rotation in two directions. A recommended pattern is:

- Groove depth equal to the nominal running clearance.
- Land width equal to twice the groove width (note: use the top curve in Fig. 4 for this design).
- Three patterns opposite a smooth surface; either surface may rotate.

This step bearing should support at least half the load of an equivalent spiral-groove gas thrust bearing while permitting shaft rotation in either direction. This recommendation is supported by the computer and experimental investigation.

This investigation shows that the higher-order terms sometimes neglected in the gas bearing analysis may represent an error on the order of 20 percent. The load deflection of the step thrust bearing is linear to about the same extent as other common self-acting gas bearings.

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DISCUSSION

J. S. Ausman[2]

This is a very worthwhile paper and one that will be interesting to gas bearing designers because there are many instances in which the designer would prefer a bearing which would accommodate either direction of rotation, if only to protect the bearing against inadvertent reversal of direction of the drive motor. The author shows one configuration, namely, the step thrust bearing without feed grooves, which has this capability. One wonders if any other configurations were considered other than the Nahavandi and Osterle "wobble plate" bearing. For example, did the author consider the use of feed grooves placed in the center of the grooved regions of the step bearing? It would seem that such grooves would tend to lift the whole pressure distribution between the bearing surfaces above ambient pressure, thereby increasing the load-carrying capacity.

Normally, the feed grooves on a step thrust bearing are located where the land region steps down to the grooved region. This unsymmetrical geometry is obviously inappropriate for a reversible bearing, and the author's dismissal of this geometry is understandable. However, instead of removing the feed grooves altogether, why not move them to the center of the grooved region, a position which does have reversible symmetry?

M. Wildmann[3]

The author has investigated a gas thrust bearing which eliminates one serious shortcoming of self-acting thrust bearing configurations presently used, namely, the fact that the configurations are limited to one direction of rotation. As the old saying goes, "You don't get anything for nothing." So, in order to obtain two-directional operation, load capacity has to be sacrificed. As rightly pointed out by the author, this may very often be an acceptable compromise.

In comparing the load capacity of the two-directional bearing to the spiral-groove bearing, the author indicates that it has about 20 percent of the load capacity of an equivalent spiral-groove bearing. However, he does not state at what value of the bearing number Λ this comparison is made. The load capacities of both bearings are different functions of Λ, so this comparison is obviously made at some specific value (or range of values) of the bearing number. At low values of the bearing number, the load capacity and the rate of change of load capacity with respect to the two-directional bearing are very small. Therefore, its load capacity is also much less than 20 percent of the equivalent spiral-groove bearing. At high values of Λ, all stepped bearings have load capacities which are much lower than equivalent spiral-groove bearings of optimum configuration and large number of grooves. If the load capacity at high Λ of a grooved stepped bearing is compared to the load capacity of a stepped bearing without grooves, their performance is probably equal.

In the conclusion, the author gives a recommended pattern. However, no indication is given of the bearing number at which this pattern is optimum. In stepped bearings with grooves, the optimum configuration changes as a function of the bearing number. This is undoubtedly also the case for the stepped bearing without grooves.

The author also states that the second-order terms sometimes neglected in gas bearing analysis may represent a significant error. He is apparently referring to the sprial-groove analysis by Whipple. It is true that in the Whipple analysis second-order effects are neglected. For an optimum spiral-groove bearing with a large number of grooves, these second-order effects are indeed small. For the degenerate spiral-groove bearing (zero-degree spiral angle), with only a few grooves treated by the author, these second-order effects may well be important. However, for that particular case, the Whipple analysis gives a zero load capacity, and anything is large when compared to zero.

The main practical disadvantage which this reviewer has found with any two-directional bearing is that, for such bearings, the rate of change of load capacity with respect to speed, at zero speed, is zero. Thus it takes a relatively high speed to get the bearing "airborne." Therefore, starting, and particularly starting under load, may be difficult. Description of the start-up procedure used by the author would be useful.

Author's Closure

The discussions by Ausman and Wildmann are appreciated for their insights into the general class of gas bearings which will support load for either direction of rotation. The range of compressibility numbers which was examined and from which the conclusions were made was about 4 to 40. Other pattern configurations than those considered, such as the centered feed groove mentioned by Ausman, should tend to increase the pressure in the bearing resulting in a corresponding improved load support.

Increased start-up wear, as mentioned by Wildmann, should be expected because of the higher speed necessary to support a given load. No visible wear, however, was noted in the test bearings after several hundred start-stop cycles. Start-up torque should not change with pattern configuration. The same drive systems performed starts equally well for either the spiral groove or step-thrust gas bearings.

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