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AIR LUBRICATION OF BEARINGS IN CENTRIFUGES AND OTHER HIGH-SPEED MACHINERY IN USSR

Modern Requirements

One of the most vital questions in designing up-to-date machines is the development of machines whose separate elements operate at high speeds. In recent years, the operating speed of the working parts has risen considerably. This is true of machine tools for turning, milling, and grinding. It is also true in the field of light industry. The operating speed of spinning spindles is already reaching 20,000-30,000 revolutions per minute. In many cases high speeds are a necessary condition to the normal course of the technological process, as in electric spindles for grinding small holes, turbine-driven compressed-gas engines, and supercentrifugal and ultracentrifugal apparatus. In the last 10-15 years, the operating speed of hydroscopic instruments has increased from 8,000-10,000 to 20,000-25,000 revolutions per minute. The increased speed also increases the accuracy and dependability of the instrument.

It is very difficult to achieve high operating speeds with the prevailing types of bearings. In the case of rolling friction bearings, an increase in speed produces a progressive increase in dynamic intensities, which makes great demands on the materials used and the accuracy of manufacture. The practical speed limit at which it is possible to use standard rolling friction bearings is 10,000 revolutions per minute. The production of bearings for speeds in the 20,000-revolution-per-minute range already appears to be expensive and complicated, and their period of service does not exceed 200-300 hours.

In the case of sliding friction bearings with liquid lubrication, the situation is basically more favorable. However, losses due to friction increase proportionally, at the rate of approximately the square of the increase in speed. Therefore, with oils or liquids of great viscosity, work at high speeds is possible only with the use of complex apparatus for forcible lubrication supply and heat elimination.

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The low viscosity of gases, and in particular of air, opens up new possibilities for the use of sliding friction bearings. Spindles on bearings lubricated with air can rotate at practically unlimited speed, with negligible heat generation and small losses due to friction.

Work has been going on in this direction for some time. A number of machines and instruments with air-lubricated bearings have been designed. A survey of the work done abroad can be found in Fuller's article "Hydrostatic Lubrication" in Machine Design, No 6,7,8,9, 1947. In the bearings described by Fuller, a buoyant supporting cushion is formed by blowing in compressed air from the outside. One of the best known designs of this type is the ultracentrifuge, which rotates at 80,000 revolutions per minute. Compressed air at a pressure of 0.5 atmosphere is used for lubricating the step bearing.

The most significant failing of such aerostatic bearings is the fact that they require a steady and dependable source of compressed air. If the blowing is momentarily interrupted, irreparable damage is inevitable.

Our own technologists have developed aerodynamic bearings with compressors which are not inadequate. Air is drawn into the lubrication opening directly from the atmosphere as the shaft rotates. These bearings are simple in their working principle and, as experience has shown, dependable in operation. These features open up wide possibilities for their use.

The Machine-Building Institute of the Academy of Science USSR has worked with industrial enterprises for a number of years on the problems of gas lubrication. The successful solution of a number of design problems and the invention of an aerodynamic step bearing made it possible to use aerodynamic bearings in 1948 in the production of a continuous-motion rotor supercentrifuge.

Rotor centrifuges greatly surpass previous types in productivity. Their working principle consists of passing a purifying liquid through a simple steel cylinder which rotates on a vertical axis. The normal acceleration of the liquid can reach a magnitude of tens and even hundreds of thousands of g (the acceleration of gravity, equal to 9.81 meters per second.) This requires a rotating speed of 15,000 or more revolutions per minute. Thus, supercentrifuges, and, to a greater extent, ultracentrifuges working at speeds of up to 150,000 revolutions per minute, are adaptable to gas lubrication.

Observation of the work of supercentrifuges with a speed of 21,000 revolutions per minute on aerodynamic bearings has shown the bearings to be highly efficient. One of the first machines has already been in operation on a production basis for more than 10,000 working hours, with no breakdown of the bearing unit. This fact gives reason to suppose that aerodynamic bearings will soon find wide application in technical fields. Therefore, a knowledge of their working principle, methods of computation, and special features is of interest to those who are concerned with the subject of high speeds.

Working Principle of Aerodynamic Bearings

The principle can be explained on the basis of a gas-lubricated cylindrical bearing, which differs from a liquid-lubricated bearing only in the fact that its working surface is executed with greater accuracy and fineness of finish. The same is true of the surface of the journal. The difference between the diameters of the journal and the bearing is ordinarily from 10 to 30 microns.

When it is not rotating, the journal lies on the bottom of the bearing. The eccentricity, which is equal to the mean clearance, coincides with the alignment of the load on the journal. The space between the journal and the bearing, filled with air at atmospheric pressure, is of unequal breadth, varying from zero at the bottom to twice the mean clearance at the top. After the journal begins to rotate, air, trapped by its working surface, is forced into the wedge-shaped clearance and compressed. The increased pressure in this lubrication layer separates the journal from the bearing. The magnitude of the eccentricity depends on the size of the bearing, the magnitude of the mean clearnace, the load on the journal, and the speed of rotation. The eccentriciity of operation increases with an increased load. Thus, to insure a buoyant air cushion, the breadth of the clearance must change in the direction of the sliding.

In cylindrical bearings, this condition is automatically fufilled. In step bearings, which serve for the pickup of axial loads, the working surface must impart the required contour. Research has shown that a gas-lubricated step bearing with an oscillating working surface has good supporting capacity.

The step bearing consists of a round block with three or more radial ribs, to which the supporting plate is fastened with screws, one in each of the interradial spaces. The supporting surfaces of the ribs are polished and ground. The plate is a tempered steel, polished and ground, plane-parallel disk. When the screws are tightened, the plate undergoes elastic deformations, assuming an oscillating form very much like a sinusoid. The plate should be of such thickness as to insure the depth of curvature neccessary for maximum supporting capacity when the screws are firmly tightened.

When the toe rotates, the air forced into the narrowing space is compressed, forming a buoyant air cushion which separates the toe from the step bearing. The plate has radial grooves which intersect the screw axes. These grooves facilitate the drawing of air from the atmosphere into the lubrication opening. In this way they increase the supporting capacity of the step bearing, at the expense of increasing the pressure on the whole of its surface. If there were no grooves, the pressure at the point of maximum clearance would be less than atmospheric pressure.

Structure of the Supercentrifuge and Its Basic Elements

The rotor centrifuge, composed of nine units mounted on one base, is designed for the continuous centrifugal purification of liquids. The rotor is suspended by a flexible shaft to a spindle which rotates in the aerodynamic bearing unit. Transfer of the rotation from the pulley of the motor is accomplished by a knitted belt. The motor is secured to a revolving mechanism for maintaing belt tension.

The liquid, supplied by a feed pipe, is injected into the intake nozzle of the rotor. Inside the rotor the liquid is distributed in an even layer along the rotor's walls. Under the action of centrifugal force the residue is precipitated from the liquid and deposited on the walls. The "centrifugat" (the purified liquid) passes into the mouth of the rotor and is ejected through holes in the latter into an overflow trough. From the trough it drains into a receiving container. The machine is stopped periodically, and the rotor dismantled so that the residue which has accumulated may be cleaned off its walls.

The speed of the rotor is 21,000 revolutions per minute. The centrifugal force generated is 12,000 times as great as the force of gravity. Productivity is about 10 liters per hour, depending on the liquid processed and the extent of cleaning required.

When the design of the centrifuge was being developed, it was necessary to limit the rotating speed to a comparatively low rate. Although the aerodynamic bearings caused no difficulty at higher speeds, the drive was a limiting factor in any given case. During experimentation, the number of revolutions reached 30,000, but the durability of the belt at this speed was completely inadequate. Experiments have shown that by far the best belts are those composed of rings of seamless knitted hose which have been saturated with a 5-percent solution of shoemaker's wax in petroleum ether.

The best solution would be to use a built-in electric drive operating on a stepped-up frequency. However, in this case, it would be necessary for every consumer to have a stepped-up frequency generator. This would scarcely be feasible under the conditions which exist in medical, nutrition, and similar laboratories which are the basic consumers of the centrifuges described above.

The aerodynamic bearing unit consists of a hollow spindle pressed into a pulley and rotating on three supports, two bearings and one step bearing. The toe is screwed onto the pulley. The bearings are attached by spring fixators on the bushing and the cap. Since the balls of the fixators are adjusted by springs, and the edges are rounded off at the fitting sockets of the bushing and cap, the bearings are self-adjusting along the axis of the spindle. The step bearing is mounted on the spherical edge of the bushing, so that it also is self-adjusting.

When the spindle rotates, air is drawn from the atmosphere into the spaces between the working surfaces and the supporting surfaces of the bearings and step bearing, forming air cushions which separate the spindle from the bearings. At the moment of starting, the air cushions are lacking. The moment of friction between the toe and the step bearing, which are squeezed together by the weight of the rotor and the spindle (about 2.5 kilograms), is so great that the belt cannot make the spindle start to rotate. A centrifugal clutch coupling placed inside the spindle and attached to the rotor serves to decrease the starting torque and insures fast warming up of the spindle. It thus lessens wear and tear on the working surfaces in starting, when dry friction occurs between the spindle and the bearings.

When the machine runs down, the air cushion between the toe and the step bearing is retained down to speeds of 400-500 revolutions per minute, after which the spindle is stopped almost instantaneously as a result of the dry friction which has set in. The action of the clutch coupling permits the rotor to revolve freely until the machine stops completely. Thus wear and tear on the step bearing when the machine runs down is also avoided.

Another centrifugal clutch coupling, by which the motor pulley is connected with the shaft of the electric motor, serves to decrease wear and tear on the belt at the starting of the machine.

During normal operation of the machine, the spindle is completely insulated from the bearings by the air cushions. This is the basis for automatic control of the bearings, which is achieved by an electric signaling device. It consists of a galvanometer switched into the electric circuit of a dry cell with a voltage of 1.5 volts. The circuit runs through the spindle, the bearings, and the step bearing, but carries no current unless normal operation of the unit is interrupted.

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Method of Computing Bearing Capacities

The bearing in the aerodynamic bearing unit of the centrifuge may be used as an example for illustrating the method of computing the technical characteristics of gas lubrication. The technical data is as follows: diameter of the spindle, 17 millimeters; mean clearance between the spindle and the bearing, 8 microns; breadth of the bearing, 50 millimeters; speed of rotation of the spindle, 21,000 revolutions per minute; atmospheric pressure, one kilogram per square centimeter; working temperature of the bearing, 30 degrees.

The position of the journal in the bearing shifts when the load on the journal is changed. With an increased load, the eccentricity is increased and the minimum clearance is decreased. The mean clearance remains constant, since it does not depend on the eccentricity or the minimum clearance.

It is impossible, however, to decrease the minimum clearance beyond a certain limit. If the clearance is too small, dry friction will occur in certain places as a result of unavoidable errors in the macrogeometry of the working surfaces of the journal and the bearing, and the machine will break down. Experimental research has shown that 3 microns can be considered the minimum for bearings with gas lubrication. This is the extent of error in ovalness and conicity with which the journals and bearings are made at present. When greater accuracy in their manufacture is achieved, the minimum clearance can be decreased.

If the minimum clearance is assumed to be 3 microns, the load capacity of the bearing is 11 kilograms. Since the tensile strength of the belt, distributed over the two bearings, does not exceed 4-5 kilograms, there is a fourfold margin of supporting power.

In designing the bearing, it is important to determine the proper mean clearance, in order that the minimum clearance will be such as to afford the greatest supporting capacity to the bearing.

It must be kept in mind that when the mean clearance is increased, there is a greater shift of the spindle axis from its central position under the weight of the load. In certain cases (grinding spindles, for example), the extent to which the eccentricity may shift is limited by the nature of the work. Therefore, after the proper mean clearance has been determined, it is necessary to make sure that the eccentricity produced by the load will not exceed the prescribed limit.

The moment of friction on the journal is greater than on the bearing. However, in gas lubrication, and especially at high speeds of rotation, the difference is negligible. The greatest moment of friction is equal to 12.7 gram-centimeters. The total power expended in friction, including both bearings, is less than .01 horsepower. The increase in temperature of the bearings does not exceed 3 degrees.

Computation of the step bearing is done by the same methods. It may be noted only that the supporting capacity of the step bearing is 12 kilograms, whereas its load does not exceed 3 kilograms. The diameter of the step bearing is 70 millimeters; the moment of friction under the working load is 57 gram-centimeters.

Some Special Features of Gas Lubrication

The supporting capacity of a gas lubrication layer is limited, whereas the supporting capacity of a liquid layer increases with speed (where a laminar flow exists). This is the fundamental difference between gas and liquid lubrication.

At high rotating speeds, the load on the bearings is usually small, and the supporting capacity of the gas layer is adequate, as in the case of the centrifuge. Where great supporting capacity is required, it can be achieved by an increase in atmospheric pressure. At high rotating speeds, the supporting capacity is almost directly proportionate to the atmospheric pressure.

It is sometimes convenient to feed compressed air directly into the bearing. It is particularly advantageous to blow it into the section where the pressure is lowest. It is important to note that losses due to friction are not increased by the blowing, since the viscosity of gases is not dependent to any great extent on pressure. Temperature also has small effect on the viscosity of gases as compared with oils.

This feature opens greater possibilities for using aerodynamic bearings under conditions of extreme temperatures. Their efficiency is attested by the steady work of the centrifuges which have been installed in refrigeration compartments.

Conclusions

The proper use of aerodynamic bearings is at high rotating speeds. However, it is impossible to state the minimum speed at which they can be used, since, with small loads, the gas cushions can exist even at low rotating speeds. Generally speaking, it is not efficient to use aerodynamic bearings at low speeds, because under these conditions, oil-lubricated bearings and rolling friction bearings have a much greater supporting capacity.

When the dependability and durability of other types of bearings are inadequate, the lower speed limit for the use of aerodynamic bearings may be fixed at 8,000-10,000 revolutions per minute. The upper limit depends only on the sturdiness of the material in the rotor, since losses due to friction are always small because of the low viscosity of gases.

Among the merits of aerodynamic bearings are their simplicity -- since the surrounding atmosphere is a lubrication reservoir -- and their insensitivity to high and low temperatures. In view of their operational attainments, it may be assumed that in the near future they will find varied application in machines and instruments which require high rotating speeds under moderate loads.

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