# MINIATURE INTEGRATING GYRO DESIGN

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ABSTRACT

The design described in this paper is for a gyro having the drift stability and reliability required by inertial navigation systems but of smaller size and weight than its predecessor. To accomplish this goal, simple rugged design concepts were followed. The evaluation of units demonstrates that drift stability and reliability as required were achieved in the miniature gyro design.

## INTRODUCTION

Inertial Guidance Platforms a few years ago weighed between 100 and 150 lb. These platforms were large and bulky compared to the state of the art developments of other electronics packages used in aircraft systems. In 1954 a program was started to reduce the size of the inertial components, gyros and accelerometers, which are the heart of the inertial platform. Reduction size of these components resulted in inertial platforms weighing 20 to 25 lb. The component size reduction was the result of a design program that had as its goal not only the reduction in gyro size but also improved gyro performance. The performance parameters of main concern to the platform engineers are the stability and magnitude of gyro drift coefficients. Particularly these coefficients apply to drift which is not sensitive to acceleration, drift which is sensitive to the first power of acceleration, and a drift which is sensitive to the second power of acceleration.

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The miniature integrating gyro (GG49) is the result of this design program. In 1954 the program was started and was based on the experiences gained with six generations of integrating gyros. These experiences on the predecessors to the MIG resulted in "know how" which indicated that the size could be reduced without compromising performance. To accomplish this, strict attention was paid to all details of the gyro design and of the subassemblies design. The subassemblies were designed so that they were rugged and simple for maximum dimensional stability and with a minimum of external appendages and adjustments for added dimensional stability. The dimensional stability of the gyro and its subassemblies has a direct effect on the gyro performance.

In gyro design technology the first design is not the last nor the best design. It is, therefore, important to properly evaluate both the capabilities and limitations of the design. The environmental testing on the GG49 has provided the gyro designer and the applications engineer with a specific set of data from which it is possible to properly apply the gyro to almost any environment to which an inertial system can be expected to be subjected. In collecting the data it also provided the gyro designer with knowledge that was required for him to make modifications and improvements in the design. The first MIG design was successfully completed and the first gyro was shipped in late 1956.

## DESIGN CONCEPTS

MIG gyro design is made up of several subassemblies. Each of these assemblies contributes to the final gyro performance and ultimate system performance, because every assembly has a direct affect on the gyro drift coefficient magnitude and stability. Therefore, each must be designed with full realization of its affect on drift coefficients. Each was designed to be a simple, rugged assembly requiring no final adjustments in the final gyro assembly, because adjustments are subject to shifts under environmental stressing. The subassemblies of the MIG gyro are the spinmotor, gimbal, pickoff and torquer, damping fluid, and case and heaters.

### Spinmotor

The spinmotor of the gyro is the very heart of the unit and contributes the major portion of the acceleration sensitive drift coefficients. This assembly must, therefore, be designed for maximum dimensional stability so that the acceleration sensitive drift coefficients are not subject to shifts during operation or during periods of environmental stress.

The spinmotor is a 400 cycle, three-phase, hysteresis motor. The spinmotor stator, a stationary member, is at the center of the motor with the symetrical rotor outside resulting in maximum angular momentum.

The mechanical design of the spinmotor uses, as far as is possible, materials having the same temperature coefficient of expansion so that temperature stressing of the gyro would not result in movements of one piece part with respect to another piece part. The mechanical design was based on a careful analysis of the spring compliance of the total assembly and piece parts used so that these compliances would be not only matched for a low drift coefficient sensitive to the second power of acceleration, but also so that these compliances would be very stiff for a low and stable drift coefficient sensitive to the first power of acceleration. The assembly of this motor is achieved as a completely separate assembly and the preload loop of the motor is independent of the spinmotor mounting.

Evaluation of spinmotor bearings and the amount of preload required was carefully analyzed prior to setting of the MIG spinmotor design. At about the time of this design, bearing assemblies were improved to the point where 24,000 rpm operation was practical. This advance in the state of the art of bearings allowed the increase in angular momentum for small weight motors; this is one of the significant factors in a practical miniature integrating gyro design.

Gimbal Assembly

The gimbal assembly is a simple, rugged shell structure in which the spinmotor is mounted. It is made in two halfs, the cup holding the motor and the cover over the motor. These two parts are assembled together on screw threads and then sealed. The screw thread is the part of the joint which supplied the strength. The sealing does not have any strength whatsoever. The gimbal shell, after sealing, is filled with a helium atmosphere to provide a maximum spinmotor operating atmosphere.

The gimbal assembly in addition to providing the spinmotor mounting provides the means of mounting the rotor for the pick-off and torquer and a means for adjusting the gimbal end to end balance and rotational balance. These functions are also best performed in a gimbal assembly that is dimensionally stable and not influenced by environmental stressing. The end to end balance adjustment and rotational balance adjustment on the MIG gimbal are designed with a minimum of external appendages.

## Pickoff and Torquer

Pickoff and torquer is a magnetic device serving two functions with one common magnetic core, therefore, referred to as a dualsyn. Because the dualsyn is a moving iron magnetic structure, it affects the gyro drift coefficients that are not sensitive to acceleration. The design of this device must, therefore, be made in such a way as to minimize these coefficients. Since the drift coefficients are a function of asymmetries in either the stator, rotor, or copper circuitry, this design must have maximum symmetry of stator, rotor, and copper circuitry. The stator is a 16 pole device, the rotor an 8 pole device. Both are punched with precision compound dies and stacked on precision stacking fixtures so that the mechanical dimensions of the parts in final assembly is extremely close. The 16 pole device was chosen because of the natural averaging of the asymmetries which occurs. The resulting drift coefficients from this magnetic structure is many times less than the 4 pole devices used in the design's predecessors to the MIG gyro. Copper wire for the dualsyn is wound into skeins. These skeins are woven about the poles in the proper manner. Such an arrangement provides absolute assurance that the individual torque generator poles and the signal generator poles have exactly the same number of turns, i.e., there is no difference from pole to pole. To achieve stability of the sensitive drift coefficients it is important that the materials of the dualsyn be assembled such that environmental stressing of the device does not result in changes to the magnetic structure. The dualsyn rotor is mounted on the gimbal of the gyro. The stator of the dualsyn is mounted in the case in a position having both axial and radial symmetry with respect to the rotor. No adjustments in the final device are made to select the best position. The MIG is purposely designed without adjustments, because there is a possibility that adjustments could shift during operation or environmental stressing. Strict attention to these details has resulted in the dualsyn which not only has low coefficient of nongravity sensitive drift but also a most stable coefficient of drift.

## Flotation Fluid

Fluorolube used in the MIG design serves two important functions: 1) the flotation of the gimbal, and 2) the damping of the gimbal. The flotation of the gimbal minimizes gimbal bearing friction. The damping of the gimbal, a function of the fluid viscosity and the geometry of the gap between the case and gimbal provides the integration of the integrating gyro. Design experience in MIG predecessors indicated that the fluid viscosity should be as low as possible, since the lower the viscosity the better the low temperature storage characteristics of the fluid. Both functions are best served with fluorolube since this liquid is chemically inert, i.e., does not react with any of the materials in the gyro.

The process for filling the gyro is a most critical one. The gyro must be 100% filled with fluorolube, i.e., there must be no voids or bubbles in the liquid, because bubbles act as balloons when attached by surface tension to the gimbal's surfaces and cause changes of the gravity sensitive drift coefficient. Therefore, extreme care was used in selecting the fill procedure for the GG49. The gyro design aids the filling process of the gyro by providing fill paths that are clean and as straightforward as possible. In the several years history of the GG49 the instance of bubbles in the fluorolube has been extremely rare indicating success in these details in this design.

## Bellows

The bellows assembly is required in an integrating gyro to take up the volume changes of the flotation fluid during temperature cycling. Experience in the designs preceding the MIG indicated the importance of the bellows and the bellows size. It was felt that the bellows itself must be large enough to more than follow the flotation fluid expansions and contractions during the temperature excursions which might be expected. Only 1/3 of the MIG bellows is required to follow the volume displacement of fluid from 200° to -65°F. The bellows design has a significant effect on gyro operation by minimizing the amount of gaseous bubbles and leaks that might occur in the gyro.

## Case and Heaters

The case assembly of the gyro provides a sealed container for the flotation fluid. The heater assembly, an integral part of the case assembly, is required to maintain the gyro flotation fluid at the proper temperature of operation. This is necessary since the viscosity of the fluorolube is a temperature coefficient about 4%/°F. A precise operating temperature of a precision gyro is also a desired feature, since it is not possible to match absolutely the thermal coefficients of expansion of all materials in the design. Therefore, changes of the operating temperature as a function of the operating ambient would result in various physical relationships between the piece parts, and the drift coefficients would shift as a function of operating temperature. The design of these two assemblies, therefore, does affect the total drift of the gyro, and careful attention to the details of these designs was required.

The MIG case is, as far as possible, a one-piece construction for maximum uniform heat transfer about the gyro. There must necessarily be a couple of joints so that the gyro can be assembled. In the MIG gyro these joints all rely on threaded members for the strength of the joint. The sealing of these joints does not provide strength.

The heater design includes warmup and control heaters and a sensing element. The heater is wound in grooves around the case, as is the sensor, for intimate application and control of heat to the aluminum case. Such a configuration of the heater and sensing element, along with the aluminum case, provides a uniformly distributed heat source around the gyro thus reducing gradients across the gyro because of heater excitations.

DESIGN EVALUATION

Evaluation of a gyro serves two useful functions: 1) to determine the capabilities of that design; and 2) to determine the limitations of the design so that corrections can be made. Evaluation of the MIG design is a process that has been going on continuously since the first unit. The data collected on the design are generated from two sources. First gives data that describe the depth of the design resulting from measurements made on each unit prior to shipping. Evaluation includes not only measurements of the scaling factors of the unit and drift coefficients, but also the effect of temperature and vibration stressing on the drift coefficients of the gyro. Second gives data that describe the breadth of the design resulting from repeated exposures of a given unit to environmental stressing. A unit may be subjected to 20 or 30 temperature cycles or vibration cycles to measure the stability of the drift coefficients. In these two manners of testing, the breadth and depth of the gyro characteristics can best be established and the gyro performance in a system application can be predicted.

The results of MIG design evaluation have been analyzed in many ways. The most significant means of analyzing the drift coefficient capabilities of the gyro has been through the use of statistics. A good tool for analyzing the data is a histogram plot of the gyro drift coefficients and stability of the drift coefficients. From the histograms it is also possible to pick out the probable limits to which the design can be produced or the probable limits to which the drift coefficients can be expected to shift for repeated stresses due to a given environmental condition. In testing a given gyro on the production line it is easy to determine whether that gyro is typical of the design and process of the gyro type, and in the repeated testing of a given unit it is possible to determine the typical capabilities of the gyro design for repeated environmental stressing. Together this information completely describes the gyro capabilities.

Initial evaluation of the GG49 was accomplished against the scaling factor goals of the subassemblies. Evaluation of the final gyro assembly included measurements of drift coefficients of the gyro. In a gyro the drift coefficients are a function of torques acting about the output axis of the gimbal. Drift coefficients are equated to the torque acting about the gimbal.

$$\text{torque about OA} = \text{angular momentum X drift about IA} \quad [1]$$

The torques acting on the MIG gimbal were measured by connecting the gyro in a closed electronic rate loop.

The non-gravity sensitive torques, or drift coefficients, in the typical GG49 are less than 2°/hr. These torques are made up of reactions due to signal generator excitation, torque generator excitation, and flex leads which supply spinmotor power into the gimbal. By solving simultaneous equations these torque components can be separated.

Gyro Orientation: Output Axis Vertical, Input Axis East

$$T_1 = SGRT + TGRT + FLRT \quad [2]$$

$$T_2 = 1/2\ SGRT + TGRT + FLRT \quad [3]$$

$$T_3 = SGRT + 1/2\ TGRT + FLRT \quad [4]$$

where $T_1$ = reaction torque with all normal excitations
$T_2$ = reaction torque with the signal generator excitation reduced by 70.7%
$T_3$ = reaction torque with the torque generator excitation reduced by 70.7%

SGRT = signal generator reaction torque
TGRT = torque generator reaction torque
FLRT = flex lead reaction torque

The gravity sensitive drift rate of the gyro resulting from the center of gravity or center of buoyancy being displaced from the output axis produces a torque or drift. Mass unbalance along the two major axes perpendicular to the gyro output axis can be found by proper orientation of the gyro and solving the following simultaneous equations.

Gyro Orientation: Output Axis Horizontal Along North-South Line

$$T_4 = MU_{IA} + RT \quad [5]$$
$$T_5 = MU_{IA} + RT \quad [6]$$
$$T_6 = MU_{SRA} + RT + ER \quad [7]$$
$$T_7 = -MU_{SRA} + RT - ER \quad [8]$$

where $T_4$ = torque with IA East
$T_5$ = torque with IA West
$T_6$ = torque with IA up
$T_7$ = torque with IA down
RT = reaction torques
$MU_{IA}$ = mass unbalance along the input axis
$MU_{SRA}$ = mass unbalance along the spin axis
ER = torque due to earth's rate

Fig. 2 shows typical histograms of the drift coefficients that are sensitive to acceleration.

## Vibration Stresses

The vibration stressing of the gyro results in changes to the previously described drift coefficients. The more severe the vibration the more sizable are the changes in the drift coefficients. The effects of vibration in the evaluation program at Honeywell can be divided into two categories: changes resulting from high, and that from low, level vibration.

The low level vibration used in the evaluation program was 5.4 g of white noise band limited to 20 to 500 cps. The changes in drift coefficients due to this level of vibration were less than 0.08°/hr/G. The high level vibration used in evaluation of the GG49 was 12 g white noise band limited to 20 to 1500 cps. These vibrations were applied along each of the three major axes of the gyro, output axis, spin axis, input axis, for a total unit vibration of approximately 3 min. The second vibration is considerably more severe than the first vibration from two standpoints; the gravity level is considerably higher and the frequency is higher and beginning to approach the rise in the resonant curve of the spinmotor gimbal assembly so that the spinmotor itself is seeing more than the 12 g applied. Resulting changes in the drift coefficients due to this vibration were less than 0.40 deg-G/hr.

Vibration effects on the drift coefficients reveal a Gaussian distribution to which statistics can be applied. It is apparent from these results that the vibration level and the frequency level have a significant effect on the stability that can be expected on a given gyro design.

## Temperature Stresses

The results of temperature stressing of the GG49 were measured by storing the gyro at various ambient temperatures and then raising the gyro temperature to the proper operating temperature and repeating measurements of the drift coefficients. It is possible then to compare the drift coefficients before and after temperature storage. Such comparisons plotted as histograms make it possible to predict the shift that can be expected of the gyro due to any level of temperature storage. Testing on the GG49 has been done at storage temperatures ranging from operating to -65°F. A typical set of histograms is shown in Fig. 4. It was observed that the amount of shift experienced in the drift coefficients increase as the storage temperature was decreased. This background of data is used to satisfactorily predict the gyro performance for a given system environment requirement.

These data were also used to indicate needed modifications in the gyro design. The first GG49 did not have the desired distribution drift coefficient shifts. The data indicated that the shifts along the input axis were two to three times greater than the changes along the spin axis. From that initial data the designer could immediately see that a soft condition existed along the input axis but not along the spin axis. The gyro spinmotor assembly was then carefully analyzed to determine ways and means of making the mass stability stiffer along the input axis. The needed changes were instituted, and subsequent gyros produced the data shown in Figs. 1-4.

Life Stresses

Life data on the GG49 have been accumulated in various platform applications and various evaluation tests over the last several years. The initial motor life did not satisfactorily meet the needs of many platform applications. The careful analysis of the cause of spinmotor failures resulted in changes that significantly improved the running time of the gyro motor. A useful life of 5000 hr is presently indicated.

Life is important not only from the standpoint of spinmotor operation but also from the standpoint of the gyro drift coefficient's capability to remain within some specified tolerance. A GG49 running for 7200 hours and having been exposed to various environmental conditions during that period showed a change of only a few tenths of a deg /hr /g in $MU_{IA}$ and $MU_{SRA}$.

MIL-E-5272 Environments

The GG49 has been qualified to environments equal to or more severe than those specified in MIL-E-5272. Fifty gravity shocks along each of the gyro axes, 20 g acceleration along each of the major axes, humidity, explosion, salt spray have been run on the GG49. The GG49 has satisfactorily met these environmental conditions and so is a qualified device against military-type requirements.

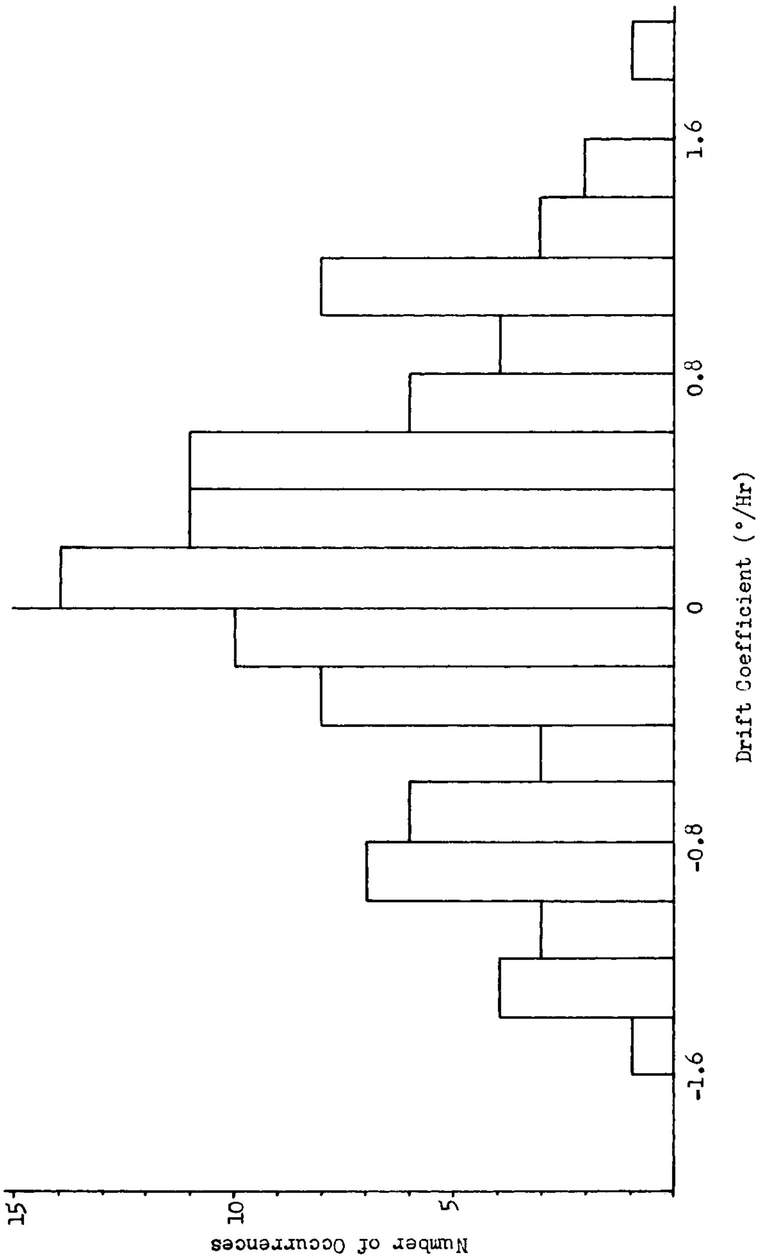


Fig. 1 Distribution of non-gravity sensitive drift coefficient after subjecting gyros to -25°F and 12 g vibration

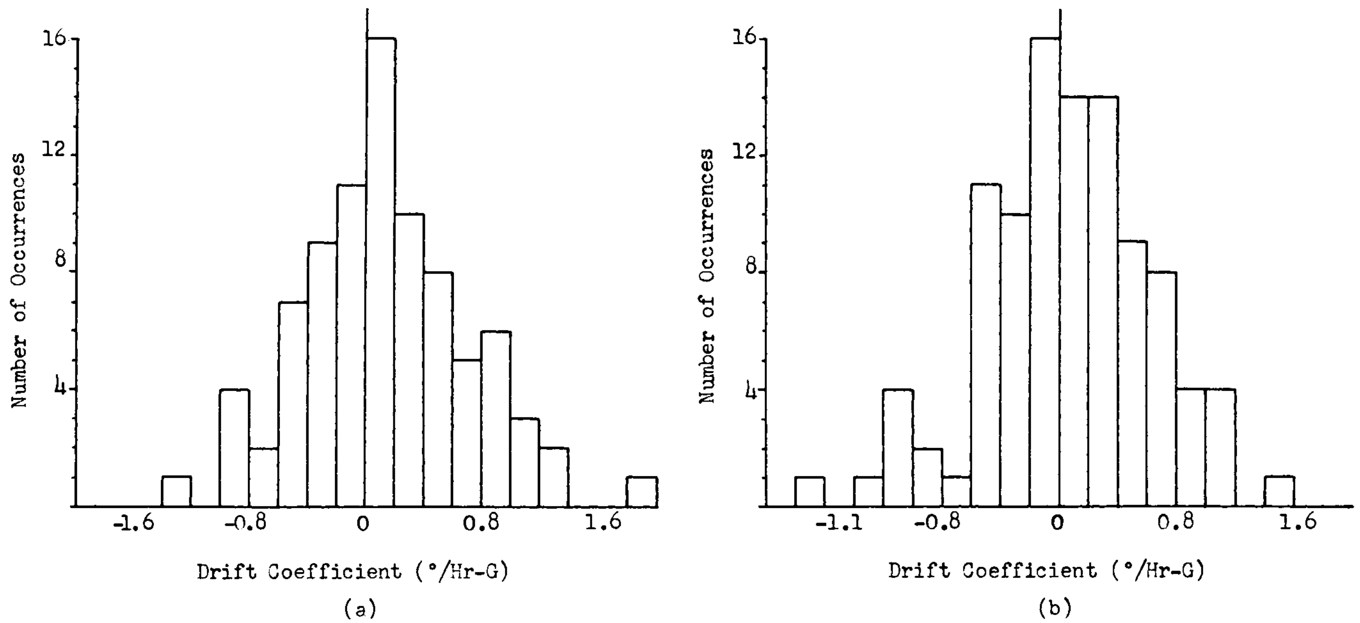


Fig. 2 Distribution of gravity sensitive drift coefficient after subjecting gyros to -25°F and 12 g vibration. a) Drift coefficient along the input axis; b) drift coefficient along the spin reference axis

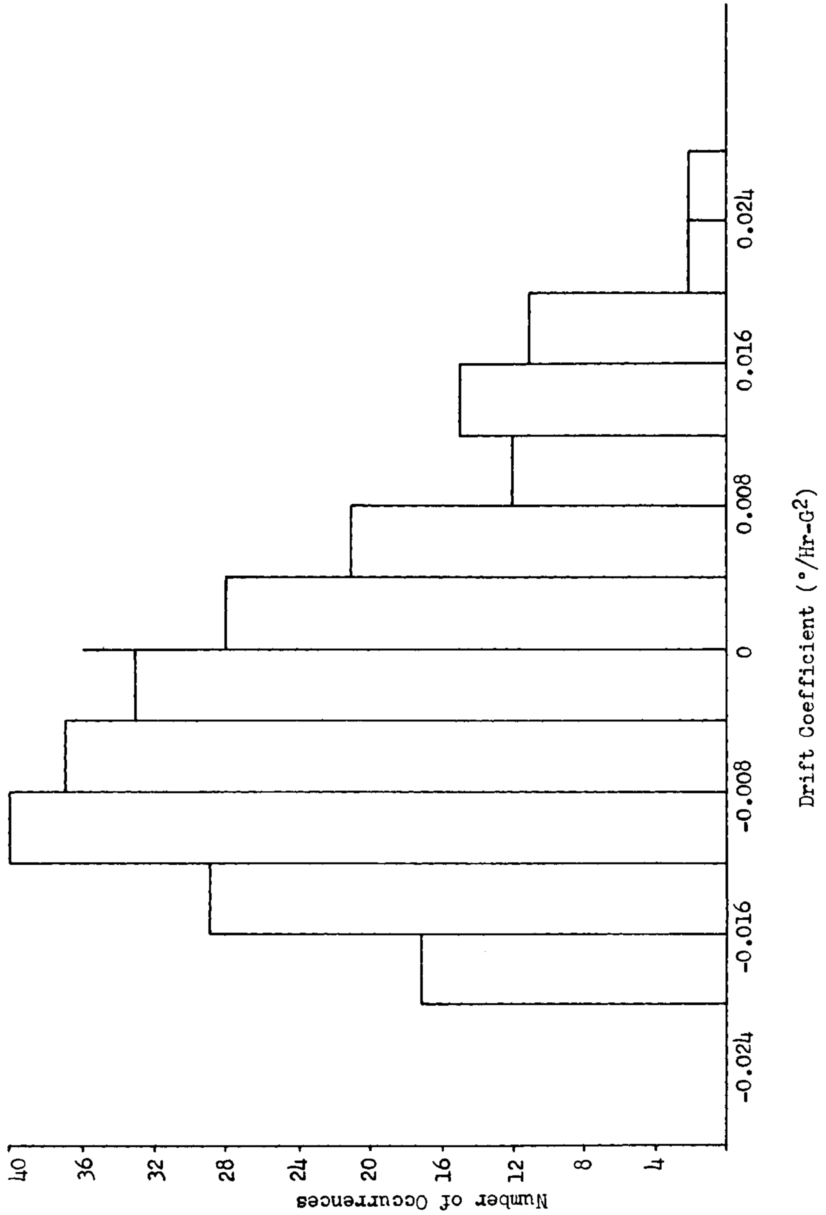


Fig. 3 Distribution of gravity squared sensitive drift coefficient after subjecting gyros to -25°F and 12 g vibration

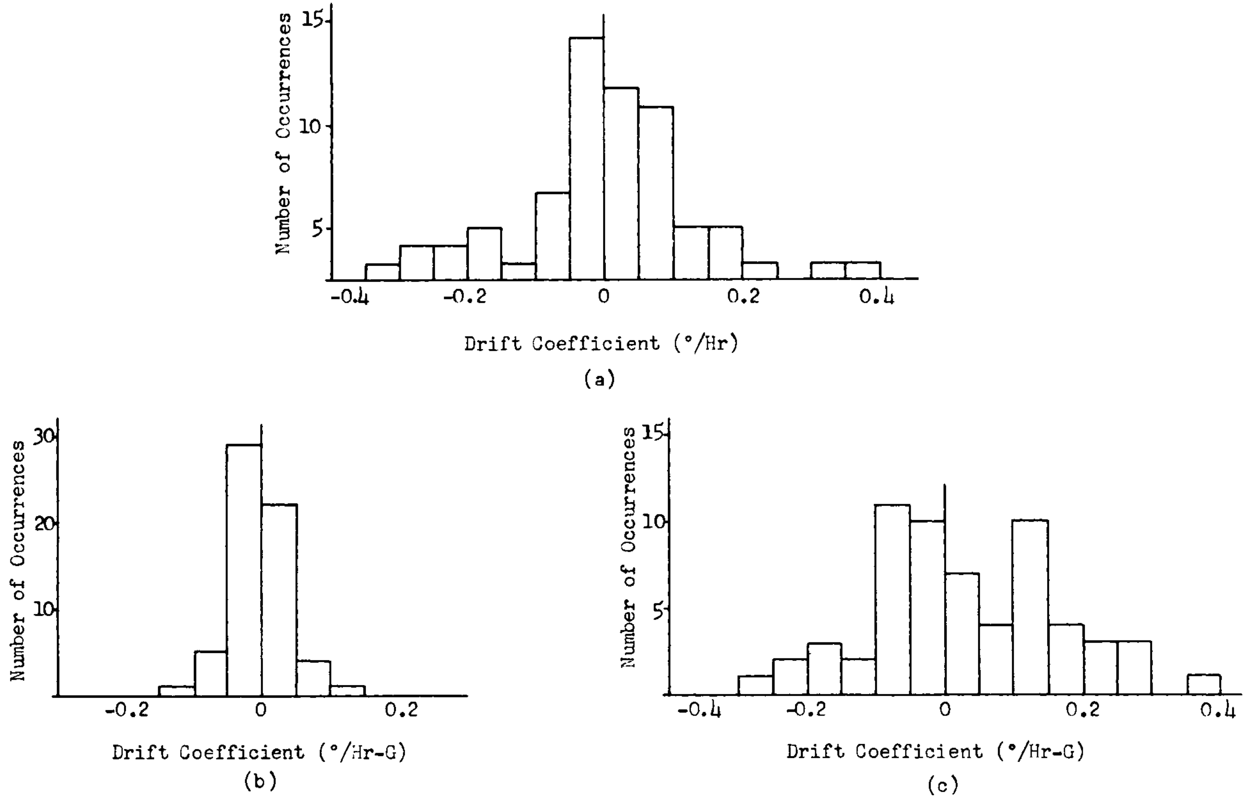


Fig. 4 Distribution of the changes in drift coefficients as a result of -65°F temperature storage. a) Non-gravity sensitive drift coefficient; b) gravity sensitive drift coefficient along the input axis; c) gravity sensitive drift coefficient along the spin reference axis