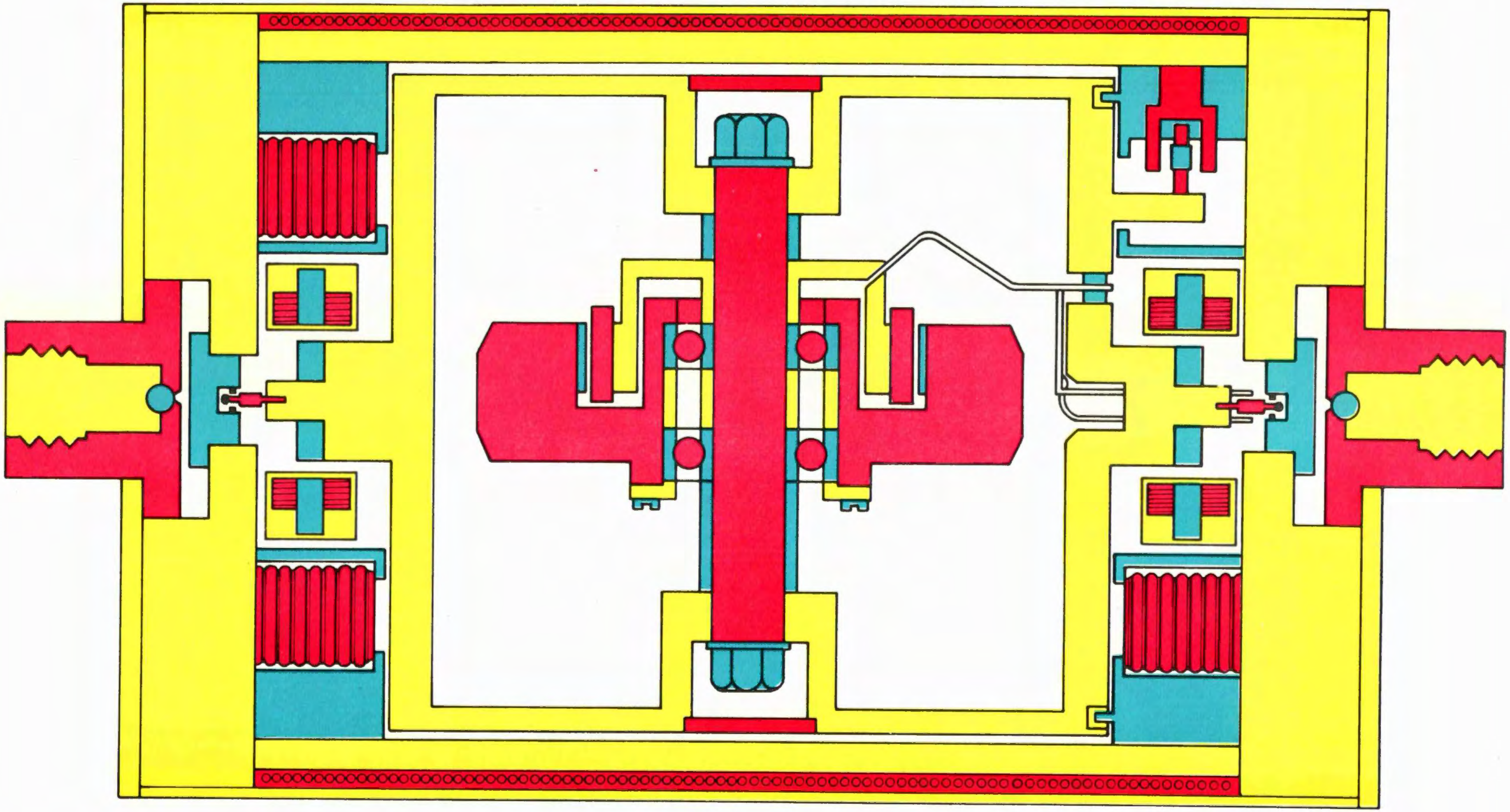
Gyro Float



Signal and Torque Microsyns



Gyro Case Features



Floated, Integrating Gyroscope

SECTION IV

GYRO TESTING

A. PRELIMINARY TESTING

1. ELECTRICAL TESTS — STABILIZATION AND PENDULOUS GYROS

These tests apply to the microsyns, wheel motor, and heater and temperature sensing elements where they are wholly contained within the gyro.

a. Temperature Sensor Calibration

Since the measurement of electrical quantities is dependent upon ambient temperature, the first check performed is calibration of the temperature sensing element, if any. This is done by completely submerging the gyro unit in a liquid bath, the temperature of which is kept stable to within a fraction of a degree. The resistance of the sensing element is then determined to within a fraction of an ohm at the stabilized temperature. In the AC Spark Plug 10^7 stabilization gyro, no temperature stabilizing bath is used, and the sensor resistance is measured when flotation has been achieved.

b. Resistance and Continuity Checks

The dc resistance of the microsyns, motor stator, and heater and sensing elements, if any, is measured with a resistance bridge or equivalent.

c. Insulation Resistance and Megger Checks

These checks are performed to be certain that the components have sufficient insulation resistance between their points of high potential and ground to provide assurance against parts breakdown.

d. Polarity Checks

The purpose of these tests is to determine that the microsyns and wheel motor have been properly wired and installed in the gyro. Separate tests on these three components are necessary since it is possible that the incorrect polarities of any two components would negate each other and no error would be observable from a functional check of the entire gyro unit. The best starting point for determining polarities is a dynamic check that uses the inertia of the float to establish an absolute reference for the polarity of the signal microsyn.

The case of the gyro is accelerated rotationally about the OA and the float lags with respect to the case due to its inertia. The oscilloscope pattern of the signal microsyn output signal is then observed to see if its polarity agrees with the known sense of the case rotation. The test should be conducted with the microsyn rotor at its null position, as the sensitivity of the test is greater when the signal voltage due to the rotation is a large proportion of the total signal microsyn output.

The polarity of the torque microsyn is then determined. This is done by applying currents of known like instantaneous polarities to both the primary and secondary windings of the microsyn. The product of these currents will cause a float rotation of known sense, and the signal microsyn output will indicate whether the actual direction of float rotation is in agreement with this rotational sense, thus verifying the proper wiring of the microsyn windings.

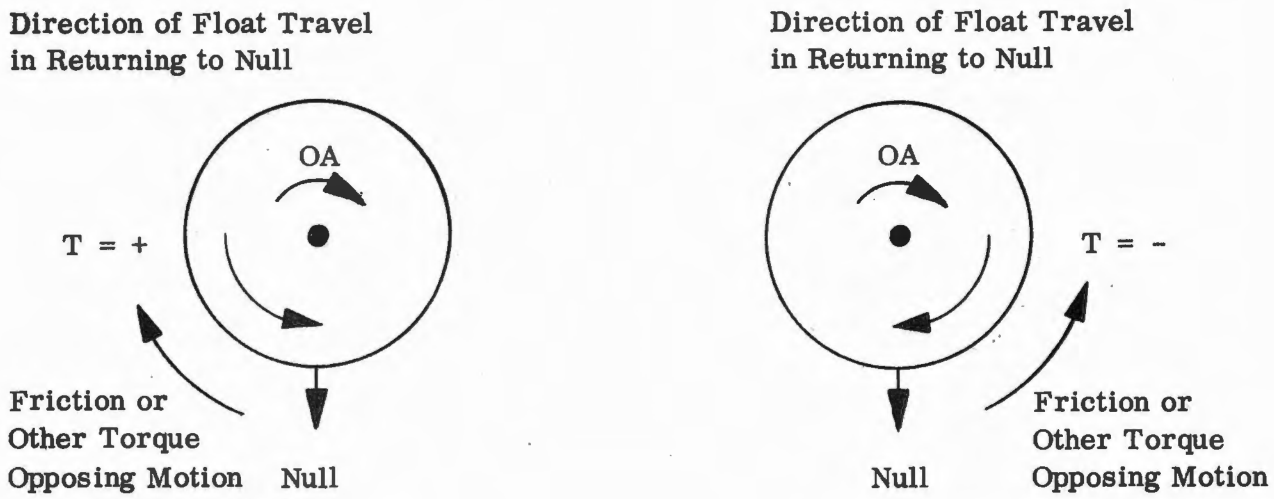
The polarity of the gyro wheel spin motor is checked last. The motor is excited from a source of known phase. The gyro is then rotated positively about its IA and the signal microsyn output is observed to see that precession occurs in the positive direction.

2. FLOAT FREEDOM AND FLOTATION TESTS — STABILIZATION GYROS

The checking of float freedom is the most important of all preliminary tests, since the freedom of the gyro float directly affects the gyro performance in all subsequent tests. In addition, servo and tumbling type tests of a malfunctioning gyro may consume much time, while a few moments of conscientious observation of the float motion might have located the difficulty. In all float freedom tests the value of an experienced and alert test operator cannot be overemphasized. While these tests can be mechanized to provide some type of recording, judgement in observing oscilloscope and meter indications of float travel is still necessary, since restrictions to float freedom may vary in degree from a slight sliding contact to a completely immobile float.

a. Unbalance Uncertainty Test

A gyro unit of good quality has associated with it a specific value of torque required to hold the float at its null position, the magnitude and sense of this torque depending upon the unbalance coefficients and the manner in which the gyro is positioned with respect to the gravity vector. If the specific torque at a given float position is noted and the float rotated some amount and then returned to the original position the value of torque required to maintain this position should remain the same. The unbalance uncertainty test measures the torque required to hold the float at this position. It is generally made with the wheel off, so that wheel vibration will not free a sticky float. The float is driven alternately positive and negative to accentuate any spread in null torque due to the opposing directions of friction or other retarding torque. (See figures 4-1a and 4-1b.) This test is primarily useful in detecting air bubbles, dirt particles, or interference between gyro float and ease.



a. Float Driven Plus and Returned to Null

b. Float Driven Minus and Returned to Null

Figure 4-1. Unbalance Uncertainty Test

b. Gravity Transient Test

This is a similar test in which the gyro is oriented with its OA horizontal, wheel off, and the value of torque required to hold the float at null is recorded. The entire gyro is then rotated about OA in four 90 degree steps and the new value of torque required to hold the float at null in each position is recorded. Because of unbalances these values of torque will probably be different. The new torques should appear instantly upon orienting the gyro to the new position. If the torque appears to wander upon indexing the gyro, or a considerable time is required for the torque to reach its final value, some float abnormality is indicated. Originally this test was designed to detect flotation fluid or bearing oil in the float. However, present manufacturing techniques have been perfected to the point where this problem is practically eliminated, but the test is retained to discover air bubbles, dirt in gap between float and case, or other causes of float malfunction.

c. Flotation Test

The flotation test is made to determine the gyro temperature at which flotation occurs, or to measure the load upon the float pivots if the gyro is operated at some fixed temperature. The gyro is usually mounted with the output axis horizontal, and the microsyns are used to obtain indications of float radial motion.

In the 10^7 gyro, microsyn radial output voltages (obtained by reading four pole microsyn center-tap voltages) are recorded with the unit in a fixed position and the float held at null. The gyro is then rotated 180 degrees about OA and the radial voltages observed for a period of time. If the unit is perfectly floated (and perfectly balanced longitudinally) no change in voltage will occur. If the voltages begin to change, the rate at which they are changing can be interpreted to determine how close the float is to flotation. The temperature is readjusted and the test repeated until an acceptably low radial float rate is obtained.

In gyros containing magnetic suspension microsyns, the test is run in a similar manner, except that the radial output magnitudes themselves, and not their change, indicate pivot loading, since the float is suspended by the microsyns. The difference in radial voltages between the two 180 degree gyro positions thus indicates the degree to which flotation has been achieved.

d. Float Freedom Tests — Pendulous Gyros

The preliminary remarks made under 2. above also apply to the pendulous gyro. The presence of the large pendulous mass (offset wheel) somewhat restricts the orientation that may be used in checking float freedom. However, the pendulum may be used as a tool to rotate the float, and its behavior with gravity acting upon it tells a great deal about float freedom.

The Angular Spread Test is a test that is similar to the Unbalance Uncertainty Test performed on stabilization gyros, in that the spread of float torque is measured after the float has been displaced in both directions. The pendulous gyro is positioned with OA horizontal with the pendulum down, and the case is rotated about OA so that the signal microsyn output is near null. The torque microsyn is then used to rotate the float, lifting the pendulum from its vertical down position. After rotating to a certain point the torque generator torque is removed, and the pendulum begins to return the float to its starting point. If any float obstruction is present, the float will stop before the starting point is reached. The test is then repeated but with the float driven in the opposite direction. The spread in final signal microsyn output voltages from the two runs is examined to determine the float freedom. The angular spread test is illustrated in figure 4-2 (for the case with restricted float freedom).

3. GYRO WHEEL TESTS

a. Wheel Run-Up and Run-Down Time

The spin motor is energized and a record kept of the time required for the wheel to reach synchronous speed (motor current remains steady). From synchronous speed the motor is deenergized and the time recorded that is required for the wheel to come to a stop (as noted by an oscilloscope indication). These two checks are used to check the quality of the wheel bearings.

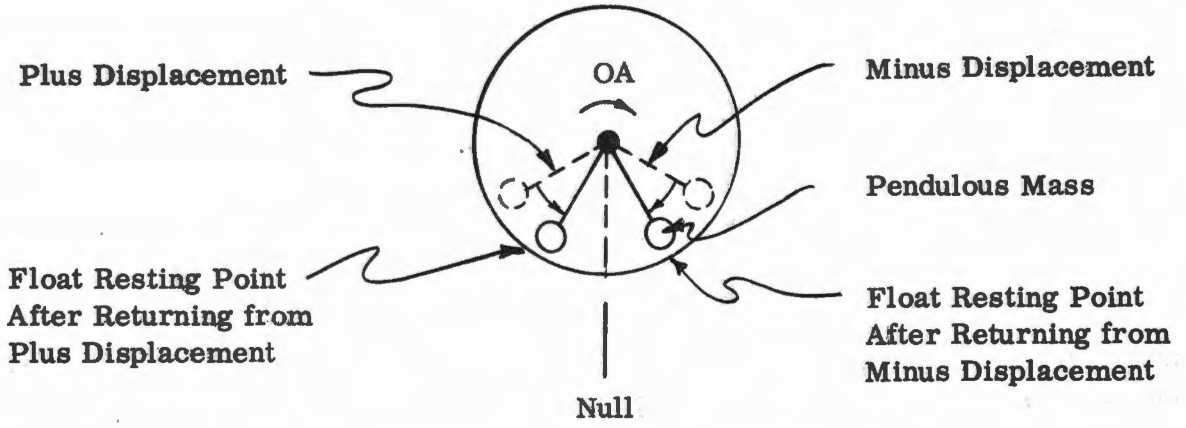


Figure 4-2. Angular Spread Test

b. Wheel Deceleration Tests

As mentioned earlier in the section on wheel bearings, the wheel deceleration rate is measured by timing over an interval the frequency of the spin motor back emf.

c. Wheel Voltage, Current, and Power Checks

Measurement of these quantities is made at synchronous speed.

4. MICROSYN TESTS

Microsyn centering is accomplished as outlined in the section on four-pole microsyns, and adjusting the half power point to effect magnetic suspension at the correct operating point is discussed in the section on the eight-pole microsyn.

a. Torque Microsyn Sensitivity

This parameter is found by allowing the gyro to servo drive a turntable, with earth rate and unbalance inputs, with and without the application of torque microsyn current. The difference in turntable rates is then related to the torque current applied to give the sensitivity in dyne-cm/ma^2, MERU/ma^2, or as desired.

b. Coincidence of Signal and Torque Microsyn Null Points

It is important that the electrical nulls of these devices be nearly coincident rotationally since microsyn reaction torque is a function of rotor angle, the lowest value usually occurring near null. The degree of coincidence is found by rotating the float to the null indicated by the signal microsyn and, without moving the float, connecting the torque microsyn as a signal microsyn (exciting the primary winding). The voltage at the secondary winding of the torque microsyn is then read and should be near null within tolerable limits.

c. Float Stop Check

The signal microsyn null should lie approximately midway between the float stops. To determine compliance with this requirement the float is rotated to each stop and the output voltages noted. The values of stop voltages should agree within a specified percentage of their average.

5. FUNCTIONAL TESTS

a. Angular Gain — Transfer Function

Angular Gain and Transfer Function are two different forms of expressing the same property of the gyro; namely, its ability to precess through a definite angle about OA in response to a definite angle of case rotation about IA. When these angles are expressed as the ratio

$$\frac{\theta_{OA}}{\theta_{IA}},$$

the ratio is called Angular Gain, and is mentioned on page 2-3.

The test may be run with the gyro mounted on a turntable with IA aligned parallel to the table axis. The signal microsyn output voltage is recorded. The table is then rotated about IA through a known angle (θ_{IA}) and the signal microsyn output again recorded. The float rotation is found from the difference between starting and finishing microsyn voltages (ΔE_{SG}). If the values are left in this form, the ratio

$$\frac{\Delta E_{SG}}{\theta_{IA}}$$

is called the transfer function. This is the most useful form for the user of the gyro, since the electrical gyro output is used by the servo amplifier in mechanizing the servo loop. If Angular Gain is desired, the sensitivity of the signal microsyn must be known to convert ΔE_{SG} into θ_{OA}.

The test may also be run using a known constant angular velocity about IA, (such as a component of earth rate) and timing the resulting float precession. Knowing the time and the velocities, Angular Gain can be found as shown on page 4-6.

b. Damping Coefficient

As mentioned on page 2-3, the damping coefficient C_D is an expression of the torque exerted by the damping fluid upon the float, as the float is rotated in the fluid. In the stabilization gyro, the torque microsyn is used to rotate the float, and the resulting float rate is measured by timing its travel between two pre-selected signal microsyn voltages. A series of known torques is used, and a plot of torque versus float rate may be made, as shown in figure 4-3.

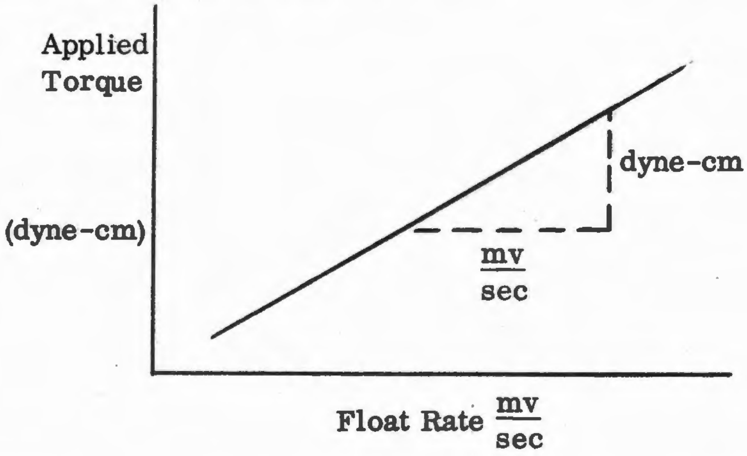


Figure 4-3. Plot of Torque versus Float Rate

The slope of the curve, dyne-cm per $\frac{\text{mv}}{\text{sec}}$ may be converted, using the signal microsyn sensitivity, to dyne-cm per $\frac{\text{rad}}{\text{sec}}$, which is the damping coefficient.

In the pendulous unit, the unbalanced mass, rather than the torque microsyn, may be used to supply the torque. The resulting float rate is then measured, and the damping coefficient is computed.

B. TUMBLING TEST

1. PURPOSE

The tumbling test determines the magnitude and direction of torques caused by gravity acting on mass unbalances within the gyro (U_{SRA} and U_{IA}), compliance (K_{SRA} - K_{IA}), and power lead flex and microsyn reaction torques (R-term). These unbalances, except for the R term, are functions of the angle that the unbalances make with the gravity vector (g). During the test the gyro is rotated through 360 degrees so that the effect of g on the unbalances in various gyro orientations can be observed. The tumbling test also has the secondary objective of indicating, in qualitative terms, whether the gyro operation is satisfactory.

2. TEST CONDITIONS

For this test the gyro is mounted on a turntable in the orientation shown in figure 4-4, and is shown pictorially in figure 4-5.

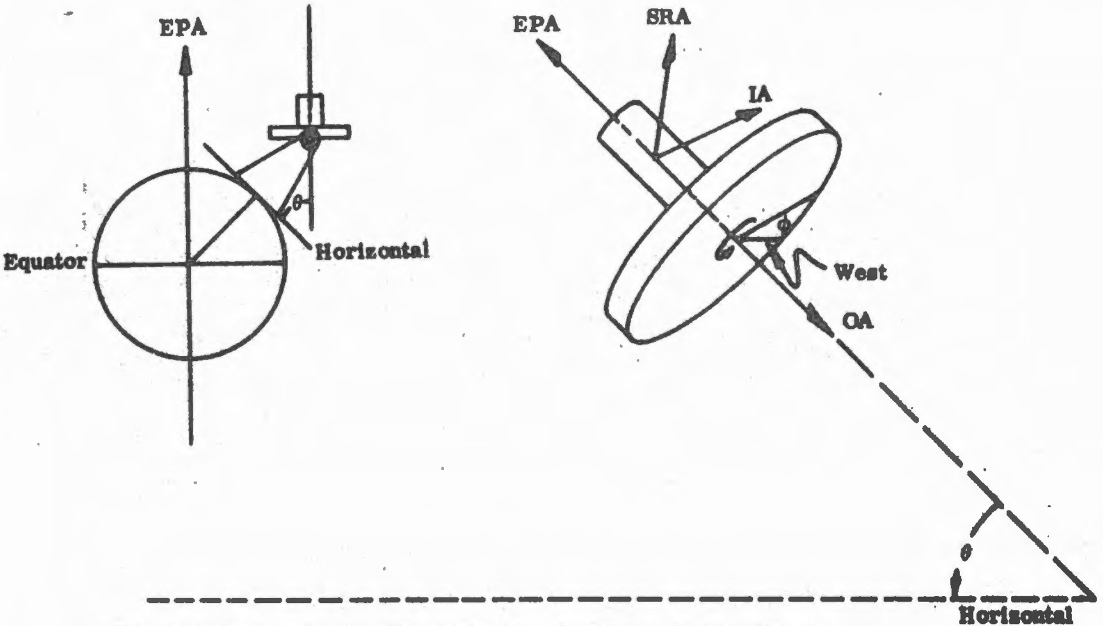
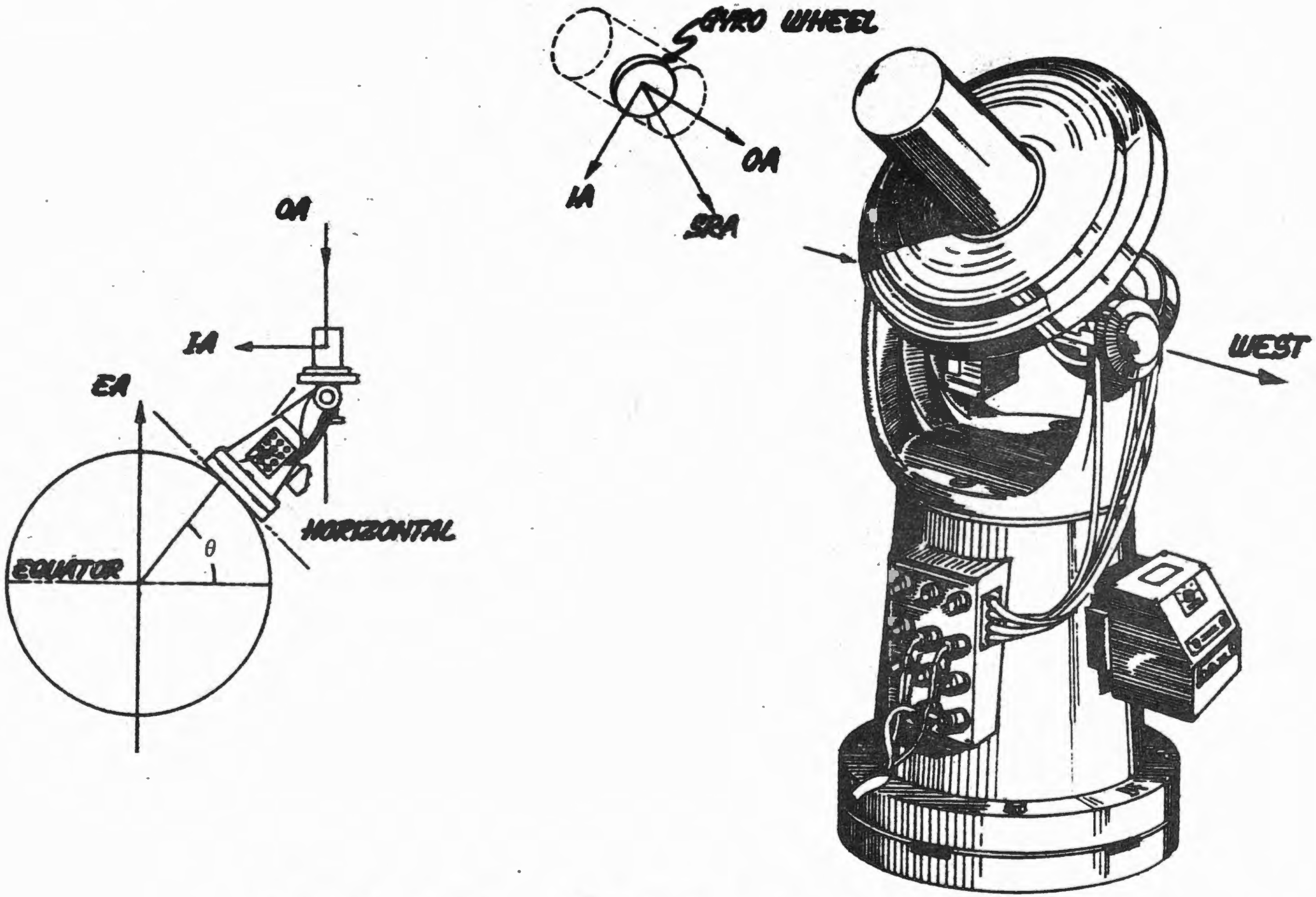


Figure 4-4. Gyro Orientation for Tumbling Test

Since the input axis of the gyro is in the equatorial plane, the gyro experiences no earth rate during the test, and the only inputs to the gyro are those caused by g acting on the unbalances. The turntable is rotated at 8 times earth rate so that a complete tumbling run is completed in three hours. Figure 4-6 shows the gyro axes with the gravity components in those directions superimposed upon them. Note that these components vary with both the latitude of the test site (θ) and the turntable rotation angle (ϕ).

Thus the mass unbalance terms in the equations shown later appear as $g \cos \theta U_{SRA}$ and $g \cos \theta U_{IA}$, while the compliance term appears as $g^2 \cos^2 \theta (K_{SRA} - K_{IA})$. Since the gyro coefficients are normally expressed for the full g case, these values must be divided by $\cos \theta$,(0.733 for Oak Creek) and $\cos^2 \theta$,(0.537),respectively. The terms will than appear as gU_{SRA}, gU_{IA}, and g^2K. The component of g along the output axis causes no torque about OA, and is therefore not shown in figure 4-6.



OA ∥ EA (TUMBLING)

Figure 4-5. Tumbling Test (Orientation Shown 90 Degrees After Start of Run)

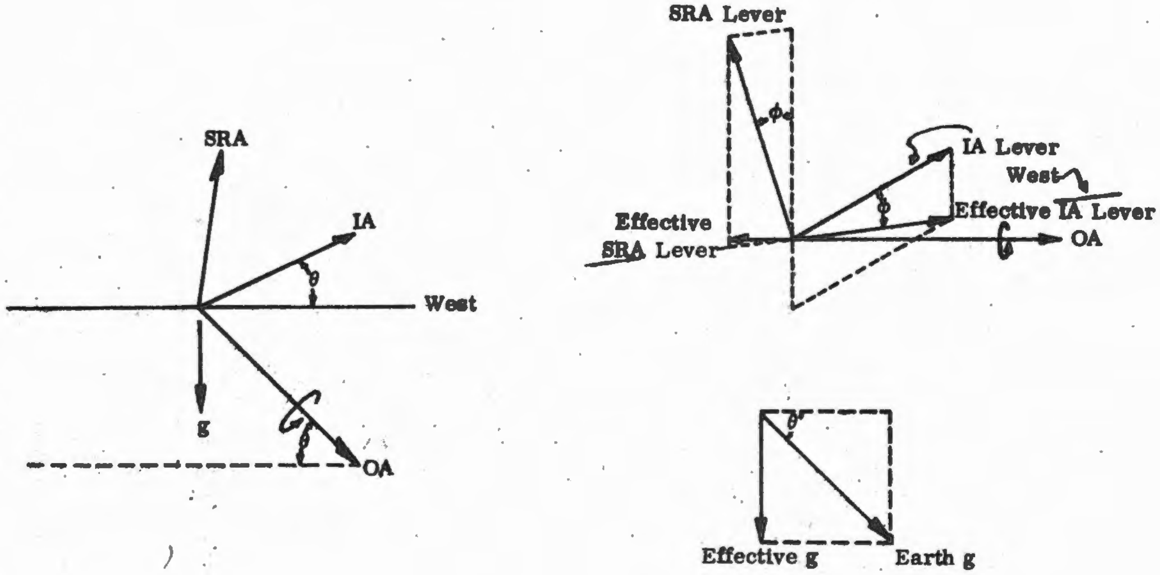


Figure 4-6. Gravity Components During Tumbling Tests

In order to measure the float torques during the tumbling test, the gyro float is held at null by feeding the amplified signal microsyn output back to the gyro torque microsyn in the proper phase. The torque microsyn current that is required to hold the float at null is recorded (see recorder, figure 4-7) and is a measure of the unbalance torques. The resultant plot of this current (or torque) versus turntable rotation angle is analyzed to determine the values and signs of U_{SRA}, U_{IA}, $(K_{SRA} - K_{IA})$, and R. The mechanization used to hold the gyro float at null is shown in figure 4-8.

3. THEORY OF OPERATION

As explained previously, mass unbalances are caused by minute imperfections in production and assembly, and lack of homogenity of materials. The result is the same as if small masses (gm) were attached to the gyro axes at short distances (cm) from the intersection of the axes. The units of mass unbalances then are gm cm (mass x distance). See figure 4-9.

Since torque is produced when a mass at a distance is accelerated (T = mad), the unbalances along the spin reference axis and the input axis can cause torques about the

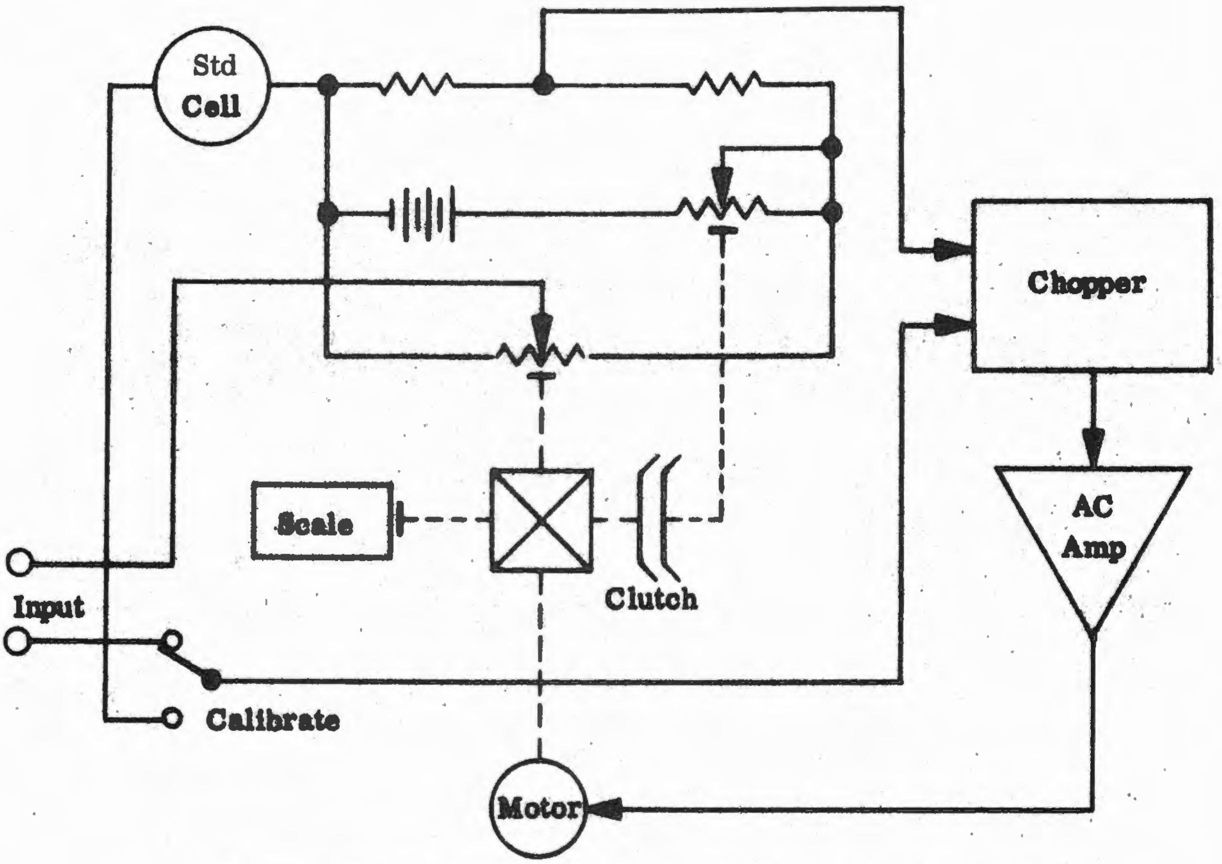


Figure 4-7. Simplified Mechanization Drawing of Recorder

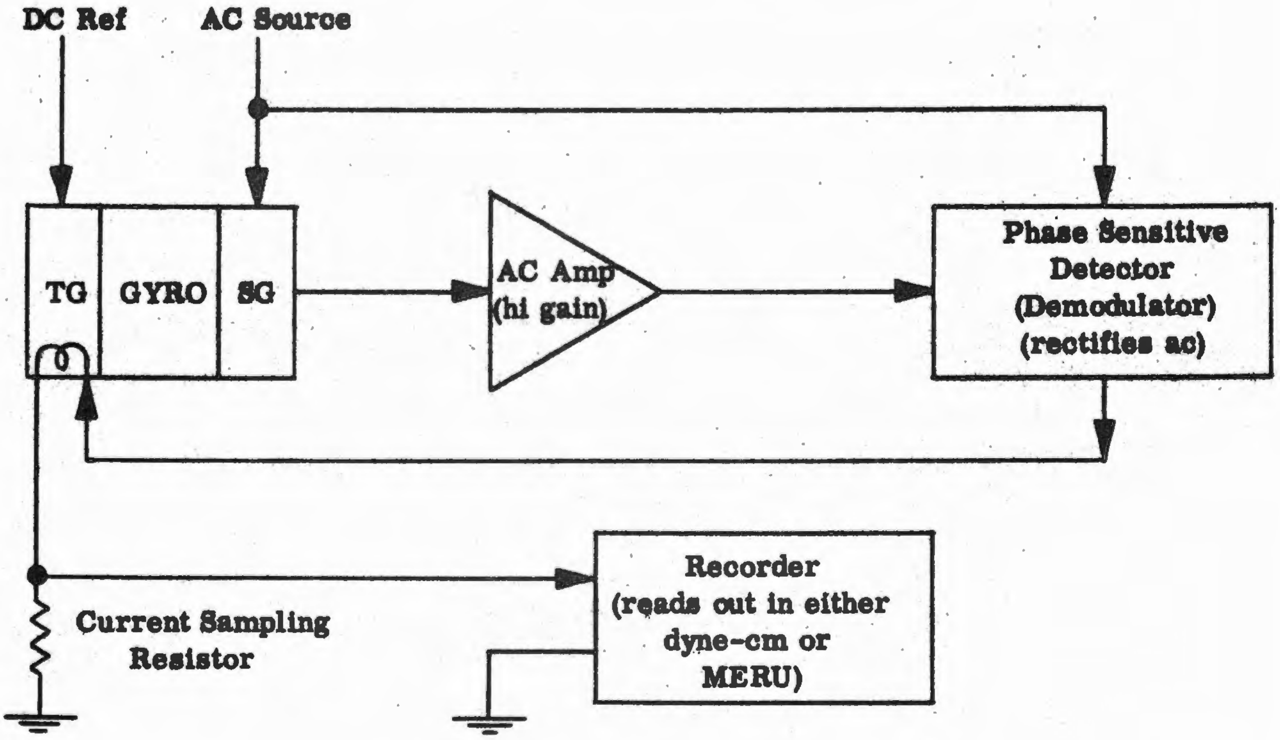


Figure 4-8. Mechanization of Tumbling Tests

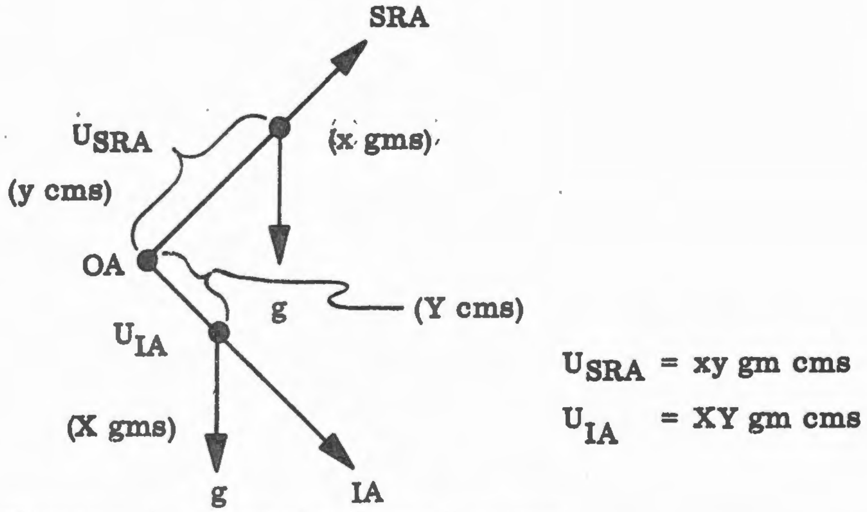


Figure 4-9. Mass Unbalance Torques

output axis when acted upon by the acceleration of gravity. The magnitude and direction of the torques is dependent upon the orientation of the axes. As shown in figure 4-10, when g acting on U_{SRA} at 0 degrees passes through OA, no torque results (the same result occurs at 180 degrees and 360 degrees). The clockwise torque produced by g acting on U_{SRA} at 45 degrees is .707 (sin 45 degrees) maximum. The torque reaches its maximum positive value (clockwise rotation) at 90 degrees and its maximum negative value (counterclockwise rotation) at 270 degrees.

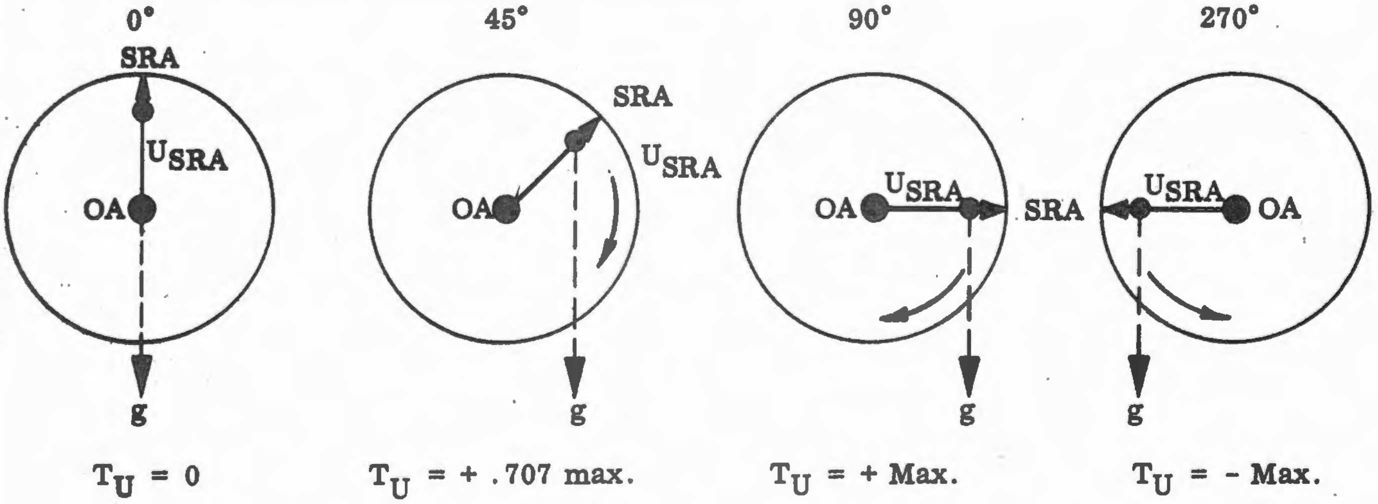


Figure 4-10. Mass Unbalance Torques
During One Revolution of Tumbling Run

The effect of compliance, which is caused by the fact that the gyro float is not equally rigid around its circumference, is the same as if the mass of the wheel and motor assembly were suspended by two sets of unequally stiff springs (one set along SRA and one set along IA). The action of components of gravity on the mass causes it to sag by an amount proportional to the stiffness of the springs supporting it. If the sagging mass is displaced from the plane containing OA and g, a component of gravity acting on the mass causes torque about OA. The torque thus developed is a maximum at positions that are a multiple of 45 degrees, and changes direction as the mass crosses the vertical. In figure 4-11, it can be seen at 0 degrees that, even though the mass has sagged a small amount, no torque is produced because the mass lies in the OA-g plane and the force of g acting on the mass passes through OA. At 90 degrees a larger sag occurs but the mass is still in the OA-g plane and no torque results. At 45 degrees, however, the position of the mass is the resultant of displacements along both axes and g acting on the mass causes a positive torque about OA. Similarly, at 135 degrees the mass has sagged the same amount but the torque produced is negative.

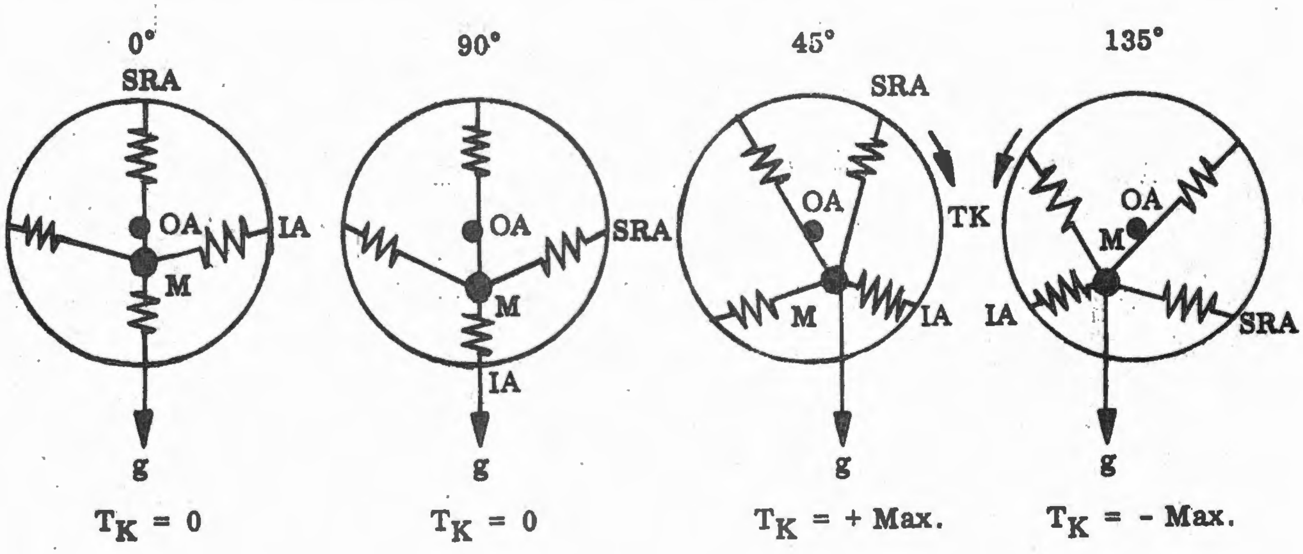


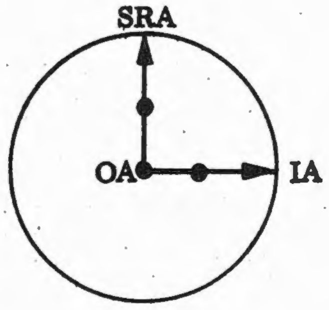
Figure 4-11. Compliance Unbalance Torques During One Revolution of Tumbling Run

Now with some understanding of what the unbalances are and how they are caused, let us look at the gyro axes every 45 degrees for one revolution of a tumbling run and write the torque equation for every point in terms of R (understood to be positive in this case), U_{IA}, U_{SRA}, and the sum of the compliance terms ($K_{SRA} - K_{IA}$), since they act in opposite directions. (See figure 4-12.)

Table 4-1 can also be constructed by referring to the nine figures shown in figure 4-12.

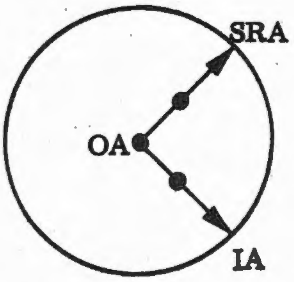
If we plotted the values in table 4-1, (T versus ϕ) we would find that g cos θ U_{SRA} describes a sine curve and g cos θ U_{IA} traces out a cosine curve, as shown in figure 4-13.

0°



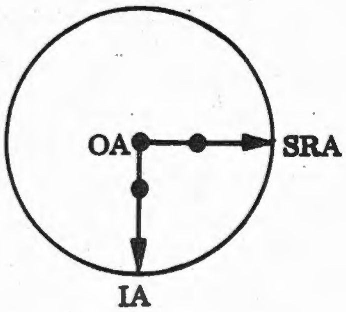
$$T = R + g \cos\theta\, U_{IA}$$

45°



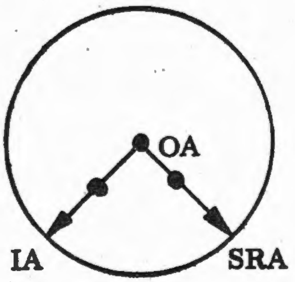
$$\begin{aligned} T = R &+ 0.707\, g \cos\theta\, U_{SRA} \\ &+ 0.707\, g \cos\theta\, U_{IA} \\ &+ g^2 \cos^2\theta\, (K_{SRA} - K_{IA}) \end{aligned}$$

90°



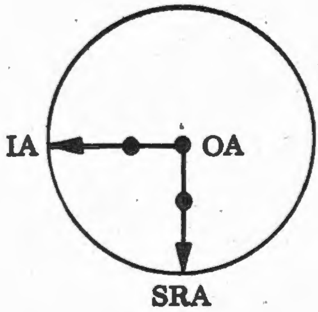
$$T = R + g \cos\theta\, U_{SRA}$$

135°



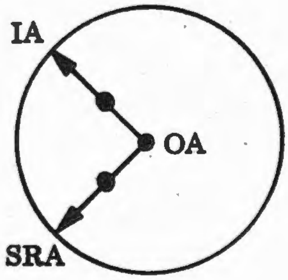
$$\begin{aligned} T = R &+ 0.707\, g \cos\theta\, U_{SRA} \\ &- 0.707\, g \cos\theta\, U_{IA} \\ &- g^2 \cos^2\theta (K_{SRA} - K_{IA}) \end{aligned}$$

180°



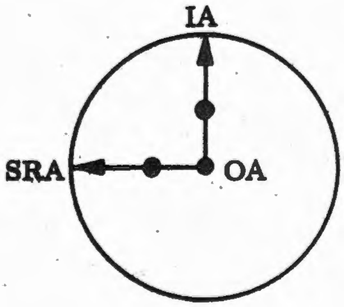
$$T = R - g \cos\theta\, U_{IA}$$

225°



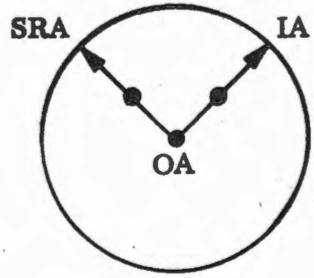
$$\begin{aligned} T = R &- 0.707\, g \cos\theta\, U_{SRA} \\ &- 0.707\, g \cos\theta\, U_{IA} \\ &+ g^2 \cos^2\theta (K_{SRA} - K_{IA}) \end{aligned}$$

270°



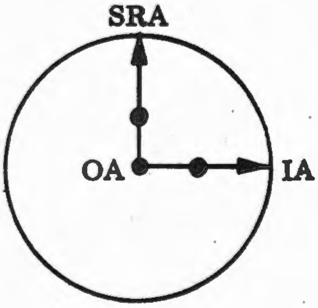
$$T = R - g \cos\theta\, U_{SRA}$$

315°



$$\begin{aligned} T = R &- 0.707\, g \cos\theta\, U_{SRA} \\ &+ 0.707\, g \cos\theta\, U_{IA} \\ &- g^2 \cos^2\theta (K_{SRA} - K_{IA}) \end{aligned}$$

360°



$$T = R + g \cos\theta\, U_{IA}$$

Figure 4-12. Total Unbalance Torques During One Revolution of Tumbling Run

Unbalance \ ϕ	0°	45°	90°	135°	180°	225°	270°	315°	360°
$g \cos \theta U_{SRA}$	0	+.707	+Max.	+.707	0	-.707	-Max.	-.707	0
$g \cos \theta U_{IA}$	+Max.	+.707	0	-.707	-Max.	-.707	0	+.707	+Max.
$g^2 \cos^2 \theta(K_{SRA} - K_{IA})$	0	+Max.	0	-Max.	0	+Max.	0	-Max.	0
R	+Max.	+Max.	+Max.	+Max.	+Max.	+Max.	+Max.	+Max.	+Max.

Table 4-1. Tabulation of Tumbling Run Unbalances

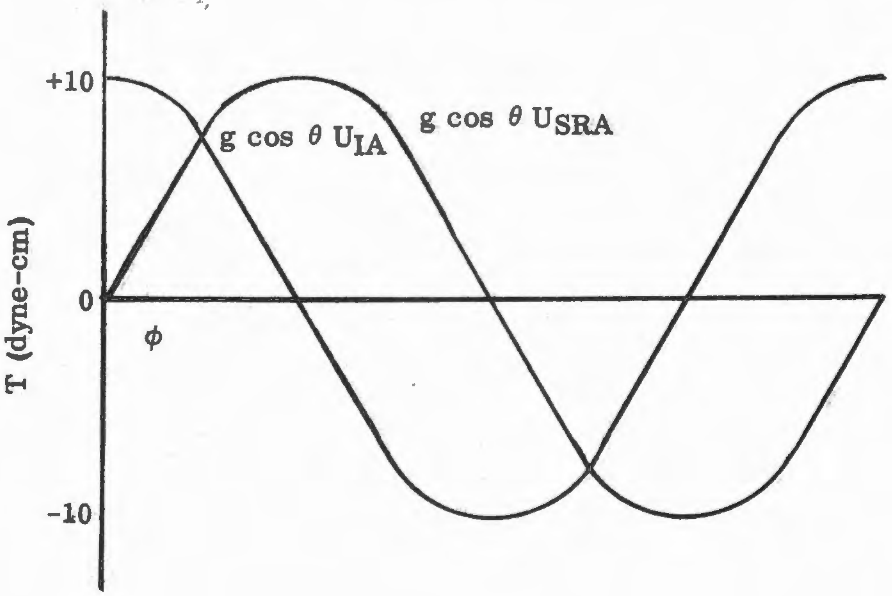


Figure 4-13. Plot of Mass Unbalance Torques versus Turntable Angle

The values of $g^2 \cos^2 \theta(K_{SRA} - K_{IA})$ indicate that it is also sinusoidal but that it completes two cycles (second harmonic) during every revolution of the turntable. As R remains constant (is independent of g) its graph is a straight line. These two curves are shown on the same axis in figure 4-14.

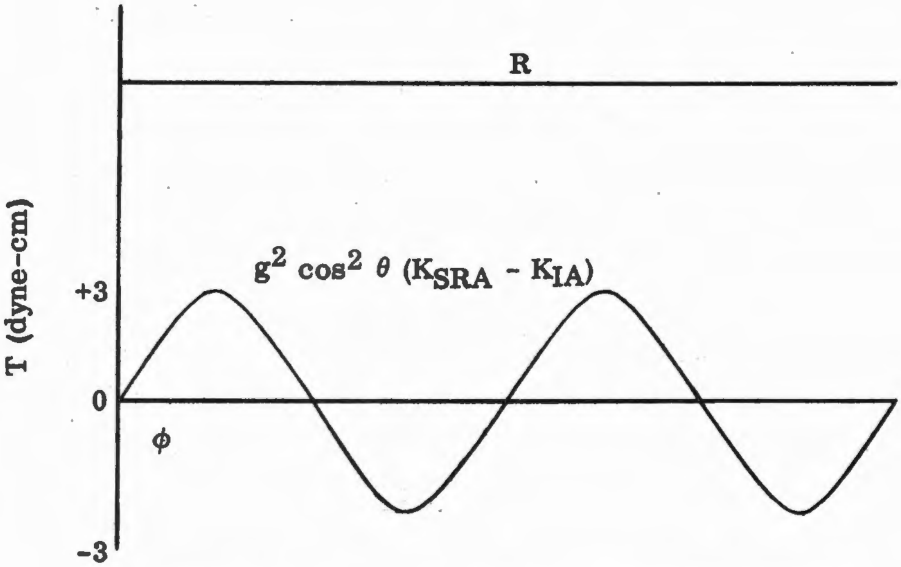


Figure 4-14. Plot of R-Term and Compliance Unbalance Torques versus Turntable Angle

The curve plotted by the recorder in the tumbling test mechanization, which looks similar to the curve in figure 4-15, is actually a composite of the four curves just developed. The small jogs in the curve are due to the cyclic action of the gyro heaters.

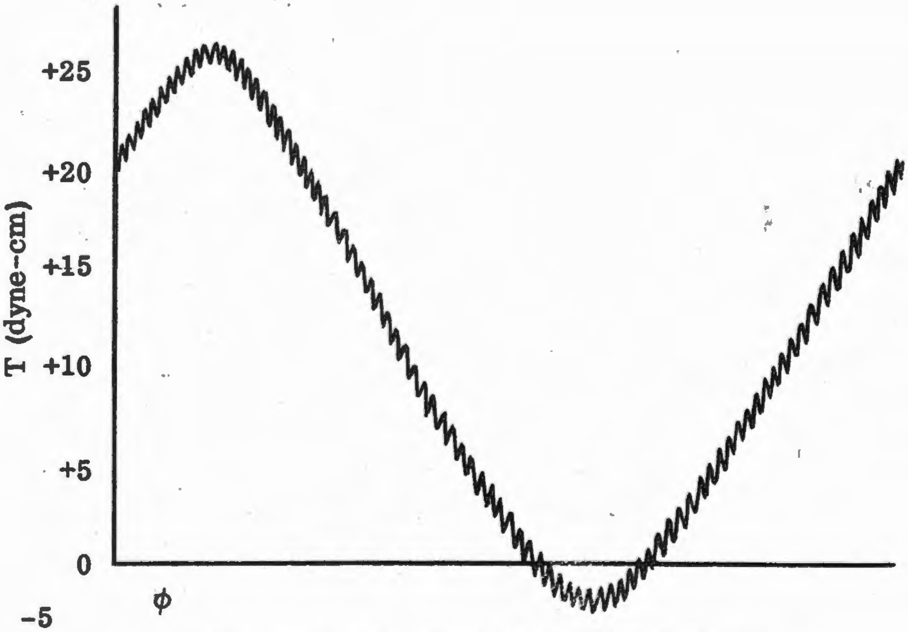


Figure 4-15. Plot of Total Unbalance Torques versus Turntable Angle

4. ANALYSIS OF TUMBLING TEST RESULTS

The T versus ϕ curve obtained during the tumbling run can be broken down to determine the values of the various unbalances by the following procedure. Table 4-1 shows that U_{SRA} is at its maximum positive value at 90 degrees and at a maximum negative value at 270 degrees. If the torque equations (found in figure 4-12) for these two positions are added, then gU_{SRA} will be eliminated and the equations can be solved to obtain R:

$$\begin{array}{rll} T_{(90\text{ degrees})} &= R + g\cos\theta\, U_{SRA} & (4\text{-}1)\\ +T_{(270\text{ degrees})} &= R - g\cos\theta\, U_{SRA} & (4\text{-}2)\\ \hline T_{(90\text{ degrees})} + T_{(270\text{ degrees})} &= 2R & \end{array}$$

$$R = R_1 = \frac{1}{2}\left[T_{(90\text{ degrees})} + T_{(270\text{ degrees})}\right]. \qquad (4\text{-}3)$$

The same thing is now done with the torques at 0 degrees and 180 degrees to eliminate gU_{IA} and solve for R again as a check:

$$\begin{array}{rll} T_{(0\text{ degrees})} &= R + g\cos U_{IA} & (4\text{-}4)\\ +T_{(180\text{ degrees})} &= R - g\cos U_{IA} & (4\text{-}5)\\ \hline T_{(0\text{ degrees})} + T_{(180\text{ degrees})} &= 2R & \end{array}$$

$$R = R_2 = \frac{1}{2}\left[T_{(0\text{ degrees})} + T_{(180\text{ degrees})}\right]. \qquad (4\text{-}6)$$

R_1 and R_2 should agree very closely, but will probably not be exactly equal. The final value of R, therefore, is found by averaging the two values.

$$R = \frac{1}{2}\left(R_1 + R_2\right) \qquad (4\text{-}7)$$

This value of R is then substituted into equation 4-1 and that equation solved for gU_{SRA}:

$$gU_{SRA} = \frac{T_{(90\text{ degrees})} - R}{\cos\theta}.$$

Similarly, the value of R is inserted into equation 4-4 and that equation solved for gU_{IA}:

$$gU_{IA} = \frac{T_{(0\text{ degrees})} - R}{\cos\theta}.$$

Now the values of R, gU_{SRA}, and gU_{IA} are put into the equation for the torque at 45 degrees, and that equation solved for $g^2 (K_{SRA} - K_{IA})$:

$$g^2 (K_{SRA} - K_{IA}) = \frac{T_{(45\ \text{degrees})} - R - 0.707 \cos\theta\,(gU_{SRA} + gU_{IA})}{\cos^2\theta}. \qquad (4\text{-}8)$$

As was pointed out earlier, with the 25 PIG and 25 IRIG gyros the aim of preloading the wheel bearings is to equalize the compliance along SRA and IA. If this effort is entirely successful, then $K_{SRA} - K_{IA} = 0$ and the compliance terms are eliminated from all the equations containing them. The physical interpretation of why equalizing the compliances along SRA and IA eliminates torque about OA is that the springs (used in the previous analogy) are equally stiff, so that the wheel and motor mass remains in the OA-g plane, as shown in figure 4-16.

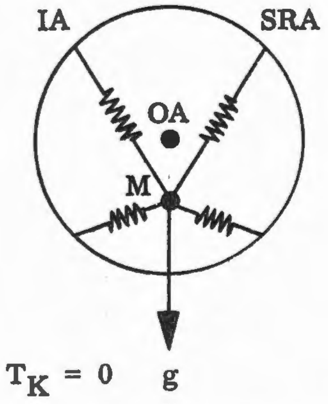


Figure 4-16. Case of Equal Compliances

If it is desired to know the unbalances that gave rise to the mass unbalance torques, it is only necessary to divide the torque by the g cos θ to obtain the equivalent mass and lever arm of the unbalance:

$$\frac{T\ (\text{dyne-cm})}{g \cos\theta\ (\text{cm/sec}^2)} = U\ (\text{gm cm}). \qquad (4\text{-}9)$$

Any of the unbalance torques can be expressed in terms of the equivalent earth rate necessary to produce the torque. This is done by dividing the torque by the angular momentum of the gyro in order to get the equivalent input rate to cause the torque, and dividing this rate by 7.29×10^{-8} rad/sec/MERU.

$$\frac{T}{H} = \omega_{IA} \text{ (rad/sec)} \tag{4-10}$$

$$\frac{\omega_{IA} \text{ (rad/sec)}}{\dfrac{7.29 \times 10^{-8} \text{ rad/sec}}{\text{MERU}}} = \text{MERU.} \tag{4-11}$$

A summary of gyro unbalances is given below.

The general unbalance equation for tumbling tests is shown in figure 4-18. Figure 4-17 illustrates the general unbalance equation for servo tests, to be discussed later.

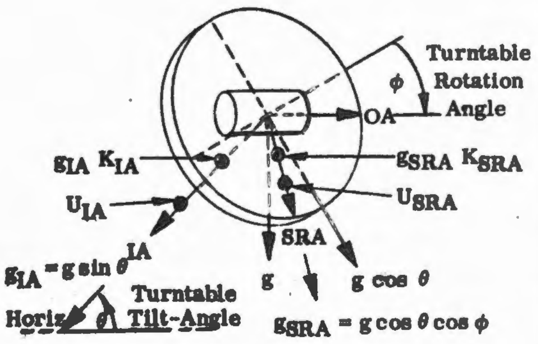
Gyro unbalances which produce torques about the gyro Output Axis are:

R	The sum of residual motor power lead torque and signal microsyn and torque microsyn reaction torque.	Units: dyne-cm
U_{SRA}	The product of a mass and the distance it is displaced along the positive Spin Reference Axis.	Units: gm-cm
U_{IA}	An unbalance, similar to U_{SRA} located along the positive Input Axis.	Units: gm-cm
$g_{SRA}\ K_{SRA}$	The product of a mass and the distance it is displaced along the positive Spin Reference Axis. The displacement results from the compliance (units: cm/dyne) of wheel and gimbal structure and is proportional to the component of gravity or acceleration along the SRA.	Units: gm-cm
$g_{IA}\ K_{IA}$	An unbalance, similar to $g_{SRA}\ K_{SRA}$, located along the positive Input Axis.	Units: gm-cm

C. SERVO TEST

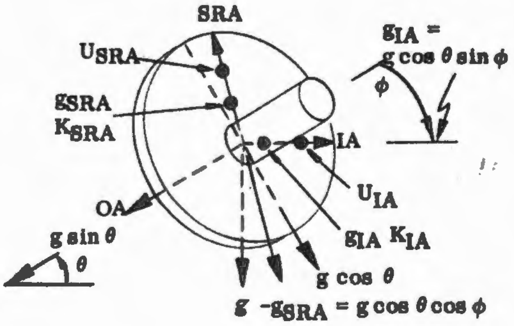
1. PURPOSE

Servo testing provides the best measure of gyro quality since the gyro being tested is used to control rotational motion in a manner similar to its final use. In servo testing of both pendulous and stabilization gyros the gyro manipulates the rotation of the turntable upon which it is mounted so that the resulting precessional torque holds the float at null. Examination of the table rotation, therefore, gives a measure of the gyro performance. The most important characteristic of the way in which the gyro controls the turntable is "repeatability" — the gyros's ability to produce



$$U_{OA} = R + U_{SRA}\, g \sin\theta - U_{IA}\, g \cos\theta \cos\phi$$
$$+ K_{SRA}\, g \cos\theta \cos\phi\, g \sin\theta$$
$$- K_{IA}\, g \sin\theta\, g \cos\theta \cos\phi$$
$$U_{OA} = R + g U_{SRA} \sin\theta - g U_{IA} \cos\theta \cos\phi$$
$$+ g^2 \frac{(K_{SRA} - K_{IA})}{2} \sin 2\theta \cos\phi$$

Figure 4-17. Servo Test (Starting Position OA Horizontal West)



$$U_{OA} = R + U_{SRA}\, g \cos\theta \sin\phi + U_{IA}\, g \cos\theta \cos\phi$$
$$- K_{SRA}\, g \cos\theta \cos\phi\, g \cos\theta \sin\phi$$
$$+ K_{IA}\, g \cos\theta \sin\phi\, g \cos\theta \cos\phi$$
$$U_{OA} = R + g U_{SRA} \cos\theta \sin\phi + g U_{IA} \cos\theta$$
$$\cos\phi - g^2 \frac{(K_{SRA} - K_{IA})}{2} \cos^2\theta \sin\phi$$

Figure 4-18. Tumbling Test (Starting Position IA Horizontal West)

identical table motions in separate tests conducted under identical conditions. Repeatability means that the gyro is stable and may be relied upon for a specific type of performance. Therefore, compensation may be planned in advance to alter this performance if desired.

2. TEST CONDITIONS — STABILIZATION GYRO

The gyro is mounted on the turntable with its input axis parallel to the table rotational axis. (The method of aligning the input axis precisely will be explained later.) The table axis is usually positioned vertical, horizontal, or parallel with the Earth Polar Axis so that a known component of earth rate may be used as the test input.

The orientation selected depends upon the type of unit to be tested and the specific objectives of the particular run. In some special tests the table axis and gyro input axis may be oriented perpendicular to the earth's axis so that no input is sensed. Figure 4-19 is a generalized mechanization drawing of the servo test equipment setup.

The phasing of the servo is such as to keep the float of the gyro at null. (It will be remembered that in the tumbling test the gyro float was maintained at null through the torque microsyn. The servo test, on the other hand makes use of the H of the gyro to produce a precessional torque to balance out the unbalance torques in the unit.) If the turntable alignment permits the gyro to experience earth rate, or some portion of it, the servo will rotate the table at that rate, plus or minus a rate dependent upon the unbalance torques present in the gyro.

The general float torque equation for gyro servo test operation is:

$$T_{OA} = \pm H\omega_{IA}(\text{Table}) \pm H\omega_{IA}(\text{External}) \pm C_D\omega_{OA} \pm R \pm gU$$
$$\pm g^2K \pm I_{OA}\,\alpha_{OA} \pm T_{TG} = 0 \qquad (4\text{-}12)$$

For steady state operation, with the float at null, the average damping and inertia torques ($C_D\,\omega_{OA}$ and $I_{OA}\,\alpha_{OA}$) are zero, and may be omitted from the equation.

The servo has the job of keeping the float at null, but can produce a torque only through the term $H\omega_{IA}$ (Table). Therefore, it manipulates the table rate and equation 4-12 may be rewritten:

$$\pm H\omega_{IA}(\text{Table}) = \pm H\omega_{IA}(\text{External}) \pm R \pm gU \pm g^2K \pm T_{TG} \qquad (4\text{-}13)$$

Thus it may be seen that the turntable rate ω_{IA} (Table) when multiplied by H, produces a torque which just cancels all the torques on the right hand side of the equation. Therefore measurement of table rate indicates the magnitude of these torques. In the test laboratory the external input, ω_{IA} (External), is precisely known (usually some portion of earth rate). Thus a certain known portion of ω_{IA} (Table) is attributed to cancelling the external input. The deviation from this portion of table rate is a measure of the lumped unbalances. The various test orientations described below alter the unbalances relative to each other so that they may be separated by combined tests.

Since the unbalance terms are known when the gyro is put into actual service, they may be compensated for, so that in use the gyro controls the motion of the table (or inertial platform) to cancel only the external inputs which are the unknowns in this case, thus stabilizing the platform in space.

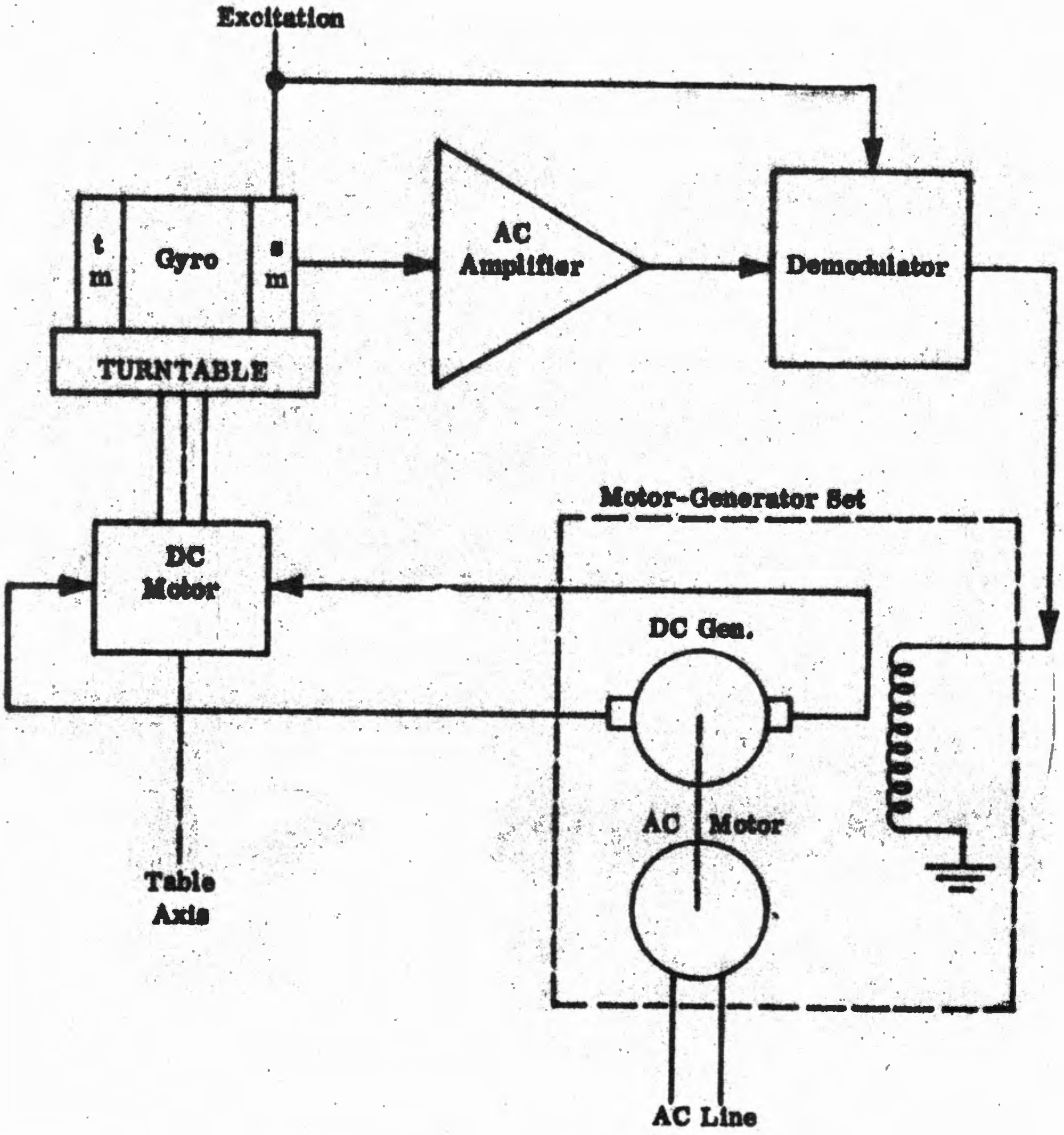


Figure 4-19. Servo Test Mechanization

Table rate measurement has a dual function: measurement of the input rate if the unbalances are known or cancelled, or measurement of the unbalances if the external input rates are known or cancelled. If we have a perfectly balanced gyro, or use the torque generator torque, T_{TG}, to cancel the unbalances, $R + gU + g^2K$, we have

$$+H\omega_{IA}(\text{Table}) - H\omega_{IA}(\text{External}) = 0 \quad (4\text{-}14)$$

and the two rates are equal. This condition produces no gyro drift (deviation of table rate from the input rate being measured).

Notice in the equation above that since H enters both terms, wheel speed regulation in this ideal case is not important. In actual practice the degree of wheel speed regulation necessary depends upon the magnitude of the unbalances relative to the external torque inputs.

3. SERVO TEST ORIENTATIONS

The common orientations for servo testing are shown in figures 4-20 to 4-22. In each of these cases the starting position is OA horizontal west.

a. Table Axis Parallel to Earth Polar Axis

Figure 4-23 shows the orientation of the gyro on the turntable for this test.

$H\omega_{IA}$(External) = Full earth rate torque, $H\omega_E$

Unbalances = $(R + C_1\,gU_{SRA}) + (C_2\,gU_{IA} + C_3\,g^2K)\cos\phi$

where C_1, C_2, and C_3 are constants and ϕ is the turntable rotation angle with the starting position shown in figure 4-23.

The table rate shows a deviation from earth rate of a constant (the magnitude of which depends upon R and a portion of gU_{SRA}) plus a cosine term (the magnitude of which depends upon portions of gU_{IA} and g^2K). Unbalances cannot be separated from this single run.

b. Table Axis Vertical

Figure 4-24 shows the orientation of the gyro on the turntable for this test.

$H\omega_{IA}$(External) = Vertical component of earth rate torque $H\omega_E$ (vert)

Unbalances = $R + gU_{SRA}$

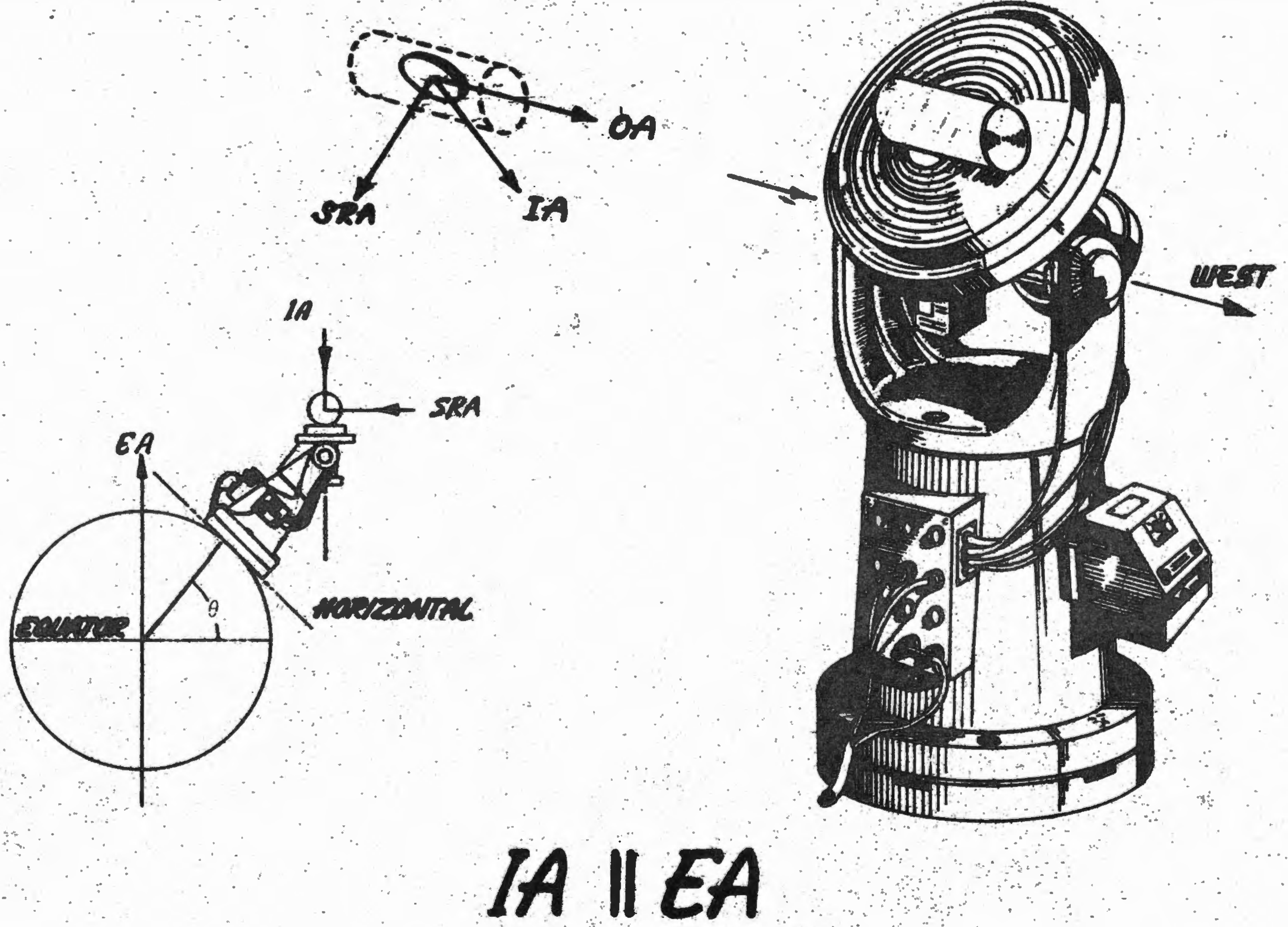


Figure 4-20. **Servo Test, Input Axis Parallel to Earth Axis**

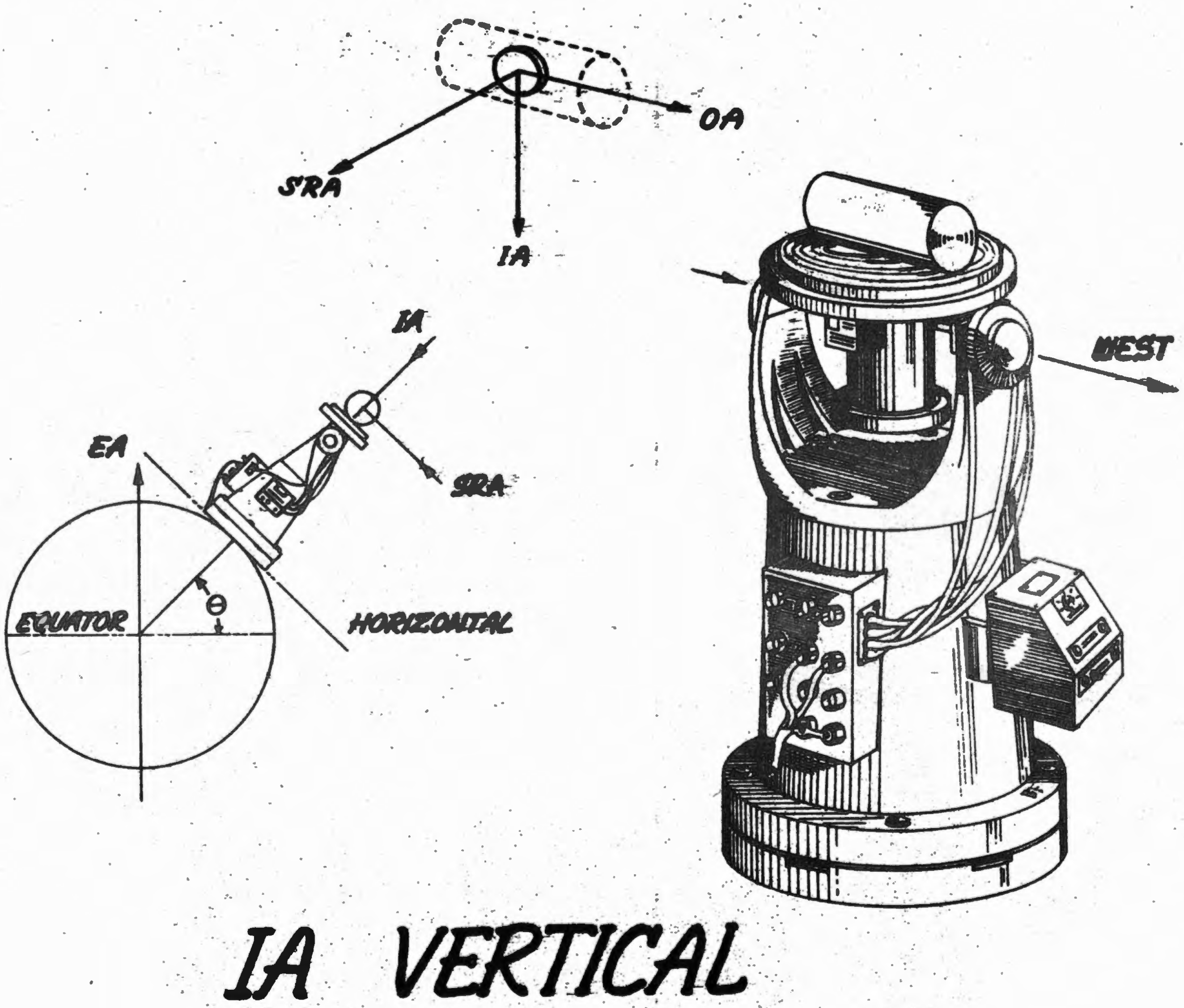
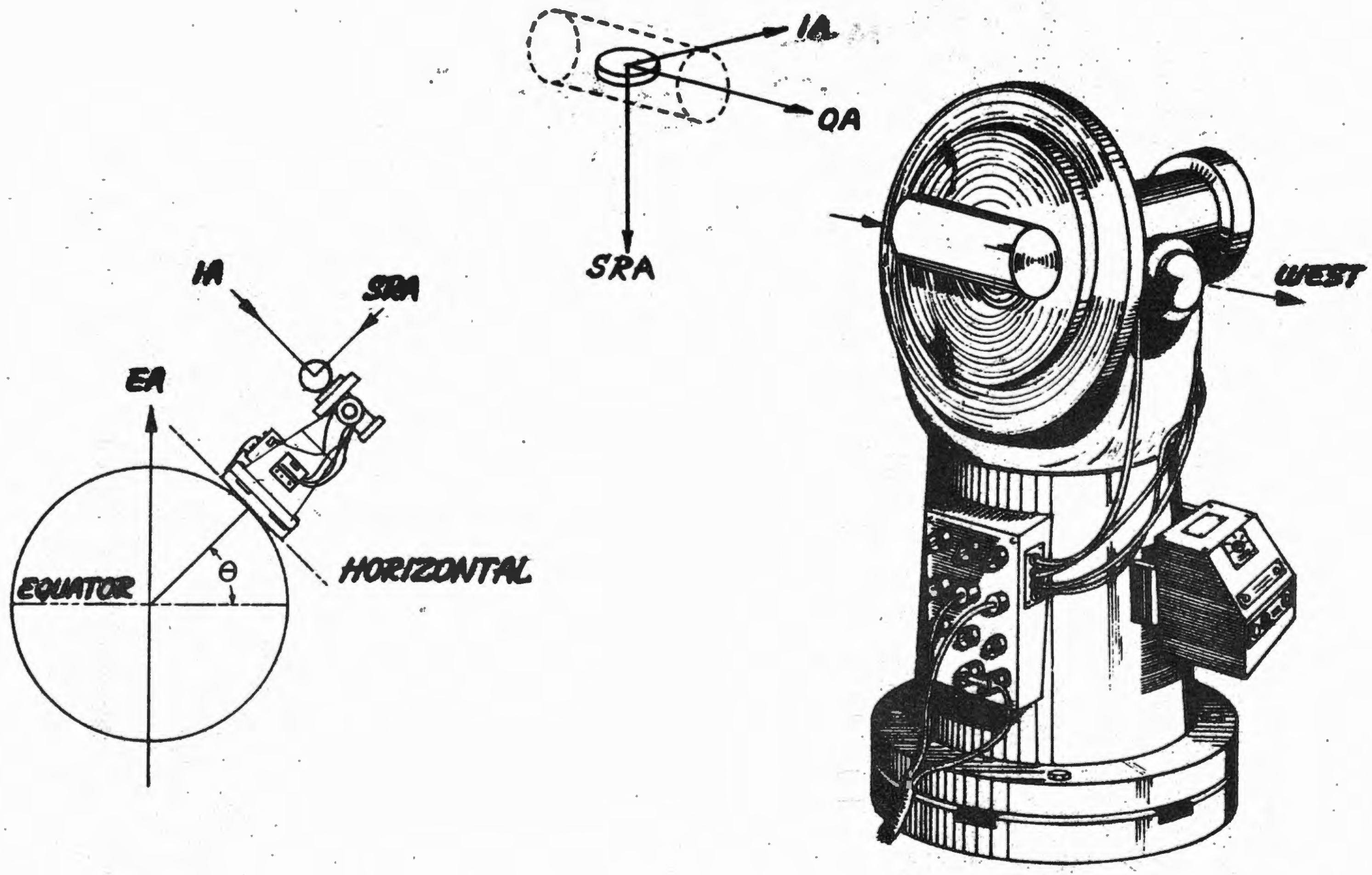


Figure 4-21. Servo Test, Input Axis Vertical



IA HORIZONTAL

Figure 4-22. Servo Test, Input Axis Horizontal

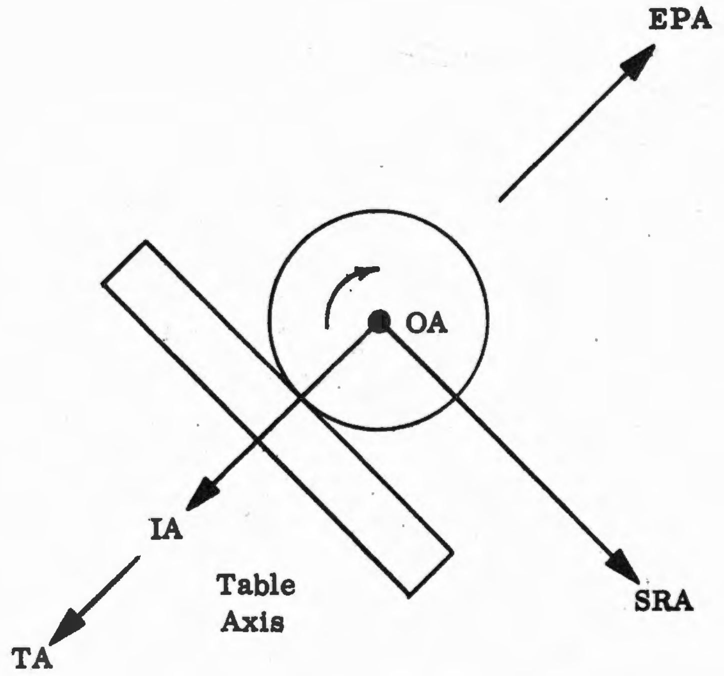


Figure 4-23. Parallel Orientation

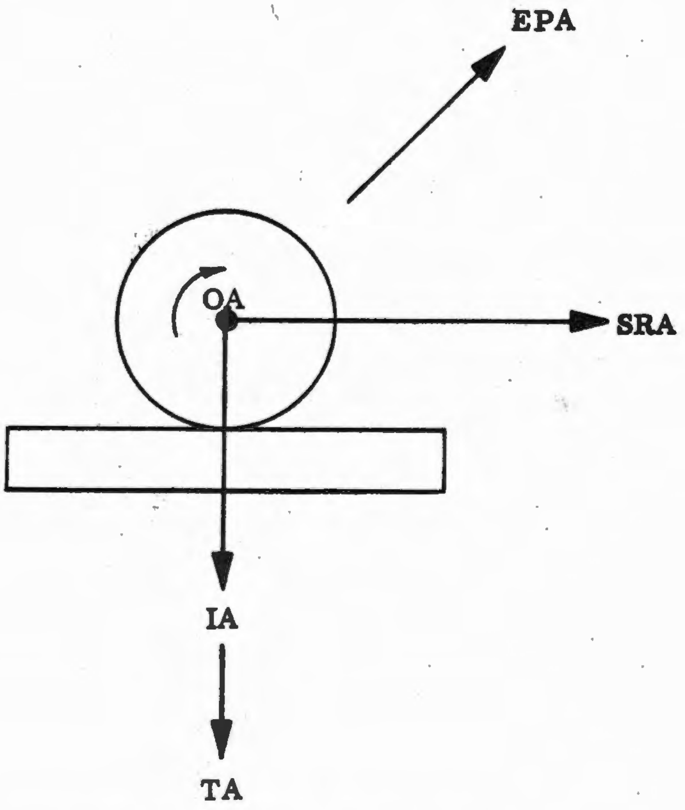


Figure 4-24. Vertical Orientation

Table rate deviation from vertical earth rate (note figure 4-24) is a constant rate, the magnitude of which depends upon the sum of R and gU_{SRA}.

c. Table Axis Horizontal

Figure 4-25 shows the orientation of the gyro on the turntable for this test.

$H\omega_{IA}$(External) = Horizontal component of earth rate torque, $H\omega_E$ (Horiz)

Unbalances = $R - gU_{IA} \cos \phi$

Table rate deviation from vertical earth rate is a constant rate, the magnitude of which depends upon R, plus a cosine term depending upon gU_{IA}. (Note figure 4-25.)

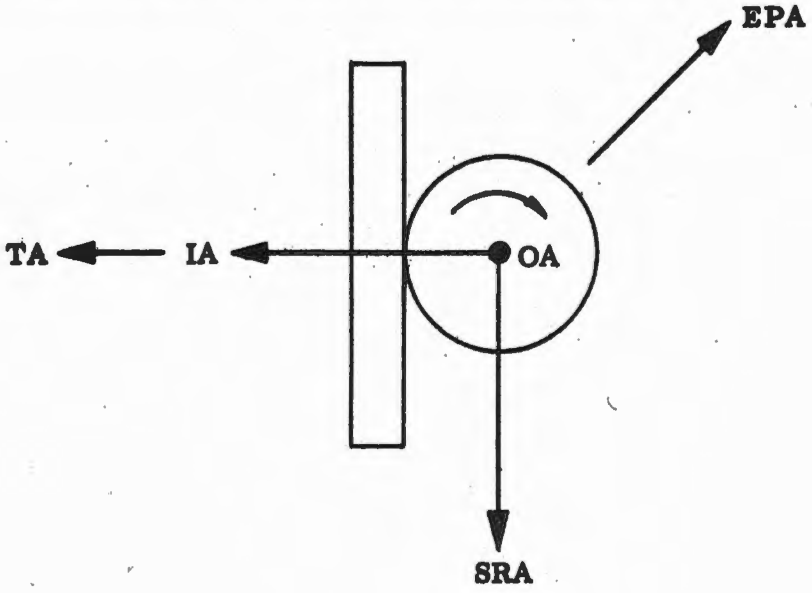


Figure 4-25. Horizontal Orientation

The testing of some gyros includes timing of the turntable for 10 degrees (5 degrees on each side of the SRA down position shown) and again for 10 degrees through the SRA up region; so that the value of cos ϕ is +1 and -1, respectively, and the unbalances are:

$U_{(SRA\ Down)} = R - gU_{IA}$

$U_{(SRA\ Up)} = R + gU_{IA}$.

Addition and subtraction of the equations therefore yield the values of R and gU_{IA}. Similarly, these values may be inserted into the equations for the orientations in a. and b. above in order to compute the remaining terms.

In one form of testing, a 10 degree segment of table rate is measured in the three orientations of IA vertical, IA horizontal with SRA up, and IA horizontal with SRA down. Unbalance coefficients are computed, and the entire test repeated after a storage period of three days. The repeatability of coefficients determines the quality of the unit.

4. ANALYSIS OF SERVO TEST RESULTS

Figure 4-27 shows the turntable rates experienced during servo testing in the three orientations discussed above. The dotted lines show the components of earth rate sensed by the gyro and would be the rate at which the turntable was driven if the gyro were perfect (without unbalances). The solid lines show the deviation of turntable rate due to unbalance torques in the actual gyro.

The repeatability of a gyro is determined by making several servo runs and comparing sets of two runs. Repeatability may be plotted as a curve of the difference between two selected runs, as shown in Figure 4-26.

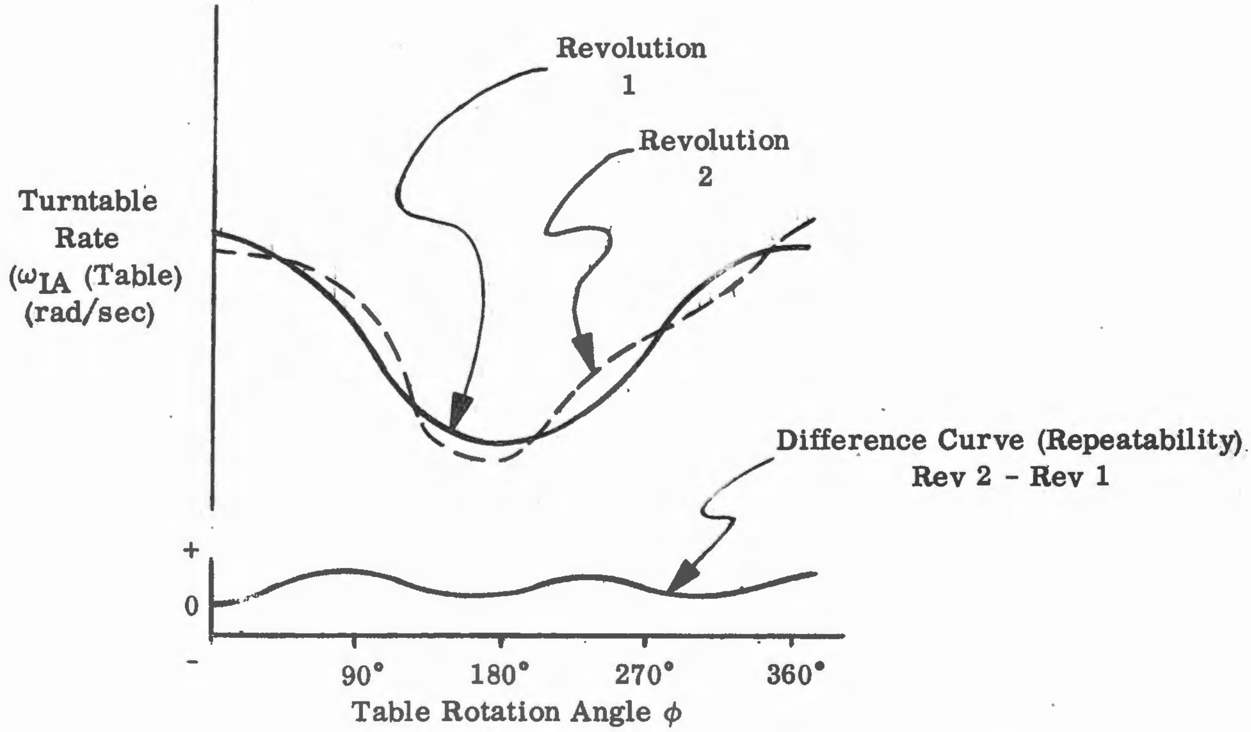


Figure 4-26. Computation of Gyro Repeatability from Servo Tests

Or, repeatability may be expressed as a single number by tabulating the values of the difference curve at 10 degree intervals and computing the RMS value of the tabulation.

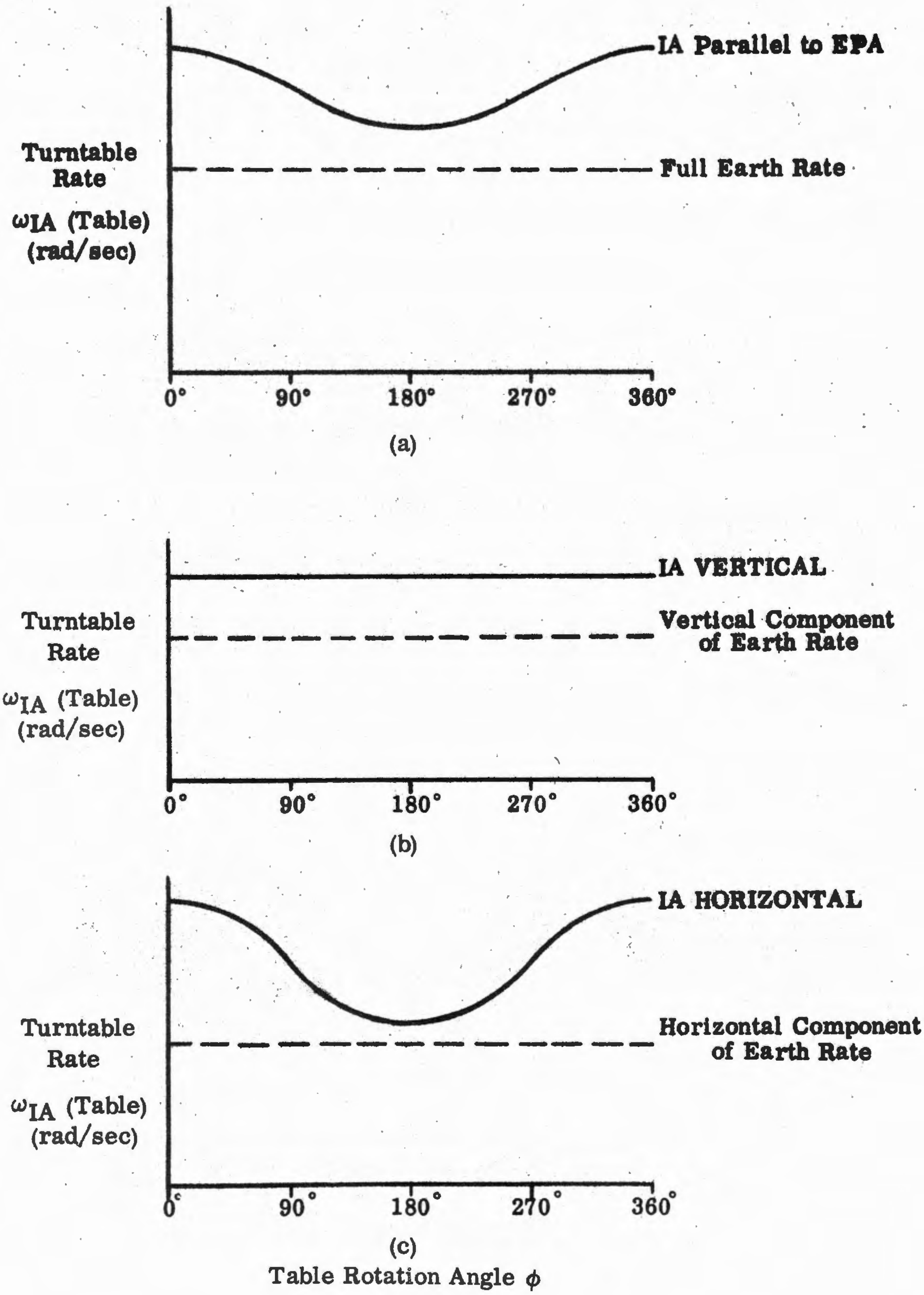


Figure 4-27. Servo Test Results

5. SPECIAL SERVO TESTS

In contrast to the dynamic testing described above, in which the gyro causes the table motion to nearly equal some input motion, tests may be run in which the gyro senses no input motion, or the torque created by the input is cancelled with the torque generator. These type tests are diagrammed in figure 4-28 (a) and (b), respectively.

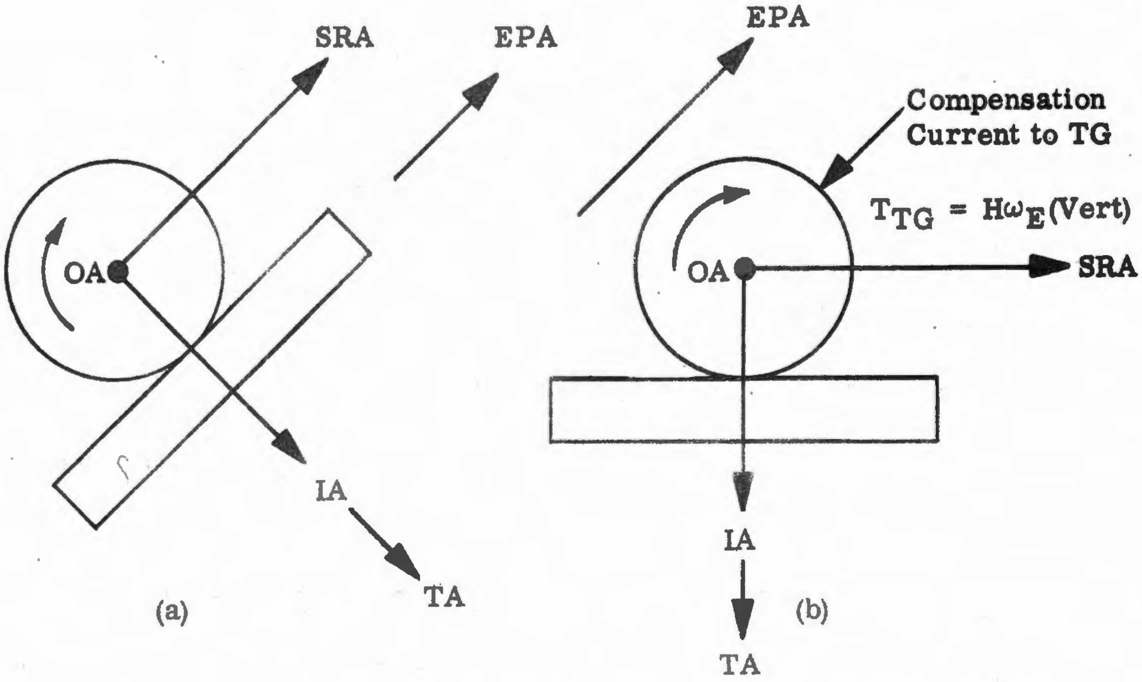


Figure 4-28. Servo Tests with IA Perpendicular to EPA and IA Vertical

If unbalances are compensated for at the start of the servo test, the table will remain stationary and its position monitored either optically or electrically. As the test progresses, a shift in table position is interpreted as meaning a change in the balance of the unit. The test offers the advantage of continuous monitoring, and sudden or short term shifts in unbalance will readily be seen. However, since any restriction in gyro float freedom will aid the turntable stability, resulting in apparently good performance from a poor gyro, care must be taken to previously determine the general quality of the gyro. In addition, periodic introduction of some float motion (electronic dither) to assure its freedom should be a part of the test.

6. TEST CONDITIONS — PENDULOUS GYRO

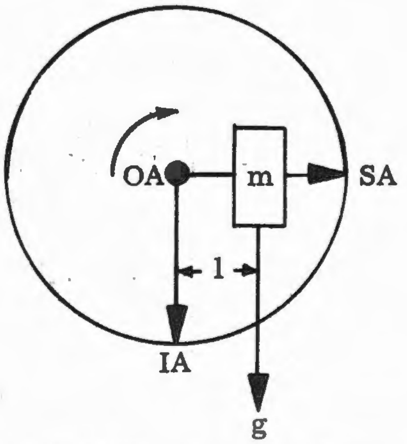
The turntable orientation for the pendulous gyro is the same as for the stabilization gyro, with the gyro input axis aligned parallel with the turntable rotational axis.

The general servo mechanization drawing (figure 4-19) used for the stabilization gyro also applies to the pendulous gyro. The differences in gyro use, as we shall see, are brought about only by the relative magnitude of the familiar unbalance terms.

We may therefore repeat equation 4-13 as being applicable to an IA vertical servo test.

$$\pm H\omega_{IA}(\text{Table}) = \pm H\omega_{IA}(\text{External}) \pm R \pm gU \pm g^2K \pm T_{TG}$$

The pendulous gyro differs from the stabilization gyro in the magnitude of spin axis unbalance, usually brought about by offsetting the wheel assembly along the spin axis as shown in figure 4-29.



$U_{SRA} = ml$

Figure 4-29. Gyro Pendulous Mass

The spin axis unbalance, U_{SRA}, consists of the mass of the wheel assembly, m, displaced a distance, l, from the center of the float. With the force of gravity acting upon this unbalance, gU_{SRA} is very, very large, (22, 400 dyne-cm for the 25 PIG gyro; a comparable stabilization gyro is balanced to about 0.1 dyne-cm). The values of input axis unbalance, gU_{IA}, and compliance torque, g^2K, are negligible by comparison. In addition, torque from the vertical component of earth rate, $H\omega_{IA}$ (External) in equation 4-13 is small (3 dyne-cm for the 25 PIG) and may be corrected for since its value is known. We therefore have a device very sensitive to the force of gravity, or to linear acceleration acting upon U_{SRA}.

If we then use a correction factor for earth rate and R, and omit gU_{IA}, g^2K, and T_{TG}, we may rewrite equation 4-12 as:

$$H\omega_{IA}(\text{Table}) = gU_{SRA} \qquad (4\text{-}15)$$

but $U_{SRA} = ml$, so that by substitution and rearrangement of equation 4-12,

$$\frac{\omega_{IA}(\text{Table})}{g} = \frac{ml}{H} \; \frac{\text{rad/sec}}{g} . \qquad (4\text{-}16)$$

We define the ratio above as the accelerometer scale factor. Noting that g = 980 cm/sec^2, we can divide the scale factor by 980 and its units will be $\frac{\text{rad/sec}}{\text{cm/sec}^2}$. Observe that the servo driven turntable angular velocity is proportional to the gravity or acceleration force acting along IA, or

$$\omega_{IA} = K \alpha_{IA}$$

where K is the scale factor. If a steady acceleration is applied for some time, t, we may multiply both sides of the equation by t:

$$\omega_{IA} t = K \alpha_{IA} t. \qquad (4\text{-}17)$$

But the angle of turntable travel $\phi = \omega_{IA} t$, while $\alpha_{IA} t$ is the linear velocity, V, being experienced along IA. It is this relationship which is used in actual practice to measure the linear velocity of the vehicle upon which the accelerometer is mounted. Since velocity, V, is the time integral of acceleration ($V = {}_0\int^t \alpha \, dt$) the accelerometer is called an integrating accelerometer. (This integrating action concerns the gyro on a servo driven mount, and should not be confused with the previously discussed integrating action of the gyro float.)

In servo testing of the pendulous gyro the IA vertical tests, with g acting along the IA, are referred to as 1g input tests. In addition, we may tilt the turntable and perform tests where a fraction of g acts along IA, as shown in figure 4-30.

The unbalance equations used for the stabilization gyro also apply to accelerometer gyros. However, since gU_{IA} and g^2K are considered negligible, the component g sin θ produces no torque about OA. Therefore g cos θ acts constantly on U_{SRA} (regardless of the table rotation about IA) and the table rate is a constant reduced to cos θ times its original 1g value. Setting in of precise tilt angles allows measurement of the scale factor linearity for values of input below 1g.

7. GYRO ALIGNMENT

a. Stabilization Gyro

Alignment of any stabilization gyro consists of orienting the rate sensitive Input Axis in a prescribed direction. Since this axis is not physically located on the case of the

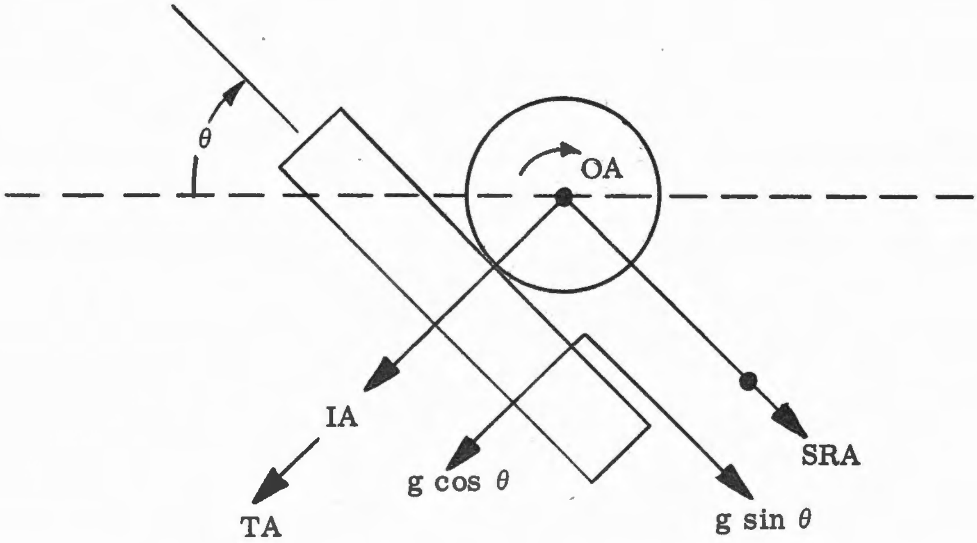


Figure 4-30. Servo Test of Pendulous Gyro

gyro, the action of the gyro in producing precessional torques must be used to achieve the alignment. It will be remembered that if an angular rotation is applied to the gyro case about IA, so that the vector representing the rotation is parallel with IA, the gyro experiences a maximum input and produces a maximum precessional torque about OA. If the input rotation axis lies at some angle with respect to IA, only the projection of the input velocity onto IA is effective, and less torque is produced. Finally, if the input rotation axis is perpendicular to IA, no torque about OA is observed. Therefore, a means of locating and aligning IA is apparent. Since aligning of IA to a maximum input is broad and insensitive, all alignment procedures (servo and tumbling) make use of the zero torque developed when the IA is perpendicular to a test input rotation. The first step in alignment for servo testing is shown in figure 4-31.

Before alignment is begun the wheel is started and the gyro is allowed a certain time to stabilize thermally. The gyro float is brought to null using torque generator current, and the current is carefully adjusted manually so that the float remains at null. This value is then held fixed during alignment. Alignment inputs are then applied about the trunnion axis, with a denoting one direction (by the right hand rule) and b the other direction. If the IA is perpendicular to these inputs, no precessional torque, and hence no float rotation from null, will be observed. However, if the IA is not perpendicular, a float motion will occur, its direction indicating the direction of misalignment. For example, if a is the test input about the trunnion axis and IA is in position 1, then IA may be projected onto a so that some portion of IA lies in the same direction as a. This is a positive input to the IA, and results in a positive float

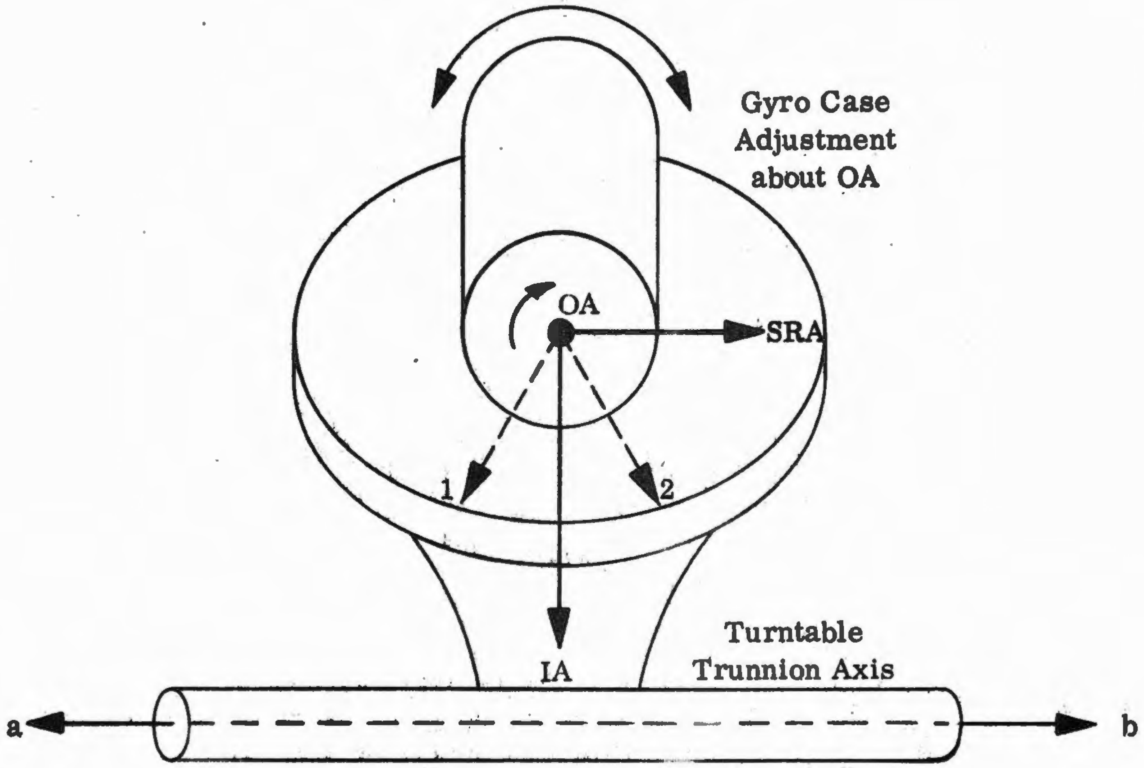


Figure 4-31. Gyro Alignment Procedure, Step 1

rotation about OA. When the trunnion rotation is reversed to b, some portion of 1 lies opposite to the direction of b producing negative torque and float rotation about OA. Similar reasoning may be applied if the IA is misaligned in direction 2.

Having aligned the gyro about OA, the misalignment about SRA must now be eliminated. The table is therefore rotated to make OA parallel to the trunnion axis and the process repeated, with adjustment this time being made about SRA as shown in figure 4-32.

After step 2 of the alignment is completed, step 1 is repeated to eliminate adjustment interaction errors.

Alignment for tumbling tests uses the same basic method. Since the orientation for tumbling places IA perpendicular to the table rotation axis, trunnion movement is unnecessary, and table axis rotation is all that is needed to assure IA perpendicularity.

b. Pendulous Gyro

Since the main function of the pendulous gyro is detection of acceleration or gravity forces acting on the large spin axis unbalance, alignment consists of properly orienting

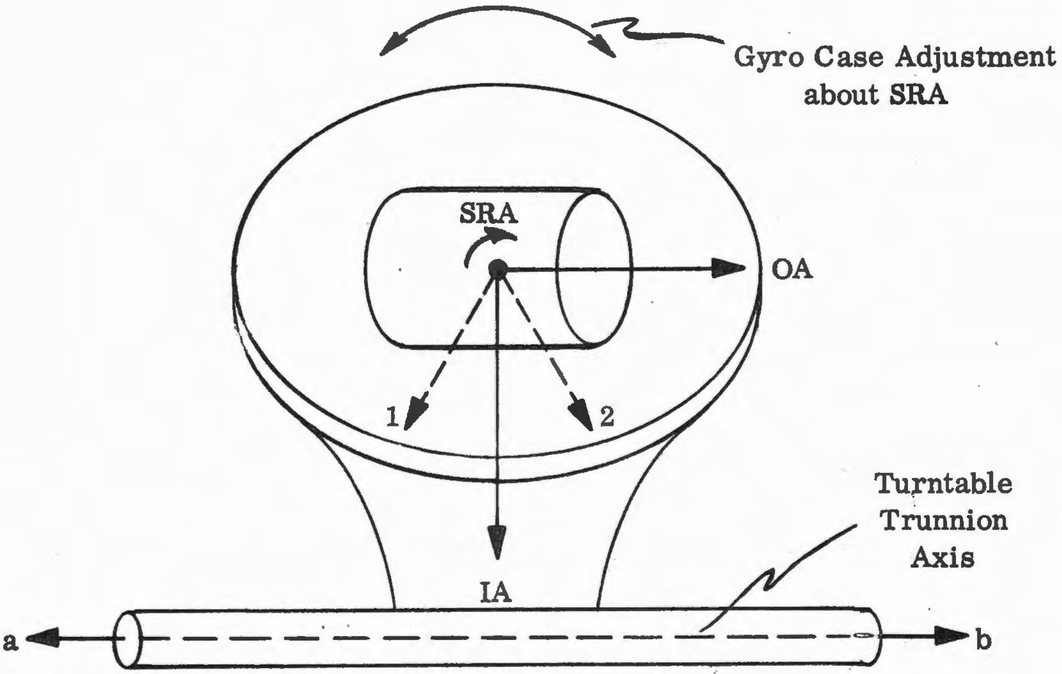


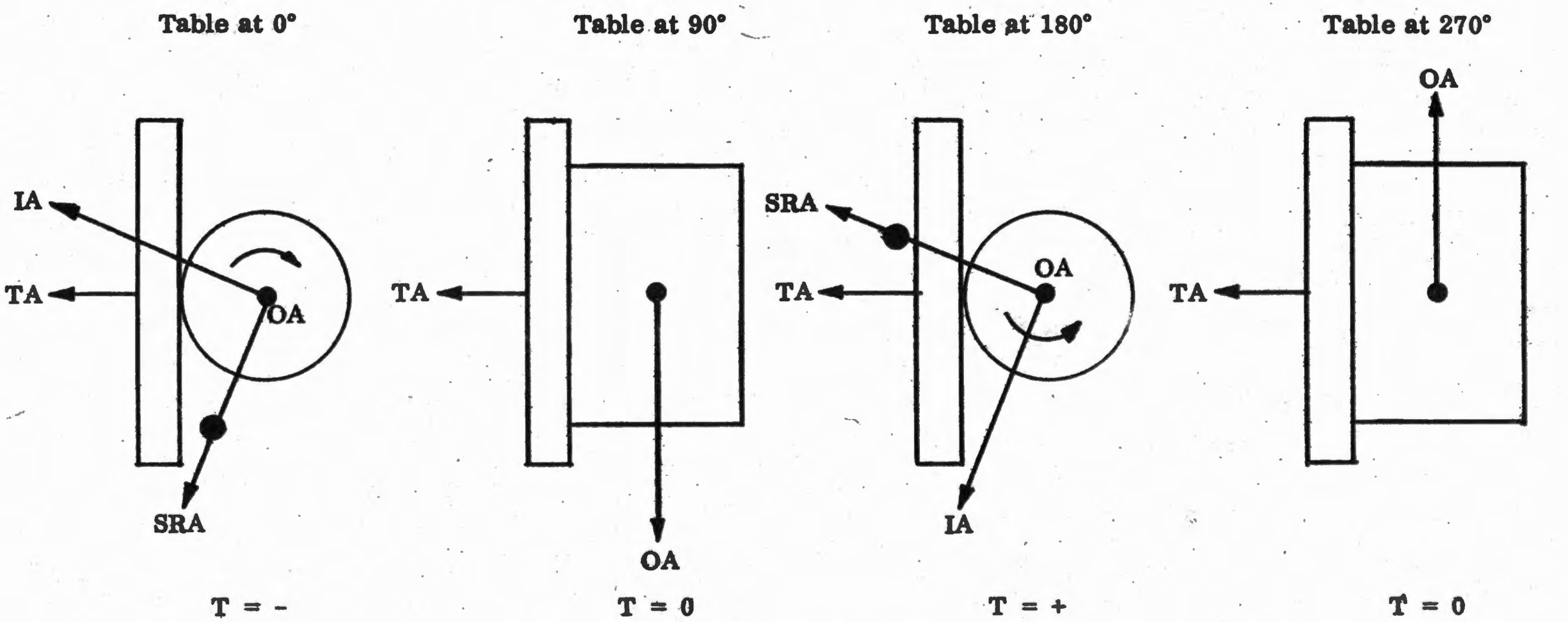
Figure 4-32. Gyro Alignment Procedure, Step 2

the unbalanced mass. Unlike the stabilization gyro alignment, the Input Axis direction is not considered, and is assumed to be perpendicular to the pendulous axis by construction of the gyro. Thus, the alignment is done by observing the effect of gravity upon the spin axis unbalance.

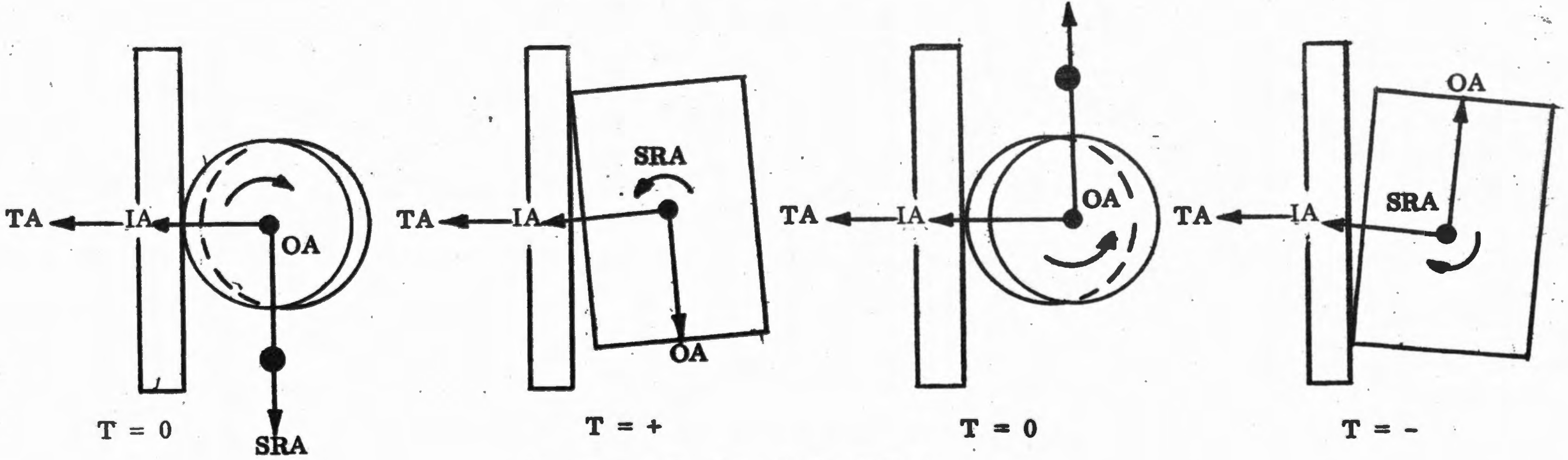
As discussed under servo testing, it is desired that the gyro spin axis containing the unbalance be perpendicular to the turntable or accelerometer rotational axis. The effect upon the torque about OA (and hence upon the turntable rate when servo driven) if it is misaligned may be seen in figure 4-33 where the torque at four positions of turntable rotation is shown.

As shown in figure 4-33, misalignment about either OA or SRA causes a torque that varies with table rotation. For the cases shown, OA misalignment causes a negative cosine curve of torque, while SRA misalignment causes a positive sine wave torque. These torques may be detected and separated in a standard tumbling test, or in a servo test with a small g input.

Misalignment of the pendulous gyro has the harmful effect of limiting the threshold of the gyro (threshold is the smallest acceleration or g input that the gyro is capable of detecting). This may be seen by first considering an aligned gyro with a small g input applied, with servo driven turntable rate versus table rotation angle plotted in figure 4-33.



a. Gyro Misaligned about OA



b. Gyro Misaligned about SRA

Figure 4-33. Gyro Misaligned about OA and SRA

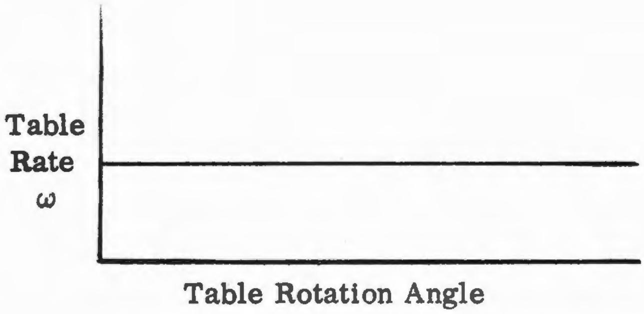


Figure 4-34. Plot of ω versus θ

If we now introduce some misalignment of the pendulum, (figure 4-35) a sinusoid of rate deviation from the applied rate will appear.

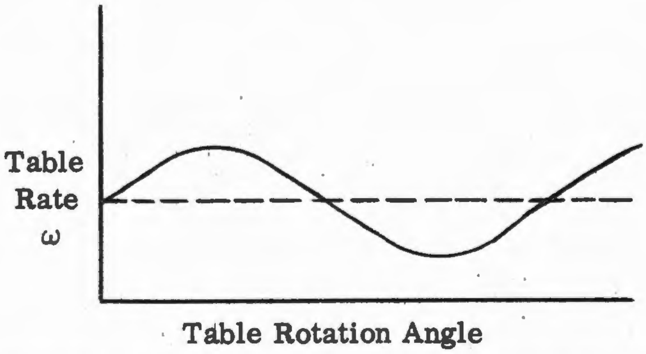


Figure 4-35. Effect of Gyro Misalignment on Table Rate

If the g input is now reduced (tilting of the IA of the gyro more nearly horizontal) the average rate will be reduced and we may reach the point where the misalignment sinusoid touches zero rate as shown in figure 4-36.

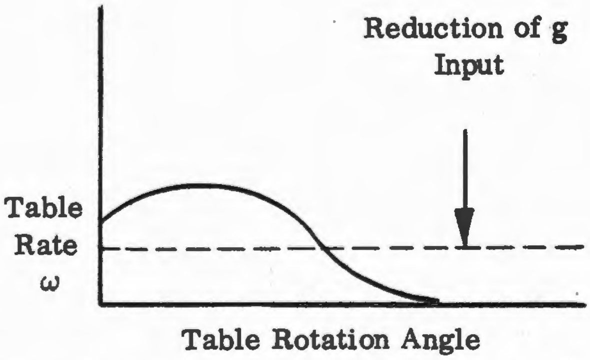


Figure 4-36. Curve of Misalignment with Reduced Input

Since the turntable stops moving at the time the bottom of the sinusoid touches zero rate, we cannot apply g inputs below this value. Therefore the amplitude of the misalignment controls the threshold in this case.

SECTION V

GYROSCOPE APPLICATIONS

A. ROTATIONAL SPEED REGULATOR

A rate gyro (float elastically restrained) connected in the servo system shown in figure 5-1 could be used to control the rotational velocity of a platform. The degree of elastic restraint is controlled by the thumb screw adjustment. The torque thus created on the float produces a signal microsyn output that is amplified and applied to a motor that drives the platform. The rotation of the platform is sensed about the input axis of the gyro and the phasing of the servo is such that the gyro precession will just null out the torque applied to the float by the spring. The rotational speed of the platform then is controlled quite precisely by varying the setting of the thumb screw.

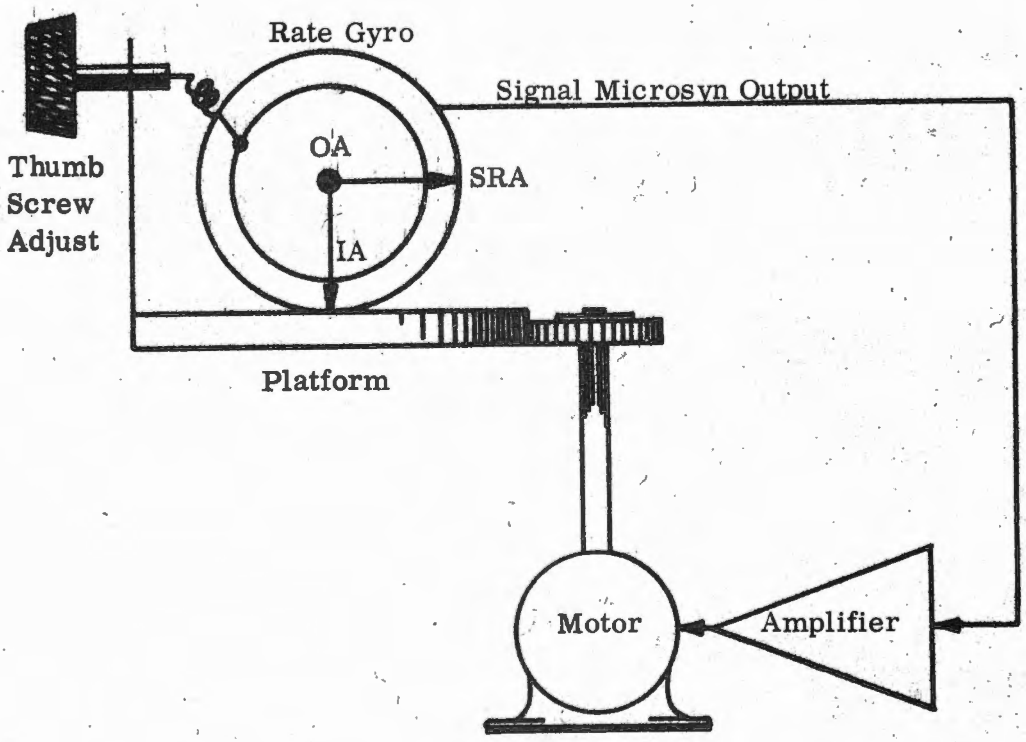


Figure 5-1. Typical Rotational Speed Regulator

B. AIRCRAFT ATTITUDE INSTRUMENTS

The Artificial Horizon and Turn-and-bank Indicator are both gyroscopic instruments. The former indicates to the pilot the attitude of his aircraft with respect to the horizon. The latter instrument indicates both the rate of turn and degree of bank of the turning aircraft. These devices make use of the gyro's property of remaining fixed with respect to inertial space regardless of motion of the vehicle on which they are mounted.

C. REGULUS GUIDANCE SYSTEM GYROCOMPASSING

As this guidance system was destined for use at sea where no azimuth reference is readily available, one of the system's three stabilization gyros (called the East Gyro) was mechanized so that it could be used during the erection mode as an east-seeking device.

In figure 5-2 the Earth Polar Axis and Equator are shown, and it is assumed that the missile to be launched is at some intermediate latitude θ. The input axes of the three stabilization gyros are mutually perpendicular (as in all AC Spark Plug guidance systems). The Vertical Gyro IA (and hence the stable platform on which it is mounted) is first aligned parallel with the EPA by means of a two-degree-of-freedom pendulum (to be described later). If the IA of the East Gyro is not straight out of the paper, that gyro will sense some component of earth rate. This input will cause the gyro to precess and the signal microsyn output is harnessed to drive the stable platform, upon which the gyros are mounted, about the vertical. When the platform has been driven to the position where the East Gyro IA is straight out of the paper, the gyro will no longer sense a component of earth rate and the servo will stop. At this orientation of the platform the North Gyro IA will be pointing toward the Earth Polar Axis, which means that it is pointing North. Similarly, the East Gyro IA will be pointing East.

D. AC SPARK PLUG INERTIAL GUIDANCE SYSTEMS

Both stabilization and accelerometer gyros are used as sensing devices on all of AC Spark Plug's inertial guidance systems. Long-time-of-flight systems, such as MACE, and REGULUS, require superior quality gyroscopes because any drift due to unbalance torques is accumulated over the entire period of flight (up to two hours). On the other hand, ballistic missile systems, such as THOR and TITAN, are guided for a relatively short period of time (not exceeding five minutes) and the requirements on gyro performance are not nearly as stringent.

1. STABILIZATION SERVO

A stable platform upon which to mount the accelerometers is common to all of these guidance systems. The platform is isolated from all random pitch, roll, and yaw

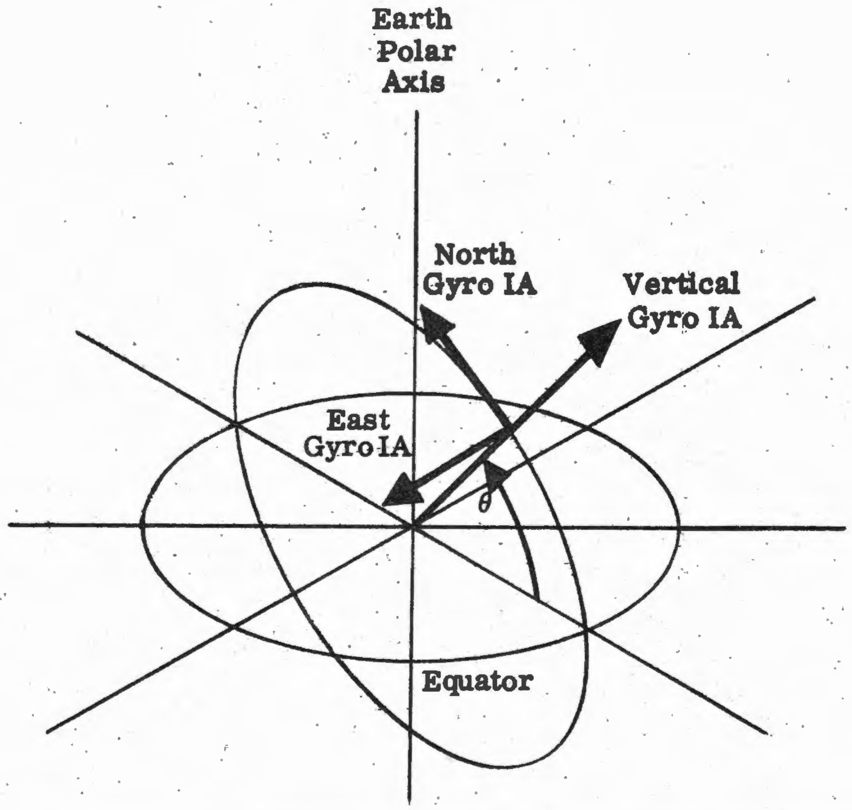


Figure 5-2. Orientation of REGULUS Inertial Guidance System Gyro Axes for Gyrocompassing

motions of the missile airframe by the stabilization servo, which uses three single-degree-of-freedom gyros to sense the pitch, roll, and yaw movements. The other components of the stabilization servo then act together to reposition the platform to correct for the disturbing motion. While the stabilization servos for each of the different guidance systems vary in detail, the composite mechanization drawing (figure 5-3) shows the general features of such a circuit. Note that the gimbals are labeled only as "outer", "middle" and "stable platform" (inner) since the relative positions of gimbals to achieve pitch, roll, and yaw isolation varies from system to system. The filters are simply to improve the signal-to-noise ratio of the gyro signal microsyn outputs. The resolver drive amplifiers are essentially for matching the impedance of the preamplifier output to that of the resolver. They also compensate for the slight voltage loss of the resolver (the amplifier gain is adjusted so that the gain across the amplifier-resolver combination is one). The construction, theory of operation, and necessity for the resolver will be discussed in detail in a subsequent paragraph. The torque exciter provides the needed power amplification to excite the gimbal drive motors. Later systems may replace this rotary equipment with a static (electronic) power amplifier. The stabilization loop operates as follows: pitch, roll, and yaw motions of the missile are sensed by one or more of the stabilization gyros.

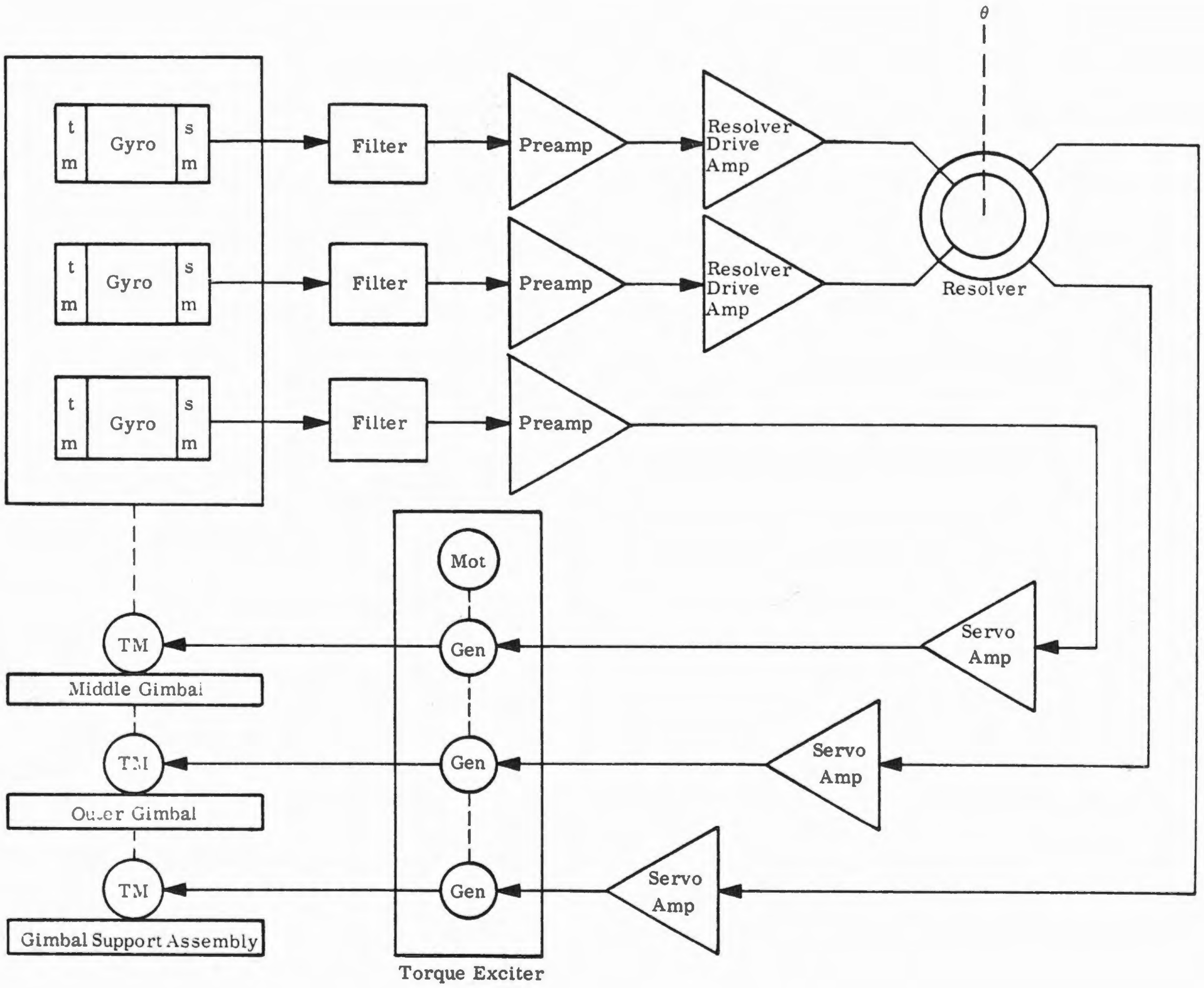


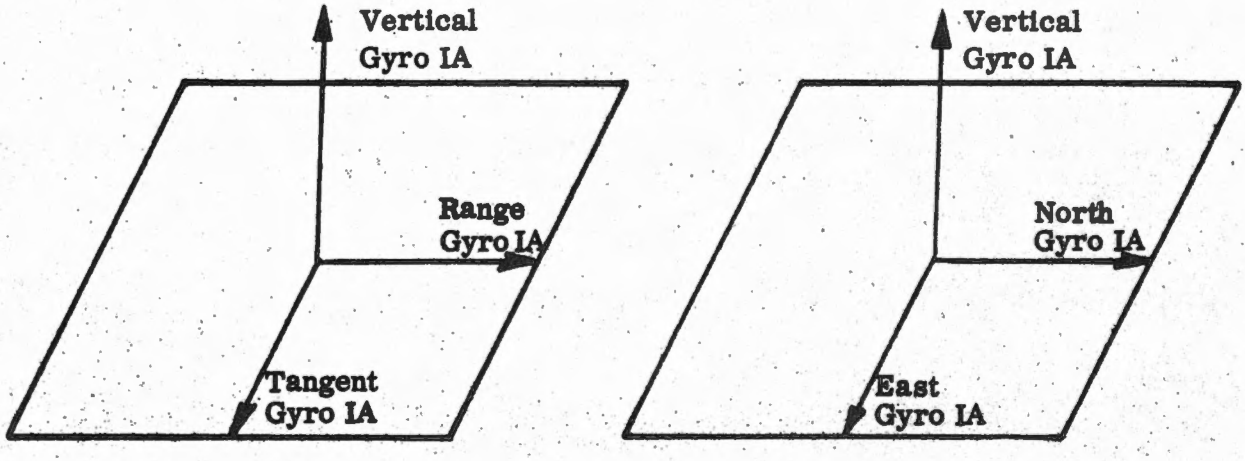
Figure 5-3. Generalized Mechanization Diagram of Stabilization Servo

The output of the gyro(s) is filtered, amplified, resolved if necessary, further amplified and used to control the field winding of a dc generator (in the Torque Exciter). The output of the generator powers a torque motor that drives the stable platform, through the gimbals, in such a direction as to null out the disturbing motion. In this manner the stable platform is isolated from all random motions of the missile.

Figure 5-4 shows the orientation of the input axes of the three stabilization gyros, with respect to the stable platform, for four typical AC Spark Plug inertial guidance systems.

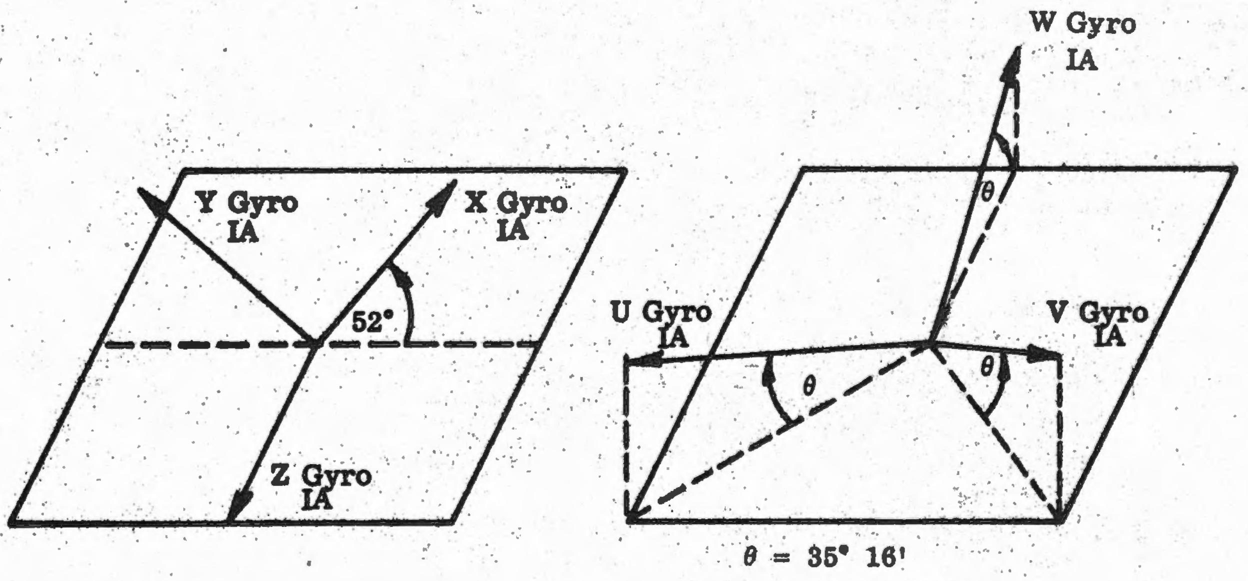
Prior to engaging the stabilization servos, most inertial guidance systems erect the stable platform to the local vertical. The vertical reference device used in most systems is a two-degree-of-freedom pendulum (the vertical must be determined in two planes). This instrument consists of a pendulum bob, made of ferromagnetic material, suspended by a fine wire and swinging freely between four wound poles positioned 90 degrees apart. Each pole is wound with an excitation and a secondary winding. The primary, or excitation, windings are all wound in the same direction and are connected in series. Pairs of secondary windings are wound oppositely and are connected in series. The windings are encapsulated and the interior of the pendulum is filled with a damping fluid (see figure 5-5). The manner of operation is very similar to that of the four-pole signal microsyn: when the bob is off null the magnetic coupling between primary and secondary of one or both pairs of windings is strengthened and the voltage induced in that secondary is increased. If the bob has swung in one direction the output will be 0 phase, and if in the opposite direction it will be π phase. Null will be achieved only when the bob is midway between both sets of poles.

If the stabilization gyro input axes were aligned parallel with the missile pitch, roll, and yaw axes in any of the inertial systems, and if the missile experienced only one of these motions at a time, no gyro error signal (signal microsyn output) resolution would be required since one gyro would sense roll (say the X gyro), one gyro would sense pitch (Y gyro), and the remaining gyro (Z) would sense yaw. However, the missile does experience combinations of two or more of these random movements simultaneously, thus making necessary resolution of the gyro signals. In the simple case shown in the drawing below the missile has experienced a yaw through the angle θ, displacing the X and Y gyro input axes from their positions along the roll and pitch axes, respectively, to the new positions shown. If now, before this yaw angle is nulled out by the yaw stabilization servo, a roll and/or pitch is also experienced, components of these motions (x, x', y and y') will be sensed by both the X and Y gyros, as shown in figure 5-6. The signal needed to drive the roll torque motor to isolate the stable platform from the roll will consist of components of the signals from the X and Y gyros ($x + x' = X \cos \theta + Y \sin \theta$). Similarly, the signal needed to



a. Mace IG System

b. Regulus IG System



c. Thor IG System

d. Titan IG System

Figure 5-4. Orientation of Stabilization Gyro Input Axes for AC Spark Plug Inertial Guidance Systems

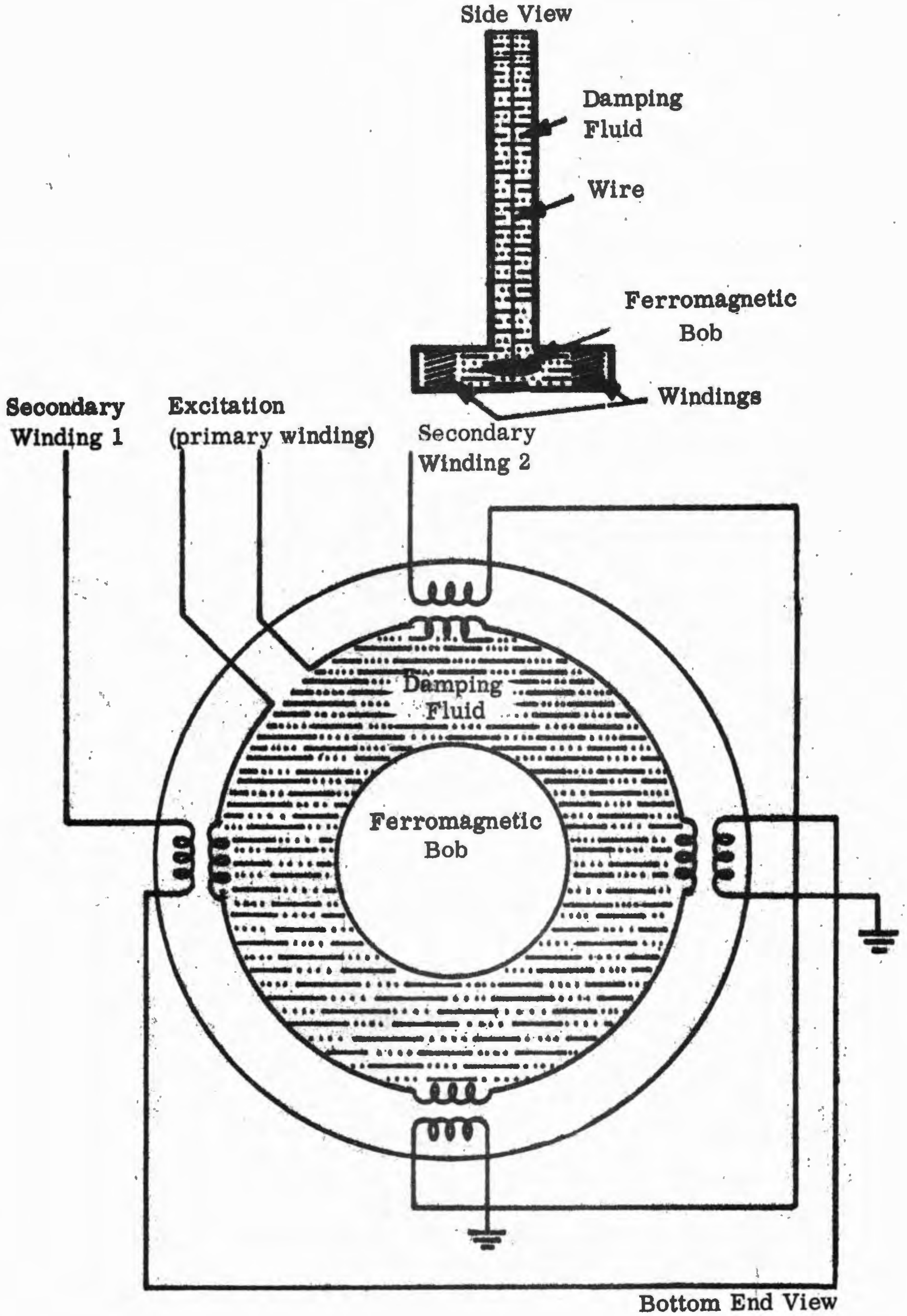


Figure 5-5. Two-Degree-of-Freedom Pendulum

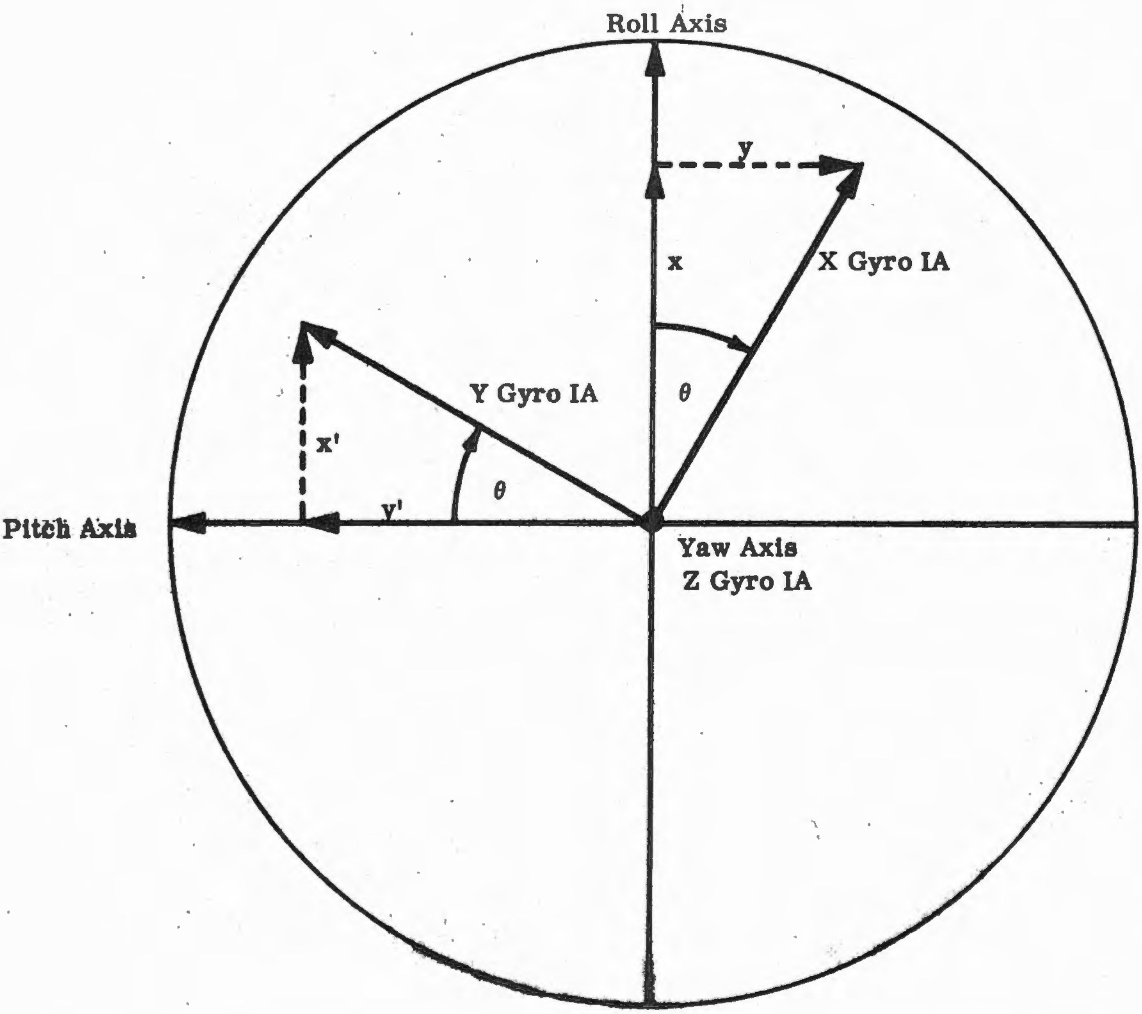


Figure 5-6. Resolution of Gyro Signals on Missile Axes

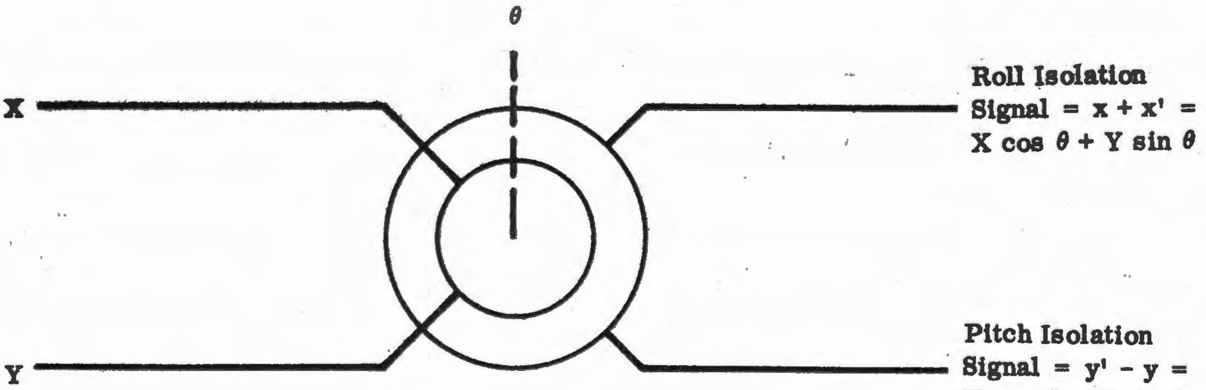


Figure 5-7. Schematic Diagram of Resolver

isolate the pitch motion must be y' - y = Y cos θ - X sin θ(the y component is negative since its direction is opposite to that of y'). The required roll and pitch isolation signals are produced in a resolver. As shown in figure 5-7, the X and Y gyro signals are applied to the rotor of the resolver. The rotor, which rotates freely with respect to the stator, is connected through a shaft to the yaw axis and can turn through any yaw angle (θ in this case). The outputs taken from the stator of the resolver are the required roll and pitch isolation signals.

2. ACCELEROMETER SERVO

A gyro accelerometer combines the functions of a pendulum and a gyro. It has the advantage of sensing accurately an extremely large range of accelerations. The action of the accelerometer "automatically" integrates the input acceleration and yields a velocity signal as its output. The gyro accelerometer also serves as a moving vertical indicator when it is Schuler tuned.

The principal part of the accelerometer is the accelerometer gyro. This unit is similar to a stabilization gyro, except that its float is deliberately unbalanced. There are two ways of unbalancing a float: one is to add an unbalancing weight to it; the other is to offset the wheel from the intersection of the spin and output axes so that the entire float acts as a pendulous mass, as shown below. The pendulosity of a particular unit is the product of the mass (of the float and the lever arm (distance of float center of gravity from output axis), or ml in figure 5-8.

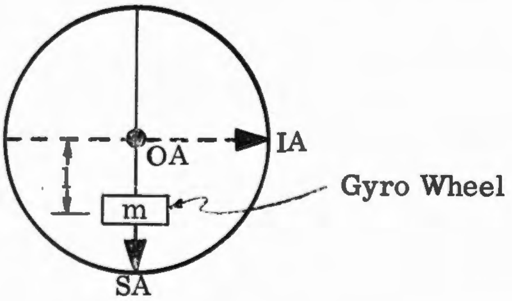


Figure 5-8. Pendulosity of Gyro Float

One property of a pendulum is that if it is accelerated in a direction perpendicular to a plane containing the axis of rotation and the float Cg (along IA in the case of our pendulous gyros) the pendulum bob will, due to its inertia, lag behind the pivot, so that at a given instant the pendulum makes an angle θ with its original position, as shown in figure 5-9.

Thus far, we have considered only the pendulous action of the accelerometer gyro, and the gyro wheel need not have been running. If pendulous action alone were used

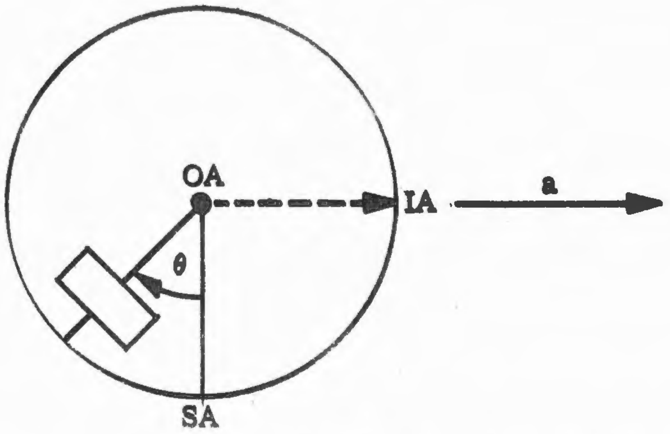


Figure 5-9. Action of Pendulous Wheel in an Accelerometer

to sense accelerations, however, the instrument would saturate (float would hit the stops and remain there). To overcome this disadvantage the gyroscopic property of the instrument is used to produce a counter torque to null out the pendulous torque. The servo is connected as shown in figure 5-10. When an acceleration occurs along IA, the wheel and float, through pendulous action alone, are displaced through the angle θ.

The displacement θ is due to a pendulous torque on the float equal to the pendulosity of the wheel times the acceleration, measured in g , or

$$T_{OA} = mlg. \tag{5-1}$$

The float displacement causes a signal microsyn output, which is amplified and used to excite a motor that drives the entire gyro case about IA. This rotation about IA produces a precessional torque from the gyro equal to

$$T_{OA} = H\omega_{IA}. \tag{5-2}$$

The two torques, equation 5-1 and equation 5-2, are equal and the servo is phased so that the sense of the precessional torque is opposite to that of the pendulous torque. Since the two torques are equal in magnitude but opposite in sense

$$mlg - H\omega_{IA} = 0 \tag{5-3}$$

which is the basic accelerometer equation.

A potentiometer is positioned, through gearing, by the drive motor shaft in order to give an electrical indication of the shaft position, ϕ. This shaft position ϕ is proportional to velocity, since ϕ is the result of the shaft rate ω_{IA} acting through the

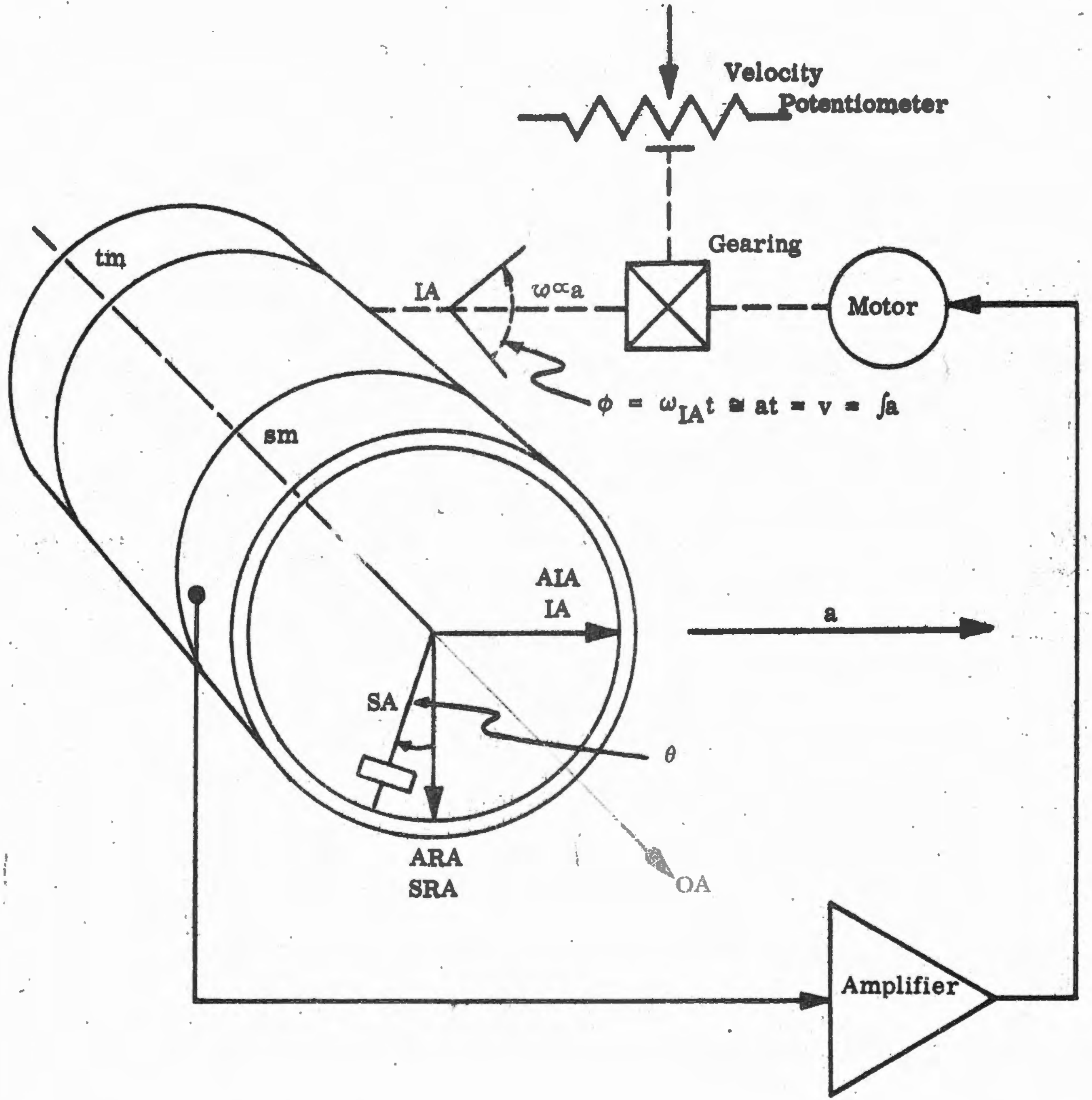


Figure 5-10. Gyro Accelerometer and Associated Servo Components

time t ($\phi = \omega t$). But ω is proportional to the acceleration being sensed so that $\phi \sim at$, and $at = V$, so ϕ is proportional to the velocity being experienced. Since velocity is the time integral of acceleration ($V = \int a dt$), the accelerometer is called an integrating accelerometer.

Rearranging equation 5-3 gives

$$\frac{ml}{H} = \frac{\omega_{IA}}{g}. \tag{5-4}$$

These quantities are the scale factor of the accelerometer (rad/sec/g). The left side of equation 5-4 gives the scale factor in terms of physical constants associated with the gyro, while the right side of the equation indicates the manner in which the scale factor is measured in the laboratory; i.e., the accelerometer is mounted on a turntable that is tilted so that g or some fraction of it (g times the cosine of the tilt angle) acts on the pendulous mass. The rate generated by the servo about IA is then measured optically and divided by the input (in g), which is known very precisely from the tilt angle.

The gyro accelerometer can also be used to furnish an indication of the instantaneous vertical upon a moving vehicle. This is accomplished by Schuler tuning the accelerometer servo and is explained as follows. The true vertical is indicated by a simple pendulum at rest. However, a simple pendulum aboard a moving vehicle would lag behind the vertical due to the acceleration(s) being experienced. But, if the angle through which the pendulum lagged (θ_1) were to just equal the earth central angle through which the vehicle traveled (θ_2), then the pendulum would indicate the true vertical, as shown in figure 5-11.

It will now be shown that if the length of the pendulum arm, l, were equal in length to the radius of the earth, R, then θ_1 would equal θ_2 and the pendulum would always indicate the vertical, regardless of accelerations being experienced.

$$l = R \text{ (by hypothesis)} \tag{5-5}$$

The linear acceleration, a, experienced by the pendulum and the vehicle carrying the pendulum are the same. Therefore,

$$\frac{a}{l} = \frac{a}{R} \tag{5-6}$$

but

$$\frac{a}{l} = \alpha_1 \text{ (by Equation 1-25)} \tag{5-7}$$

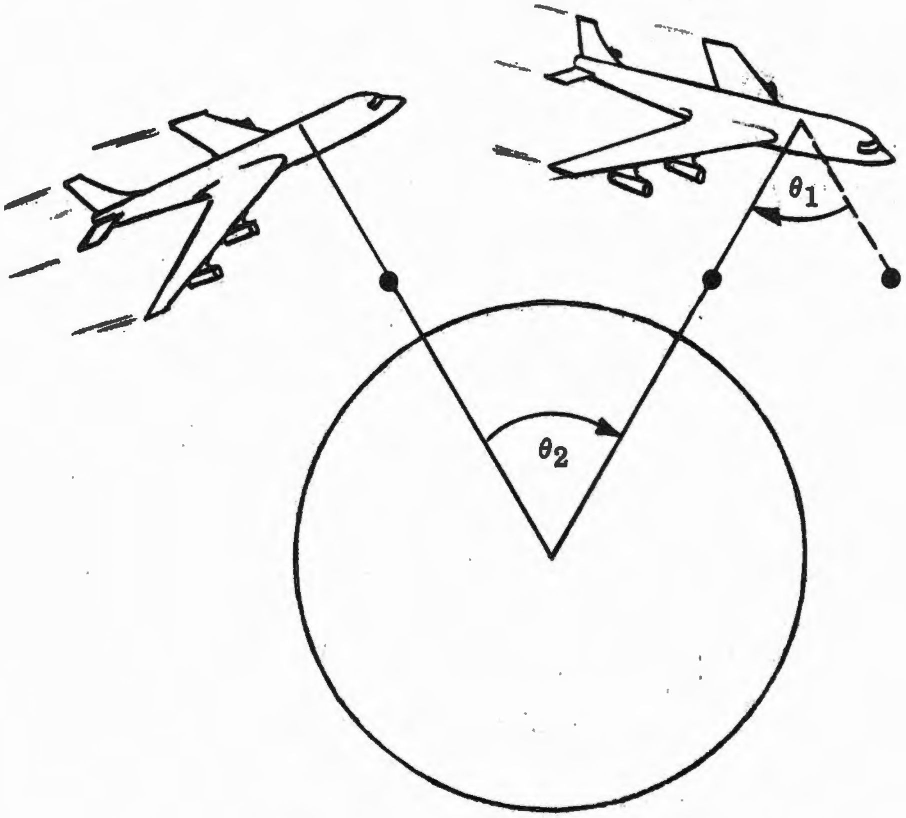


Figure 5-11. Principle of Schuler Tuning

and

$$\frac{a}{R} = \alpha_2, \text{ so that } \alpha_1 = \alpha_2 \qquad (5\text{-}8)$$

where

α_1 = angular acceleration of the pendulum

α_2 = angular acceleration of the vehicle.

Multiplying both sides of equation 5-8 by the same quantity does not change the equality, so

$$\frac{1}{2}\alpha_1 t^2 = \frac{1}{2}\alpha_2 t^2 \qquad (5\text{-}9)$$

but

$$\frac{1}{2}\alpha t^2 = \theta \text{ (by summary of rotational units on page 1-6).}$$

Therefore,

$$\theta_1 = \theta_2 \text{ as was to be proved.}$$

Obviously we cannot have a simple pendulum with an arm length equal to the radius of the earth (we ignore the height of the vehicle above the earth as insignificant compared to the radius of the earth). However, if the period (time for one complete oscillation) of a simple pendulum of any length were made equal to the period of a pendulum with an arm equal to the radius of the earth, such a pendulum would behave like an earth-radius pendulum and would indicate the vertical while moving. The period of an earth radius pendulum is 84.4 minutes ($T = 2\pi\sqrt{l/g}$). By means of a network in the servo amplifier the accelerometer servo is tuned so that the accelerometer gyro pendulous mass has a natural frequency of 84.4 minutes. This, in effect, means that when the pendulous mass is disturbed it swings back and forth once in 84.4 minutes. Thus, the accelerometer gyro is equivalent to an earth radius pendulum and will indicate the vertical on a vehicle moving over the surface of the earth, as shown in figure 5-12.

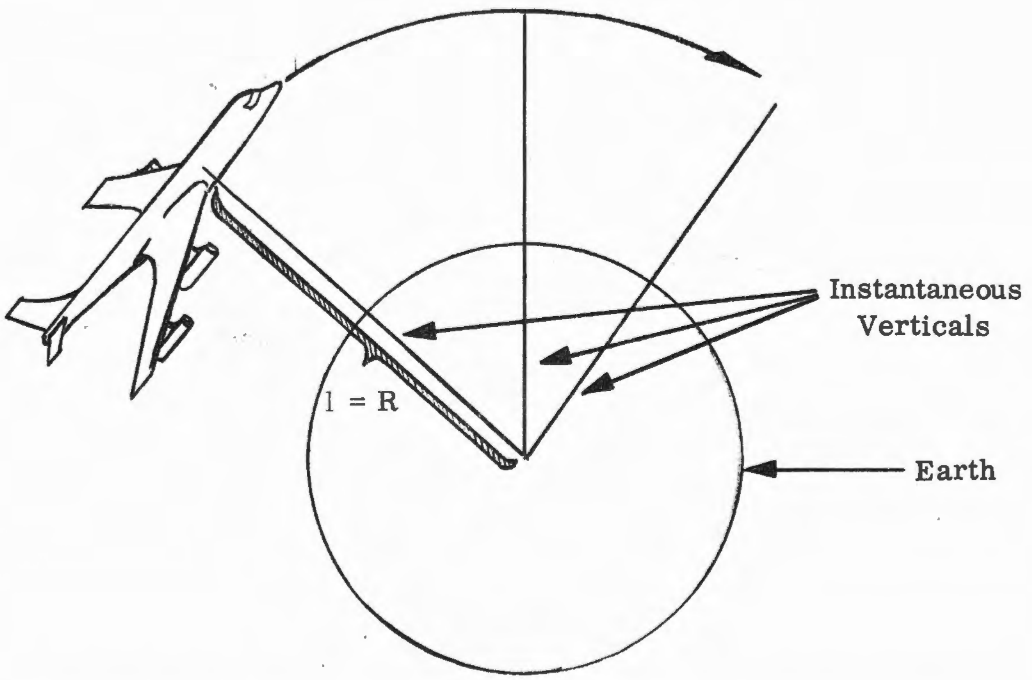


Figure 5-12. The Accelerometer as a Vertical Indicating Device

GLOSSARY

Acceleration (linear acceleration)	The rate at which velocity changes. It is determined by subtracting the initial velocity from the final velocity and dividing this difference by the time interval.
Accelerometer Gyro	A pendulous gyro used as the sensing element in an accelerometer.
Accelerometer Scale Factor	The ratio of rotation of the pendulous gyro about its input axis to the acceleration experienced, the acceleration being expressed in gravities, cm/sec^2, etc.
Accelerometer Servo	A servo that measures and integrates accelerations by nulling out the pendulous torque the accelerations create on a pendulous gyroscope.
Air Bearing	See Gas Bearing.
Alignment (of axes)	See Gyro Alignment.
Ampere	The unit of electrical current.
Amp	The abbreviation for ampere
Ampere-turns	The product of the number of turns in a winding and the current in the winding. This quantity determines the magnetomotive force of the coil, and hence the magnetic flux.
Angular Acceleration	The rate at which angular velocity changes.
Angular Gain (of a gyro)	The ratio of gyro output angle (angle about the output axis) to the input angle (angle about the input axis). This ratio may be less than, equal to, or greater than 1.
Angular Momentum	The product of the moment of inertia of a rotating body and its angular velocity.
Angular Spread	The angular distance that the gyro float may rotate in either direction (degrees of travel from stop to stop).
Angular Velocity	The velocity of a rotating object measured in rpm (or radians per second). Note that the angular velocity of all particles in a wheel is the same, while each particle actually travels at a different <u>linear</u> velocity (the particles at or near the rim of the wheel travel faster than those near the axle.

B	-	See Flux Density.
Balance Adjust Fork	-	A provision for adjusting the float rotational balance from outside the gyro case.
Balance Adjust Nut	-	A nut that rides on the balance adjust stud on the end of the float in some gyros. Its position can be varied to help achieve rotational balance of the float.
Balance Adjust Stud	-	A metal rod attached at right angles to one end of the float on some gyros. The balance adjust nut rides on this stud.
Balancing	-	See Rotational Balancing and Longitudinal Balancing.
Ball Contact Angle	-	The angle at which the balls of the ball bearing make contact with the race (referred to the plane of wheel rotation).
Ball Retainer	-	A lubricant-impregnated phenolic part that both separates the balls and lubricates them. It fits between the inner and outer races.
B-H Curve	-	The curve of flux density vs magnetic intensity (see Hysteresis)
Bearing Assembly (or Package)	-	See Wheel Bearing.
Bellows	-	Small sealed bellows chambers (usually made of brass) to help stabilize flotation by compensating for changes in volume of the flotation fluid.
Buoyancy	-	The ability of a fluid to float an immersed object.
Buoyant Force	-	The force on an object (usually upward) exerted by a liquid in causing it to tend to float. The force is related to the specific gravities (or densities) of the object and the liquid.
C	-	The symbol of capacitance.
Capacitance	-	The property of storing an electrical charge. It is equal to the electrical charge divided by the electrical potential (voltage). It causes the current to lead the voltage in an ac circuit.
Capacitive Reactance	-	An opposition to the flow of current due to capacitance. It causes the current to lead the voltage in an ac circuit. It is inversely proportional to the frequency of the excitation and the capacitance.

Cb - The center of buoyancy.

Center of Buoyancy - The point through which the buoyant force is acting; it is also the center of volume of the object.

Cg - The center of gravity.

Center of Gravity (center of mass) - The point through which the weight of an object acts; it is the center of the mass of the object.

Compensation Torque - Torque applied to the gyro float through the torque microsyn to compensate for unbalances, drifts, etc.

Compliance Unbalance - An unbalance due to the fact that the float is not equally stiff at all points about its perimeter.

Compliance Unbalance Torque - A torque on the float caused by gravity or gravity components acting on the compliance unbalance.

Conductance - The reciprocal of resistance.

Contact Angle - See Ball Contact Angle.

Control Winding - The secondary winding of a torque microsyn. The current can be varied in this winding. A torque is produced in the microsyn that is the product of control winding current and reference winding current.

Couple - A pair of parallel forces that are equal in magnitude but opposite in direction. A couple produces a torque about a point between them.

Cp - The line of float pivots.

Damping Coefficient - A measure of the amount of damping a gyro has, equal to the angular momentum of the gyro divided by its angular gain. It is also equal to the damping torque divided by the rate about OA associated with that torque.

Damping Fluid - Same as flotation fluid. The same fluid also provides a damping torque.

Damping Torque - A torque that opposes precessional torque. It is much like a friction torque, but is proportional to the rate at which the float rotates.

Degrees-of-freedom - The number of planes in which a gyro wheel and axle is free to move; dependent upon the number of gimbals the gyro has.

Density	The mass of a body (measured in lbs or gms), divided by its volume (measured in cu in or cu cm).
Drift	See Gyro Drift.
Drift Torques	See Unbalance Torques.
Dyne	The force required to accelerate one gram at a rate of one centimeter per sec per sec. $\left(\frac{gm - cm}{sec^2}\right)$
Dyne-cm	The unit of torque used in measuring float torques.
Earth Polar Axis	The imaginary axis about which the earth revolves; the line extending through the north and south geographic poles.
Earth-radius Pendulum	A simple pendulum with a length as long as the radius of the earth (obtained electrically).
Earth Rate **(earth rate input)**	The rate at which the earth rotates about the Earth Polar Axis, specifically 360° in 24 hours or 15 degrees per hour.
Earth Rate Torque	A precessional torque due to earth rate acting upon the angular momentum of the gyro wheel.
Efficiency (of a machine)	The ratio of energy out (output) to energy put in (input). The difference in input and output energy levels is the energy loss.
Eight-pole Microsyn	A microsyn with eight stator poles and four rotor poles. It may be connected for use as either a signal or torque microsyn, and also provides magnetic suspension of the float simultaneously with (but independent of) its operation as a signal or torque generator.
Electric Null	See Signal Microsyn Null.
Energy	The ability to do work. See Kinetic Energy, Potential Energy.
Energy Loss	The energy dissipated in a device, as in friction, electrical heating, etc., in transforming energy from one form to another. The energy loss determines the efficiency of the machine or device.

Farad - The unit of capacitance.

Flex Lead Baffle Plate - A round disk that fits in one end of the gyro case, perpendicular to OA, that holds the motor flex leads. This plate has channels to hold the flex leads. These channels start at equally spaced points on the circumference of the disc and curve helically into the center.

Flex Lead Torque - The torque on the float created by the wheel motor leads into the float. This is part of the R-term unbalance torque. See Motor Leads.

Flex Leads - See Motor Leads.

Float Balancing - See Rotational Balancing and Longitudinal Balancing.

Float Inertia Torque - A dynamic torque that is produced whenever the float is accelerated. It is equal to the moment of inertia of the float times the angular acceleration of the float.

Float Null - The position of the float when the signal microsyn is at its electrical null. See Signal Microsyn Null.

Float Stops - A mechanical arrangement to limit float rotational travel to about 2-1/2° in either direction. A common arrangement is a pair of pins near the top and bottom of one end housing that engage in larger holes in the float ends. The diameter of the holes then determines how far the float can travel.

Floated Gyro - An instrument in which the gyroscopic element (wheel and axle) is mounted in a sealed container that is suspended by a fluid inside the outer case of the unit. The sealed container may be a cylindrical or spherical shell.

Flotation - The fluid suspension of the gyro gimbal in the gyro case by a fluid. At flotation, the specific gravity of the flotation fluid just equals the weight of the float and its contents.

Flotation Fluid - The fluid that suspends the float inside the gyro case. The chief characteristic of the flotation fluid is that its specific gravity (and viscosity) can be changed by altering its temperature. Thus a gyro float can be suspended regardless of its weight merely by changing the temperature of the flotation fluid. (See Fluorolube).

Fluid Damping	-	See Damping Fluid and Damping Torque.
Fluorolube	-	A flotation and damping fluid in common use in AC Spark Plug gyroscopes.
Flux	-	See Magnetic Flux.
Flux Density	-	The number of lines of magnetic flux per unit of area. This is measured in gausses, and is a function of the specific material.
Force	-	The cause of the acceleration of a mass. Since all objects have mass, and since gravity is an acceleration, there is a force due to gravity.
Four-Pole Microsyn	-	A microsyn with four stator poles and two rotor poles. It may be connected for use as either a signal or torque microsyn.
Free Gyro	-	Same as a three-degree-of-freedom gyro. Also, a child's gyro top that is not mounted in gimbals, since it is free to be moved in all three planes.
g	-	The gravitational acceleration on earth; the symbol is used to denote the numerical value of this acceleration, which varies according to location on the earth but is approximately equal to 32.2 feet per second per second, or 981 centimeters per second per second.
Gas Bearing	-	A wheel bearing, or spin axis bearing, that operates on a thin, high-speed film of gas between the two bearing surfaces. AC Spark Plug gas bearing floats are presently filled with helium; this is the gas in the bearing. The bearing actually is capable of operating with any gas, and future float filling practice may replace helium with some other gas.
Gauss	-	The unit of flux density.
g_{IA}	-	The gravity component that is parallel with the input axis.
g_{SRA}	-	A gravity component that is parallel with the spin reference axis.

gU_{IA}	The symbol for the output axis torque developed by gravity acting on mass unbalance along the input axis.
gU_{SRA}	The symbol for output axis developed by gravity acting on mass unbalance along the spin reference axis.
Gilbert	The unit of magnetomotive force.
Gimbal	A frame with pivots attached. The gimbal permits the object fastened within it (wheel and axle in a gyro) to be moved about the pivot axis independent of movement of the base or other gimbals. When the term gimbal is applied to a gyro, it usually means the float.
Gravitational Attraction	The universal attraction of masses for each other. On earth this results in an acceleration or force (or attraction) of gravity. See also Gravity and "g".
Gravity	The acceleration of all objects toward the center of the earth. When the object is restrained, as by the floor, tabletop, etc., this becomes the attraction of gravity. See also "g".
Gravity Components	See g_{SRA} and g_{IA}.
Gravity Dependent Torques	The mass unbalance and compliance torques. These torques depend upon the orientation of the gyro with respect to the gravity vector.
Gyro Accelerometer	A device that uses a pendulous gyro as the sensing element — used for measuring and integrating accelerations.
Gyro Alignment	A term that is used to indicate the procedure of aligning the gyro axes mutually perpendicular with each other; it is also used to describe the aligning of the gyro axes with a turntable or stable platform axis.
Gyro Case	The cylindrical can that houses the float and flotation fluid.
Gyro Coefficients	The numerical values of U_{SRA}, U_{IA}, K_{SRA}-K_{IA}, and R.
Gyro Drift	Irregularities in the performance of a gyro (in either the plot of float rotation, or torque microsyn current required to keep the float at null) due to unbalance torques.

Gyro Drift	-	Random rotations of the float about OA due to unknown torques.
Gyro Drift Torque	-	Torques of unknown origin; same as Uncertainty Torque.
Gyro Float	-	The container in which the gyro wheel and axle are contained and that is suspended by fluid within the gyro case. In AC Spark Plug gyros the terms float and gimbal are usually synonymous.
Gyro Heater	-	The electrical device used to provide heat to the gyro in order to control the density of the flotation fluid. In some gyros this is simply a wire, with ample current-carrying capacity, helically wound around the outer case. In other gyros it is a blanket or film-type arrangement. Still other models have no self-contained heater but are mounted in a temperature stabilizing bath.
Gyro Output	-	Precession, or rotation about the output axis. See Signal Microsyn Output.
Gyroscope	-	Basically a wheel and axle; usually the wheel has a high angular momentum (large amount of inertia and is spinning rapidly).
Gyroscopic Inertia	-	The property of a gyro that tends to keep it fixed in inertial space. More simply, a gyro stands still until it is forced to move, then it precesses. In the ideal case of a three-degree-of-freedom gyro with absolutely frictionless bearings, the gyro wheel and axle would never change position.
H	-	See Angular Momentum and Magnetic Intensity.
Half-Power Point	-	The operating point of the magnetic suspension (8-pole) microsyn circuit. It is the point where the current is 0.707 times its maximum possible value (resonance) and is adjusted by altering the circuit capacitance by selecting proper values of "working" capacitors.
Heater (heater wire)	-	See Gyro Heater.

Heater Sensor - The element (resistance wire, thermistor, etc.) that indicates changes in gyro temperature and calls for additional heat from the gyro heater circuitry.

Henry - The unit of inductance.

Hysteresis - A property of magnetic circuits that prevents the flux density from following exactly the magnetic intensity.

Hysteresis Loop - See Hysteresis

Hysteresis Motor - See Wheel Motor.

Hysteresis Ring - A laminated metal ring sweated into the bore of the wheel that is necessary to the operation of the wheel motor (since the wheel, or rotor, is non-magnetic).

I - The symbol for moment of inertia.

IA - The Input Axis.

IA Horizontal - A servo test orientation in which the input axis is aligned parallel with the horizontal at the test site.

IA Parallel - A servo test orientation in which the input axis is aligned parallel with the Earth Polar Axis.

IA Perpendicular - A servo test orientation in which the input axis is aligned perpendicular to the Earth Polar Axis.

IA Vertical - A servo test orientation in which the input axis is aligned parallel with the vertical (g vector) at the test site.

Impedance - The opposition to current flow caused by the addition (vectorially) of resistance and reactance.

Inductance - A property that permits a current in one conductor to induce a voltage in an adjacent conductor. In an ac circuit inductance causes the current to lag the voltage. It is directly proportional to the flux in the winding and the number of turns and inversely proportional to the current.

Inductive Reactance - An opposition to alternating current flow due to inductance. It is directly proportional to the frequency and the inductance.

Inertia	-	The property of all matter that tends to keep it at rest if it is at rest, or to keep it in motion if it is in motion. (Newton's First Law.)
Inertia Ring	-	A heavy metal ring added to the outer edge of some gyro wheels to increase their moment of inertia, and hence the angular momentum of the gyro.
Inertia Torque	-	See Float Inertia Torque.
Inner Race Spacer	-	A ring that fits on the wheel shaft and separates the inner races of the bearing pair.
Inner Races	-	The wheel bearing races closest to the wheel shaft.
Input Axis	-	An imaginary line mutually perpendicular to the spin reference and output axes. Its positive direction is selected so that the system of axes will be a right-handed orthogonal system.
Input Torque	-	A torque about the input axis.
Integrating Gyro	-	A gyroscope in which the output angle is proportional to the input angle. This is possible only because the output angle is the time integral of the input rate (output angle varies with the produce of input rate and the time that rate is acting).
Kinetic Energy	-	The energy of a moving body, equal to one-half the mass times the square of the velocity.
$K_{SRA}-K_{IA}$	-	The symbol for compliance unbalance. The difference between compliance along the SRA and compliance along the IA. Sometimes combined into a single term, K.
L	-	The symbol for inductance.
Laminations	-	See Microsyn Laminations.
Line of Pivots	-	The imaginary line passing through the pivots of the gyro float or through the centers of the microsyn rotors. This line is also the OA and is of importance in balancing procedures.

Longitudinal Balancing	Balancing the gyro float "end-for-end". This is done after rotational balancing, which moves the centers of gravity and buoyancy to the line of pivots. Longitudinal balancing then brings the centers into coincidence.
ma	The abbreviation for milliampere.
Magnetic Energy	The energy due to the magnetic flux in a coil. It is equal to one-half the square of the current times the inductance of the coil.
Magnetic Flux	The flow of magnetic lines of force, similar to current in a pure electric circuit. It is equal to the magnetomotive force divided by the reluctance. It is dependent upon the ampere-turns in the coil.
Magnetic Induction	See Flux Density.
Magnetic Intensity	The strength of a magnetic field, measured (in oersteds) by the attractive (or repulsive) force exerted. It is directly proportional to the current in the circuit.
Magnetic Suspension	The system of suspending the float in the center of the gyro case by creating magnetic fields with the magnetic suspension (eight-pole) microsyns. This system provides the same function as, and supplements, fluid flotation.
Magnetic Suspension Microsyn	See Eight-pole Microsyn.
Magnetomotive Force	The force in a magnetic circuit, similar to voltage in a pure electric circuit. It is equal to the flux times the reluctance.
Mass	The amount of material in an object, synonymous with the weight of an object on the earth. More precisely, mass is the measure of a body's inertia.
Mass Unbalance	Unbalances created by extra masses, unsymmetric placement of masses, or misalignments. They occur about the spin reference and input axes, and consist of a mass (weight) and a distance from the axis.

Mass Unbalance Torque	-	A torque on the float created by gravity or gravity components acting upon the mass unbalance.
Maxwell	-	The unit of magnetic flux.
Mechanical Stops	-	See Float Stops
MERU	-	See Milli-Earth-Rate-Unit.
Mho	-	The unit of conductance.
Microfarad	-	One millionth (10^{-6}) of a Farad, which is the unit of capacitance.
Microhenry	-	One millionth of a Henry, which is the unit of inductance.
Micromicrofarad	-	One millionth of one millionth (10^{-12}) of a Farad, which is the unit of capacitance. Also Picofarad.
Microsyn	-	An electromechanical device operating on the differential transformer principle. See Signal Microsyn, Torque Microsyn, Four-pole Microsyn, Eight-pole Microsyn.
Microsyn Centering	-	The process of checking the float centering by connecting the signal microsyn so that it is sensitive to translational motions in two directions.
Microsyn Laminations	-	Both the cores of the microsyn stator and the microsyn rotor are made up of sheets of metal, called laminations, that are bonded together. This construction is used because of magnetic considerations.
Microsyn Poles	-	See Microsyn Stator.
Microsyn Reaction Torque	-	A torque due to electrical or mechanical unbalances in the microsyn (may be inequality in length of windings on different poles, more or less stator pole area on one pole, etc.). It is a part of the R-term.
Microsyn Rotor	-	The moving portion of a microsyn. It is attached to the float pivot and rotates within the circular microsyn stator between the microsyn stator poles, but with an air gap between rotor and stator. The rotors, sometimes called slugs, are made up of metal laminations and are circular discs with equally spaced protrusions (called poles).

Microsyn Stator	-	The fixed portion of the microsyn. It is circular on the outside with poles projecting inward toward the center. These poles are wound with electrical windings that are interconnected. The stator is made up of metal laminations. The laminated cores are sealed with potting compound after the windings have been applied.
Milliampere	-	One thousandth of an ampere (10^{-3}) which is the unit of current.
Milli-Earth-Rate-Units	-	Units equal to one-thousandth of earth rate (approximately 0.015° /hr.).
Millihenry	-	One thousandth of a Henry, which is the unit of inductance.
Millivolt	-	One thousandth (10^{-3}) of a volt, which is the unit of electrical potential.
Milliwatt	-	One thousandth (10^{-3}) of a watt, which is the unit of electrical power.
Moment of Inertia	-	The effect of the mass of a rotating body. Since the mass of each particle of the body is situated at some distance from the center of rotation (radius of the particle) it is acting through a lever arm and creates a moment of force.
Momentum	-	Mass times velocity (more simply, "weight times speed"); also the product of force and time.
Motor Lead Baffle Plate	-	See Flex Lead Baffle Plate.
Motor Leads	-	The wires (3 or 4) that bring current into the float to the wheel motor. In order to minimize the undesired flex torque that these leads exert on the float, they are made of very thin curved silver ribbons and are equally spaced around the circumference of the float.
Motor Poles	-	See Wheel Motor Stator.
Motor Stator	-	See Wheel Motor Stator.
Motor Stator Hub	-	A metal casting that clamps on the wheel shaft and on which is mounted the wheel motor stator.
mv	-	The abbreviation for millivolt.

mw	-	The abbreviation for milliwatt.
Negative Axis (Gyro)	-	The end of the axis without the arrowhead, opposite to the positive end of the axis as determined by the Right-hand rule.
Negative Rotation	-	The opposite of positive rotation.
Null (null point)	-	Zero reading.
Null Voltage	-	The voltage output of the signal microsyn at the signal microsyn null point. Theoretically, the null voltage would be zero, but due to quadrature, magnetic coupling, etc., there is always some value of null voltage (in the order of millivolts).
OA	-	The Output Axis.
OA Parallel	-	The tumbling test orientation, output axis parallel with the earth polar axis. This is the same orientation as the IA perpendicular orientation, and is used so that there will be no earth rate sensed by the gyro (since the IA is the equatorial plane).
Oersted	-	A unit of magnetic intensity.
Ohm	-	The unit of resistance, reactance.
Orthogonal System (of axes)	-	See Right-Handed System.
Outer Case	-	See Gyro Case.
Outer Race Spacer	-	The ring that separates the two outer races and, due to the difference in its thickness compared with the inner race spacer, provides bearing preload by exerting a wedging action on the balls.
Outer Races	-	The wheel bearing races next to the wheel, separated from the inner races by the balls.
Output	-	The end-product that a machine provides. See Signal Microsyn Output.
Output Axis	-	A line passing through the center of the float pivots; also, a line passing through the centers of the microsyn rotors. This line should be mutually perpendicular with the input and spin axes. Its positive direction depends upon the direction of a positive precession.

Pendulosity - A measure of pendulous torque, equal to the weight of the pendulous mass times the length of the pendulum arm. The term is applied to the gyro wheel in the pendulous gyro.

Pendulous Gyro - A gyroscope in which the float mass is offset from the output axis (not centered in the middle of the spin axis shaft) so as to act as a pendulum (produces a torque to rotate the float when an acceleration acts upon it).

Pendulous Mass - Any mass that hangs down and is free to swing like a pendulum when accelerated. (In the case of AC Spark Plug pendulous gyros, the gyro wheel acts as a pendulous mass to produce a pendulous torque on the float when the mass is accelerated.)

Pendulous Torque - A torque (on the float) caused by acceleration acting upon a pendulous mass. In the gyro accelerometer pendulous torque is created by acceleration acting on the displaced wheel, and this torque is then nulled out by precessional torque.

Pendulum - See Two-Degree-Of-Freedom Pendulum.

Phase - Time relationship.

Phase Angle - Phase expressed in angular units.

Pitch - A rotational motion about the pitch axis of a vehicle. In an airplane, the pitch axis is the axis drawn through the wing from wingtip to wingtip.

Positive Axis - The end of the axis determined by the right hand rule. This is the end of the axis that has the arrowhead.

Positive Rotation - The direction of rotation obeying the right hand rule with respect to the positive end of its axis.

Potential Energy - The capability that an object has for doing work due to its height (or distance through which it can be accelerated). It is equal to the mass times gravity (or acceleration) times the height (or distance).

Power Factor - The figure by which the apparent power (voltamperes) must be multiplied to obtain true power (or average power). The power factor is equal to the cosine of the phase angle between voltage and current.

Precession - The movement of the gyro wheel and axle at right angles to the input rotation or torque. In single-degree-of-freedom gyros (AC Spark Plug gyros) precession occurs about the output axis in response to a rotation about the input axis.

Precession Axis - The Output Axis.

Precessional Torque - The torque caused by the input rotation or torque acting upon the angular momentum of the wheel in trying to cause it to precess. If unopposed, this torque results in precession.

Projection(s) - The component(s) of a vector, not lying on the axes of a coordinate system, that can be transferred to the coordinate axes. This is done by drawing perpendiculars to the axes from the end(s) of the vector. The points at which the perpendiculars cross the axes determine the lengths of the projections.

Preload - A deliberate load imposed on the wheel bearing to maintain the plane of wheel rotation (keep it at 90° to the shaft and prevent the wheel from Preloading is accomplished and controlled in the ball bearing by selecting the thickness of the outer race spacer, which exerts a wedging action on the balls.

Quadrature Adjust Resistor - The resistor that is connected to the quadrature adjust tap of the primary winding and to either the center or end tap to minimize the quadrature voltage present in the microsyn output. The resistance value is determined experimentally.

Quadrature Adjust Terminal - A terminal in the primary winding of the signal microsyn. A resistor is connected to this terminal and to either the centertap or end terminal in order to minimize the quadrature voltage present in the microsyn output.

Quadrature Voltage - The component(s) of signal microsyn output voltage that are 90° out of phase with respect to the desired signal voltage.

R - The abbreviation for resistance.

Races - The parts of a ball bearing assembly in which the balls ride. They are two concentric metal rings, the inner grooved on its outer surface, the outer grooved on its inner surface. The balls ride between the races in the grooves. See Inner Races and Outer Races.

Radian - A unit for measuring angles; one radian is the angle enclosed by an arc of a circle equal in length to the radius of the circle.

Random Motions - See Vehicle Random Motions.

Random Torque - See Uncertainty Torque.

Reactance - See Inductive Reactance or Capacitive Reactance.

Reference Winding - The primary winding of a torque microsyn. The current remains at a fixed value in this winding.

Reluctance - An opposition to magnetic flux in a magnetic circuit, analogous to resistance in an electric circuit.

Repeatability - The ability of a gyro to repeat its performance (plot of torque microsyn current required to hold the float at null) under similar conditions. The degree of repeatability may be expressed as a curve that is the difference of the torque curves made during two runs, or the values of the curves at the same points may be tabulated and an RMS value taken to produce a single figure of repeatability.

Residual Unbalance Torque - A torque on the float due to flex lead torque and microsyn reaction torque. This torque is not gravity dependent (does not depend upon the orientation of the gyro).

Resistance - An opposition to the flow of current (either ac or dc) that dissipates power.

Resolution - The analysis of a vector into its components. There are an infinite number of sets of components that when added together (vectorially) will yield the given vector. Projection will yield one pair of components. Other pairs can be obtained by the method of completing the parallelogram.

Resolver - An electromechanical device for converting vectors from polar to rectangular form and vice-versa, or from one set of coordinates to another. In inertial guidance, the gyro axes may not coincide with the vehicle axes. When this is so, a resolver performs the necessary coordinate conversion.

Resonance (resonant point — series circuit) - The circuit condition where the internal impedance is minimum and, hence, the current is maximum. The impedance is a minimum because the inductive and capacitive reactances are equal and cancel and there is only a resistive component of impedance. Although resonant circuits are employed in the magnetic suspension (8-pole) microsyns, the circuits are tuned so that they never reach resonance (they operate at the half-power point).

Retainer - See Ball Retainer.

Right-Hand Rule - The rule that determines either the direction of the positive end of an axis, or the direction of rotation about that axis, when the other quantity is known. The rule states: Curve the fingers of the right hand about the axis in the direction of the rotation. Then extend the thumb of this hand, which will then point in the direction of the positive end of the axis.

Roll - A rotational motion about the roll axis of a vehicle. In an airplane, the roll axis is a horizontal line through the fuselage from the propellor to the tail section.

Rotational Balancing	-	Making the moments of gravitational force and buoyant force in the float equal to each other. This results in the ability of the float to remain in any set position regardless of how the gyro is oriented. It is accomplished by adding or subtracting weights of different densities to the float.
Rotor	-	The moving part of an electrically driven rotating device. See Signal Microsyn and Hysteresis Motor.
Rotor Laminations	-	See Microsyn Laminations.
R-Term	-	The residual unbalance torque.
SA	-	The spin axis.
Scalar	-	A quantity that has size only and not direction, such as mass, speed, time, etc.
Scale Factor	-	See Accelerometer Scale Factor.
Schuler Tuning	-	The process of adjusting the natural period (time of one complete swing) of the pendulous mass in the accelerometer gyro. The natural period is made equal to the period that a simple pendulum would have if it were as long as the radius of the earth. The Schuler tuning is accomplished by an electronic network in the accelerometer servo amplifier. The purpose of the tuning is to make the pendulous mass (wheel) insensitive to accelerations so that it will always indicate the vertical.
Second Harmonic	-	A term sometimes used to indicate the compliance unbalance torque term (since its frequency is twice that of the mass unbalance terms). More generally, it is the component of an alternating curve which is twice the frequency of the fundamental frequency.
Sensitivity	-	The angular gain of a gyro.
Sensor	-	See Heater Sensor.
Servo (servo mechanism)	-	A device for maintaining stability by sensing errors in the system and feeding back those errors to initiate corrective action.

Servo Test	A major functional test of a completed gyroscope in which the gyro is connected to drive the test table in such a manner as to maintain the float at null. Several orientations of gyro axes with respect to turntable axis are used. A plot is made of test table rate vs. table rotation angle. Analysis of the results of this test gives a good indication of gyro quality, especially repeatability.
Shaft	See Wheel Shaft.
Signal Generator	See Signal Microsyn.
Signal Microsyn	An electromechanical device for converting rotation of the gyro float into electrical signals. It consists of a laminated stator with wound poles (4 or 8) and a laminated rotor. The rotor is attached to the float pivots, and the stator is potted and fixed permanently to the gyro end housing. The rotor rotates inside the stator. The operation of the signal microsyn is that of a differential transformer.
Signal Microsyn Null	The position of the signal microsyn rotor where the electrical output of the microsyn is a minimum (null voltage).
Signal Microsyn Output	An electrical voltage indicating the magnitude and direction of gyro float rotation.
Signal Microsyn Sensitivity	The ratio of signal microsyn output voltage to float rotation angle.
Single-degree-of-freedom gyro	A wheel and axle mounted in a gimbal that is free to rotate in one plane only (single-degree-of-freedom).
Specific Gravity	The ratio between the weight of a substance and the weight of an equal volume of water.
Spin Axis	The axis about which the gyro wheel rotates. In the case of AC Spark Plug gyros, the spin axis (SA) is defined as a line passing through the center of the wheel shaft, perpendicular to the plane (surface) of the wheel. Its positive direction depends upon the direction of wheel rotation. The spin axis should make right angles with the gyro input and output axes. In practice, the angles may not be precisely 90°.

Spin Axis Bearing	See Wheel Bearing.
"Spin chases torque"	A simple reminder for determining the direction of positive precession for a positive input: The spin axis will attempt to align itself with the torque axis (input axis).
Spin Motor	See Wheel Motor.
Spin Reference Axis	The position of the spin axis when the float is at its null position (see Float Null).
SRA	The Spin Reference Axis.
Stabilization Electronics	Collectively, the filters, amplifiers, and resolvers that together with the gyros, torque exciter, torque motors, and gimbals make up the stabilization servo.
Stabilization Servo	A positional servo that, in AC Spark Plug inertial guidance systems, has a gyroscope as its error detector or sensor.
Stable Platform	A platform that is maintained in a fixed position (either with respect to the earth or with respect to inertial space). In AC Spark Plug inertial guidance systems the platform is maintained stable by a stabilization servo that uses gyroscopes as its sensing devices.
Stator	The stationary portion of electrically driven rotating devices. See Wheel Motor Stator and Signal Microsyn Stator.
Stator Laminations	See Microsyn Laminations.
Stator Poles	See Microsyn Stator and Wheel Motor.
Stops	See Float Stops.
Suspension	See Magnetic Suspension.
Synchronism	See Synchronous Speed.
Synchronous Speed	The gyro wheel speed at which the particles of the wheel are rotating at the same speed as the rotating magnetic field in the motor stator. A steady wheel motor current indicates synchronous speed has been reached.

Thermistor - One of the sensing devices for gyro heater circuitry control. Its resistance changes with temperature.

Threshold (threshold sensitivity) - The smallest input (rotation about IA) that a gyroscope will detect.

Tilt Table - An item of test equipment for determining the scale factor of accelerometers. It can be tilted very precisely to simulate an acceleration input of 1 g or a fraction of a g.

Torque - A twisting force, or rotational force; a force acting through some distance from the center or rotation (distance is called radius or lever arm).

Torque Axis - The axis about which a torque acts.

Torque Exciter - A motor-generator set with one motor and three generators. Each generator amplifies the output of a signal microsyn in order to drive its corresponding torque motor.

Torque Generator - See Torque Microsyn.

Torque Microsyn - An electromechanical device for converting electrical signals into float rotations. Physically it is almost identical to the signal microsyn.

Torque Microsyn Sensitivity - The ratio of torque microsyn torque produced to the square of the torque microsyn current.

Torque Motor - One of the three motors in a stabilization servo that turns a gimbal (in response to a signal initiated by a gyro or gyros) to isolate the stable platform from pitch, roll, or yaw.

Transfer Function - The ratio of energy out to energy in. In gyros, the ratio of signal microsyn output voltage to input angle. This ratio can be converted to angular gain if the sensitivity of the signal microsyn (ratio of output voltage to output angle) is known.

Transformation of Energy - The conversion of one form of energy to another; from mechanical energy to electrical energy, etc.

Trunnion Axis - The axis through the turntable trunnions, at right angles to its rotational axis. The table is tilted about this axis.

Trunnions - A pair of oppositely located pivots that permit a device to be swivelled. In the case of a gyro, trunnions are provided on either end of the outer case for mounting the unit. In the case of the test table, the trunnions permit the table's rotational axis to be tilted.

Tumbling Test - One of the major functional tests of a completed gyroscope. The gyro is mounted on a test table with the OA of the gyro parallel with the Earth Polar Axis and the test table is rotated, usually at 8 times earth rate. The gyro float is held at null by the torque microsyn which is activated by the signal microsyn output signal and a plot is made (recorded automatically) of torque microsyn current required to keep the float at null vs table angle. Because the table is rotated through 360° (several runs usually) the unbalances will undergo various orientations with respect to gravity. The tumbling test is used to identify and separate the unbalance coefficients.

Tuned Circuit - See Resonance.

Turntable (Test Table) - A table with a very stable mount that can be rotated about its axis at a very constant rate by means of a torque motor. Its rotational axis can also be tilted very precisely. It is used in tumbling testing.

Two-degree-of-freedom gyro - A wheel and axle mounted in a gimbal that is, in turn, mounted in a second gimbal. Therefore, the wheel and axle are free to change direction in two planes (two-degrees-of-freedom). This device will accept inputs in either of two planes, and will precess in either of two planes.

Two-degree-of-freedom pendulum - A pendulum that simultaneously indicates the displacement from vertical in two planes at right angles to each other. AC Spark Plug inertial guidance systems usually have such a device to align the stable platform initially to the local vertical (gravity vector).

U_{IA}	-	The symbol for mass unbalance about the input axis.
Unbalance Coefficients	-	See Gyro Coefficients.
Unbalance Torques	-	Torques produced by gravity components acting upon the unbalances. Since they are gravity dependent, these torques depend upon the position of the gyro. If unopposed (by precessional torque, compensation torque applied through the torque microsyn, etc.) they produce float rotation (gyro drift).
Unbalances	-	Various irregularities (extra masses, unsymmetrical placements, etc.) that cause unwanted rotations of the float (see Unbalance Torques). The most common unbalances are: mass unbalance, compliance unbalance and residual unbalance.
Uncertainty Torque	-	A random torque of unknown cause; the difference between the known torques and the total torque.
U_{SRA}	-	The symbol for mass unbalance about the spin reference axis.
v		The abbreviation for volt.
Vector	-	A quantity that has both magnitude and direction (such as velocity, force). A vector is represented on paper as an arrow, the head of which indicates the direction in which the vector is acting, and the length of the arrow is the absolute magnitude of the vector quantity.
Vehicle Random Motions	-	The pitch, roll, and yaw motions of a vehicle. It is necessary to correct for these motions in order to maintain platform stability (provide pitch, roll, and yaw isolation).
Velocity (linear velocity)	-	The speed and direction of an object; the rate at which an object changes position, as measured by dividing the distance travelled by the time it took to travel that distance.
Velocity pot (vel. potentiometer)	-	A potentiometer that indicates the position of the accelerometer drive motor shaft. This position is proportional to the velocity being sensed.
Viscous Damping	-	See Damping Fluid and Damping Torque.
Volt	-	The unit of electrical potential.

Watt	-	The unit of electrical power; volts × amps × cos ϕ, amps squared × ohms, or volts squared ÷ ohms.
Wheel Assembly (or Package)	-	The wheel shaft, bearing assembly, motor stator hub, motor stator, hysteresis ring, wheel (or rotor), and in some cases, an inertia ring.
Wheel Bearing	-	The bearing between the wheel and wheel shaft, also called the spin axis bearing. The conventional ball bearing form consists of a pair of assemblies, each containing an inner race, an outer race, an inner race spacer, an outer race spacer, a ball retainer, and balls.
Wheel Motor	-	Consists of a wound stator mounted on the motor stator hub, a hysteresis ring sweated into the bore of the wheel, and the rotor, which is the wheel itself. The motor is a hysteresis - synchronous type.
Wheel Motor Stator	-	The wound, stationary portion of the wheel spin motor that is attached to the float.
Wheel Shaft	-	The shaft upon which the gyro wheel rotates. In AC Spark Plug gyros the shaft is stationary within the gimbal.
Windage	-	The drag on the gyro wheel due to the gas particles in the enclosed space of the gyro float.
"Working" Capacitor	-	One of the capacitors used in the external circuit of the magnetic suspension (8-pole) microsyn. Each pair of poles in this device has a capacitor connected in series with it to effect a tuned circuit. The circuits are tuned to the upper half-power point by selecting the proper capacitance value.
X_C	-	The symbol for capacitive reactance.
X_L	-	The symbol for inductive reactance.
Yaw	-	A rotational motion (right or left) about the yaw axis of a vehicle. In an airplane, the yaw axis is a vertical line through the fuselage. The yaw, pitch, and roll axes intersect at the center of gravity.
Z	-	The symbol for impedance.

AC
SPARK
PLUG
THE
ELECTRONICS
DIVISION
OF
GENERAL
MOTORS
CORPORATION
MILWAUKEE 1,
WISCONSIN