(*Reprinted from* Mechanical Engineering *for June, 1961, with permission of Copyright Owner*)

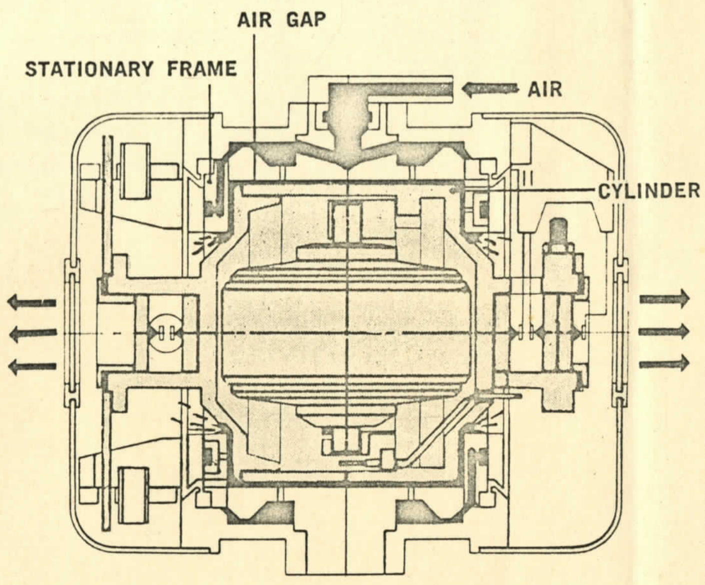


Fig. 1 Cross section of an air-bearing gyroscope. The high-speed gyro motor is encased in a gas-supported cylinder (shown in gray). Air or nitrogen (shown in black) enters a gas chamber. Small nozzles lead to the gap in the axial and radial direction. The gas escapes from the gap around the necks and edges of the cylinder. Number of nozzles varies with the size of the bearing.

Accuracy dictated the use of pressurized gas bearings in the navigational instruments of the Army's ballistics missiles. Here are the factors involved, the test methods employed.

EXTERNALLY PRESSURIZED GAS BEARINGS

By **H. C. Rothe,** Director, Astro-Space Laboratories, Huntsville, Ala.

In the enthusiasm attending the great revival in interest in gas bearings during the past few years there has been a tendency to overlook their limits and disadvantages as compared to conventional bearings. It is worth emphasizing that a gas bearing is a very specialized instrument, which will never replace ball or journal bearings in general applications. Nevertheless, there are some fields in which either pressurized or self-acting gas-lubricated bearings have established or will establish themselves as useful members of the bearing family.

The foreseeable fields of application are: (*a*) For extreme-temperature environments, (*b*) for areas where oil or grease cannot be used because of explosion or radiation problems, (*c*) for instruments with high rotational speed and long life requirements as anticipated in space vehicles, (*d*) for high load or high speed, where a change in the bearing characteristics during operation cannot be tolerated, (*e*) for negligible rotational or translatory speed, but extremely low friction.

Contributed by the Lubrication Division and presented at the Lubrication Symposium, Miami, Fla., May 8–9, 1961, of The American Society of Mechanical Engineers. Paper No. 61—LubS-4.

Advantages and Limitations

The favorable parameters of gas bearings can be surmised from the list of applications. They are: (*a*) Insensitiveness to environmental temperature conditions, (*b*) the absence of conventional lubricants and their attendant chemical or radiation-reaction problems, (*c*) absence of coulomb friction, resulting in unlimited life expectancy, coupled with stable performance characteristics, (*d*) extremely low friction level for low rotational or translatory speed.

In considering their disadvantages it is necessary to discuss the two types of gas bearings separately.

The self-acting bearing provides a film of air between the moving parts by the relative speed of these parts against each other. A fairly stable environmental pressure is required, but no special gas supply. The dry starts and stops, rather than the actual running time, determine the lifetime of these bearings and make the employment of special materials necessary. For load-efficiency reasons, a very small gap—100 millionths of an inch or less—must be used between the moving parts. This requires excellent surface finish and extremely low manufacturing tolerances.

EXTERNALLY PRESSURIZED GAS BEARINGS

Fig. 2 Cross section of a restriction nozzle. Holes of about 0.02 in. in diam are drilled in the sleeve and the thrust plates and 0.002-in-thick aluminum foil is cemented over the hole. This is dimpled by a small ball and pierced with a 0.005-in-diam pointed steel needle.

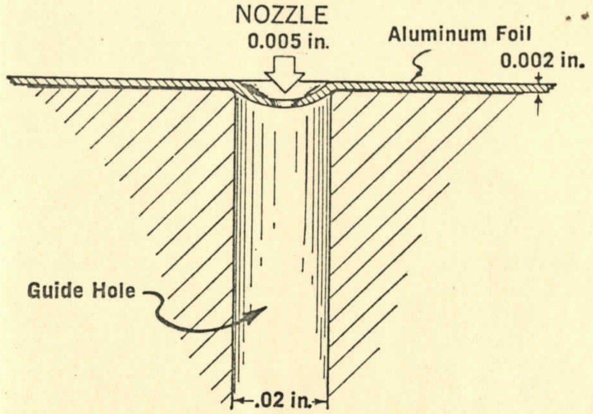


Fig. 4 The load capability of the bearing for constant acceleration in each of its principal axes is determined with a centrifuge. The bearing is used as a capacitor in an 800-cps circuit to indicate the touch point correctly. The supply pressure which just floats the bearing is found for several g-loads.

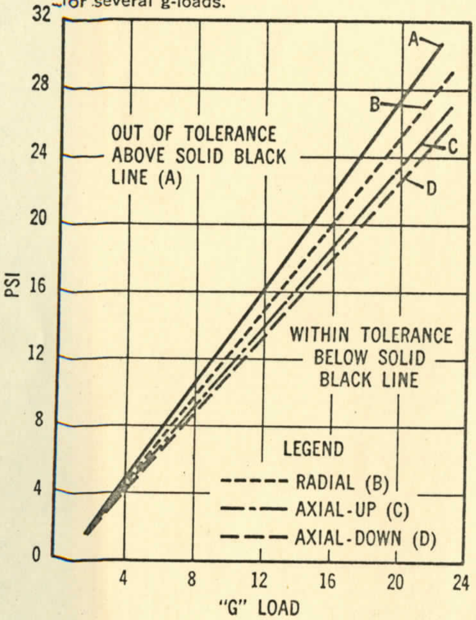
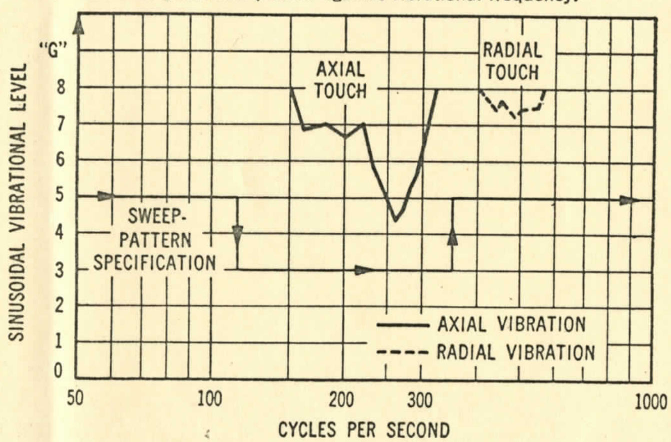


Fig. 5 Response of the air bearing to sinusoidal vibration. Tests for vibrational accelerations are performed on a shake table whereby the gas pressure is kept constant at the operational value. Limits of g-load are plotted against vibrational frequency.



At high speed, the narrow gap produces shear forces of a magnitude such that the torque is comparable to that produced by ball bearings. Another inherent shortcoming of this type of gas bearing, when used for radial load, is the angle produced between the direction of the yield and the direction of the load. In gyro applications, this phenomenon affects the accuracy in a manner very similar to that of the nonisoelasticity error.

Another problem is stability. Several kinds of instability occur or tend to occur at different rpm. More research must be done to gain better understanding of this very troublesome area.

The externally pressurized gas bearing, on the other hand, requires a constant gas supply in the form of a storage tank or a pump system. Filters must be used to insure the cleanliness of the gas. While the gap on this type of bearing is several times wider than on the self-acting one, the low-turbine-torque requirement demands very close manufacturing tolerances to insure symmetrical gas flow inside the bearing. Again, instability—introduced here by the gas-feeding system—is a problem.

Pressurized-Gas-Bearing Applications

Accuracy was the primary determinant in the decision to use pressurized gas bearings in the navigation instruments of the Army's ballistic missiles. The accuracy of a gyro is determined by the torque acting about its inner gimbal axis, since the drift rate is directly proportional to this torque.

A simple equation, $\omega = T/A$, gives the torque level which can be tolerated.

In it ω equals the drift rate in radians per sec, T equals the torque in dyne-cm, and A equals the angular momentum of the gyro in gram cm^2 per sec.

The required drift rate for today's precision gyros is a fraction of a degree per hour. If a gyro of medium size is assumed with an angular momentum of 2 times 10^6 gr cm^2 per sec, the equation yields a tolerable torque of 1 dyne-cm for a drift rate of $^1/_{10}$ deg per hr. This torque level is several magnitudes lower than that which any conventional bearing can supply. The inner gimbal axis has negligible angular speed; therefore, when using a gas bearing, it has to be externally pressurized.

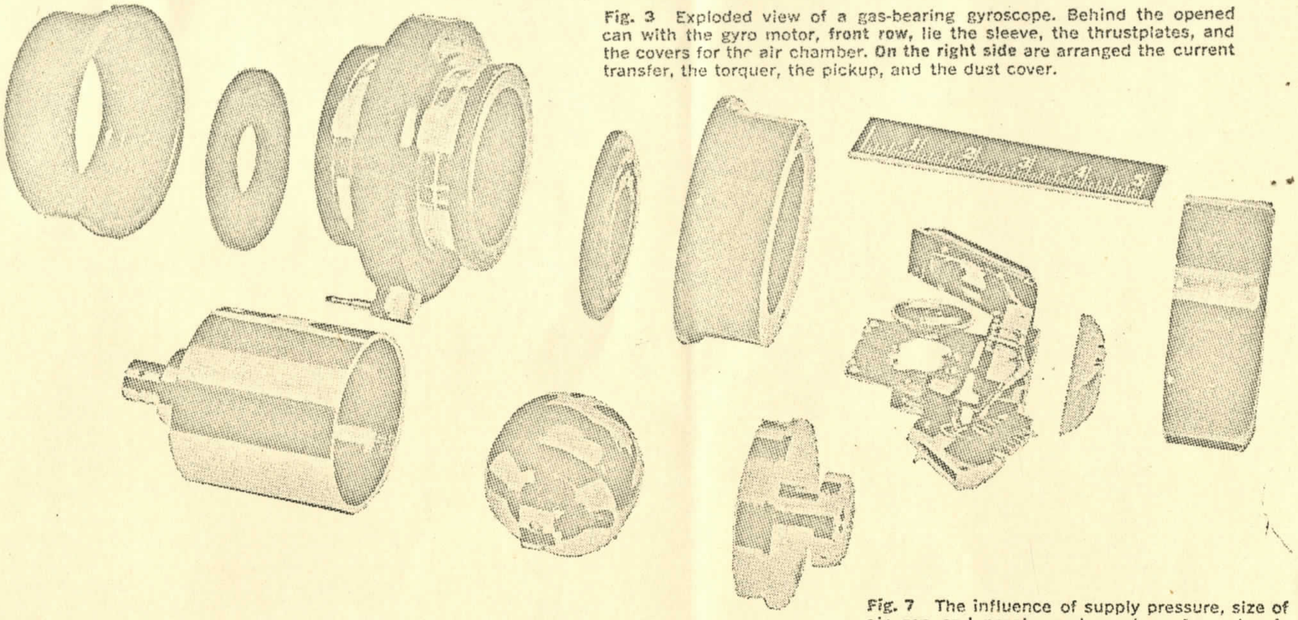


Fig. 3 Exploded view of a gas-bearing gyroscope. Behind the opened can with the gyro motor, front row, lie the sleeve, the thrustplates, and the covers for thr air chamber. On the right side are arranged the current transfer, the torquer, the pickup, and the dust cover.

Fig. 6 Stiffness is determined by recording the position of the float as a load function in the axial static-load test

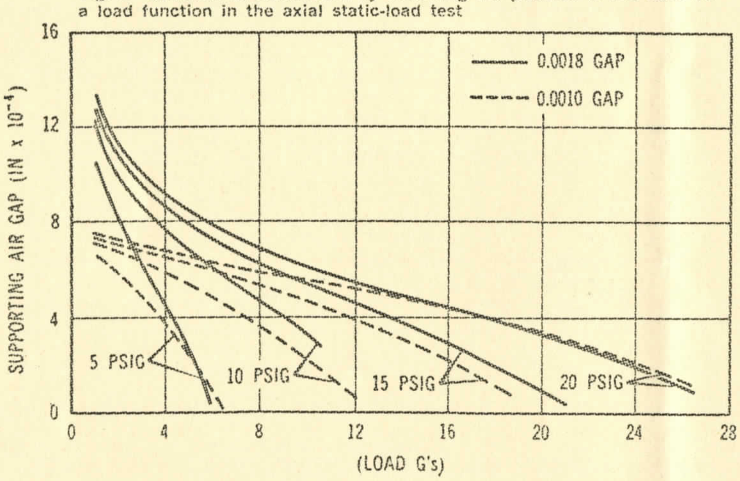
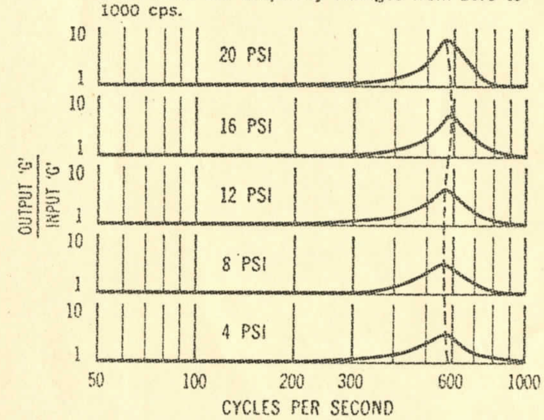


Fig. 7 The influence of supply pressure, size of air gap and nozzle, and number of nozzles is investigated in stability tests. g ratio is recorded for vibrational excitation perpendicular to the axis. The vibrational acceleration g is kept constant while the frequency changes from zero to 1000 cps.



Design and Physical Principle

A schematic cross section of an air-bearing gyroscope is shown in Fig. 1. The high-speed gyro motor is encased in a gas-supported cylinder. Air or nitrogen enters the gas chamber through a filter. From this chamber, small nozzles lead to the gap in the axial and radial direction. The gas escapes from the gap around the necks and the edges of the cylinder. The number of nozzles varies with the size of the bearing. There are two or four rows of nozzles in the sleeve with eight to 24 nozzles per row and six to 12 nozzles in each thrustplate.

A cross section of a nozzle is shown in Fig. 2. Holes of about 0.02 in. in diam are drilled in the sleeve and the thrust plates. A piece of aluminum foil 0.002 in. thick is cemented over the hole. This foil is then dimpled by a small ball and pierced with a pointed steel needle of about 0.005 in. in diam. This elaborate procedure is used to insure the uniform gas flow through the nozzles which is necessary for low turbine torques.

Actual hardware is shown in Fig. 3 in an exploded view. In front row is the opened can with the gyro motor. Behind it lie the sleeve, the thrustplates, and the covers for the air chamber. On the right side are arranged the current transfer, the torquer, the pickup, and the dust cover. Bearings of this type are manufactured in several sizes from 1 to 4-in. float diameter. The ratio between length and diameter of the float is equal to approximately one on all bearings.

The following approach proved to be useful as a start in the design. The intended application determines the size of the gyro motor required. The float is designed to fit this gyro as a housing. This establishes the weight and the projected area of the float. Weight multiplied by highest anticipated linear acceleration g and divided by the projected area results in the necessary mean pressure difference. This pressure is divided by 0.6 to find the approximate supply pressure required to prevent the bearing surfaces from touching at the highest rate of acceleration. This ratio, 0.6, may be called a load-efficiency number. It was established by measurements on several hundred bearings of this design. The actual supply pressure varies from 15 to 27 psi for different

EXTERNALLY PRESSURIZED GAS BEARINGS

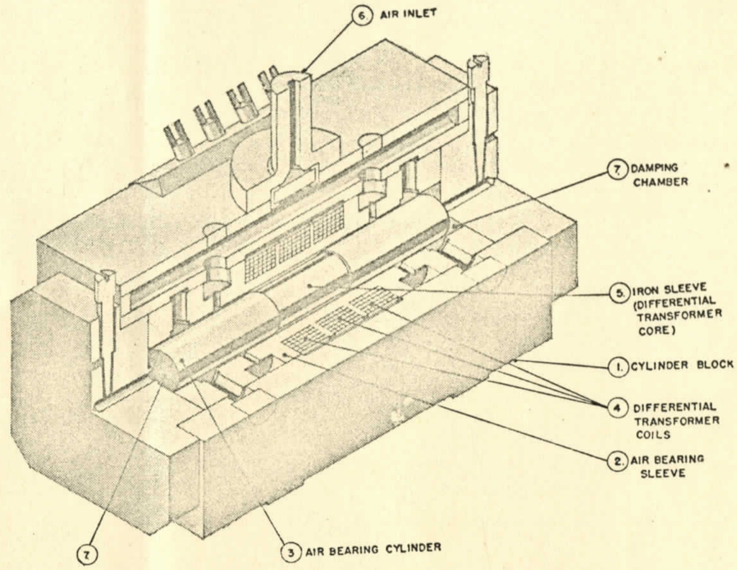


Fig. 8 An air-bearing pendulum which is used on stabilized platforms to establish the local vertical with great accuracy. A horizontal ceramic slug (3) takes the place of the well-known swinging weight. It is radially supported by air and carries an iron sleeve (5). A differential transformer (4) on the sleeve picks up the axial position of the slug. Damping chambers on both ends (7) permit adjustment of the pendulum time constant for different applications of this instrument.

applications. The air consumption at the operational pressure lies between 0.5 and 2 standard cu ft per min.

The underlying physical principle of this type of bearing can be explained very simply. Gas flow through the nozzles is constant and sustained by the exterior gas supply. An originally centered float will move to one side under load and consequently will restrict the amount of flow through the nozzles on that side. On the opposite side, the gap widens and the flow through the nozzles increases. Since the pressure drop inside each nozzle is a function of the amount of flow, the pressure increases in the smaller gap on the loaded side and decreases on the other side. The differences in pressure establish an equilibrium with the load.

Pressurized Gas Bearings in Missiles

For missile application, the performance requirements which have to be met are: (*a*) Compatible load-carrying capability in all directions, (*b*) assurance of stability under extreme environmental conditions including vibrations, load variations from zero to maximum, and ambient-pressure fluctuations, whereby the turbine torque should not increase substantially.

To insure performance under missile conditions, the following test methods are used:

Load Capability. A centrifuge is used to determine the load capability of the bearing for constant acceleration in each of its principal axes. The bearing is used as a capacitor in an 800-cps circuit to indicate the touch point correctly. The supply pressure which just floats the bearing is found for several *g*-loads, Fig. 4. These tests are repeated under different ambient-pressure environments. The tests for vibrational accelerations are performed on a shake table with the gas pressure kept constant at the operational value. The limits of the *g*-load are plotted against vibrational frequency, Fig. 5. Another test determines the stiffness by recording the position of the float as a load function. An example for different pressures and for two different air-gap sizes is in Fig. 6.

Stability. Many tests are made to determine the stability of the bearing. The influence of supply pressure, size of air gap and nozzle, and number of nozzles is investigated. The bearing is vibrated consecutively in its axial and radial directions and 45 deg to both axes. The vibrational acceleration *g* is kept constant while the frequency changes from zero to 1000 cps. An acceleration pickup is mounted on the float and the ratio between input and output *g* is recorded, Fig. 7.

Pressure Distribution. For this test a dummy float is inserted in the sleeve. This float is equipped with a row of holes, each one connected to a pressure meter. The float is slowly rotated and the pressure distribution in the air gap is recorded under different load conditions.

Turbine Torque. Torque levels of one dyne-cm and less prohibit the use of conventional torque-measuring devices. It was found that the method of measuring the angular acceleration of the float gave satisfactory results. To insure that the bearing is really free floating, it is placed with its axis in a horizontal position and an unbalance weight is attached to the float. An angular displacement is given to the float and the decaying oscillation angle is timed. The angle versus time is plotted on semilogarithmic paper; a free-floating bearing will produce a straight line. The bearing is then balanced again and mounted on a turntable. A pickup between float and sleeve is used in conjunction with an amplifier and drives the servomotor of the turntable, thus maintaining the sleeve in a fixed position to the float. The acceleration of the turntable multiplied by the moment of inertia of the float equals the torque at this particular float position with respect to the sleeve. In this way the viscous damping inside the bearing has no influence upon the measurement.

Another application of the pressurized air bearing is for an air-bearing pendulum which is used on stabilized platforms to establish the local vertical with great accuracy, Fig. 8.

In this configuration, a ceramic slug is radially supported by air and carries an iron sleeve. A differential transformer on the sleeve picks up the axial position of the slug. Damping chambers on both ends of the slug permit adjustment of the time-constant of this instrument for different applications. This instrument has also been produced and used in large numbers for many years.

Printed in U. S. A.