Gas Bearings," Mechanical Engineering Department, M.I.T., Cambridge, Mass.

6 A. A. Raimondi and John Boyd, "An Analysis of Orifice Compensated Hydrostatic Journal Bearings," ASME Paper No. 54—Lub-17.

7 R. R. Weber, "The Analysis and Design of Hydrodynamic Gas Bearings," Report AL-699, Aerophysics Laboratory, North American Aviation, Inc., Los Angeles, Calif., 1949.

8 F. Gottwald and R. Vieweg, "Berechnungen and Modellversuche an Wasser—und Luftlagern" (Calculations and Tests of Water—and Air Bearings), *Zeitschrift für angewandte Physik*, vol. 2, 1950, p. 437.

9 I. F. Gottwald, "Computations and Measurements on the Air Bearing," Archive 16/15, Foreign Document Evaluation Branch, Ordnance Research and Development Center, Aberdeen Proving Ground, Md., 1943.

10 I. F. Gottwald, "Proposal for an Air Supported Gyroscope," Foreign Document Evaluation Branch, Ordnance Research and Development Center, Aberdeen Proving Ground, Md., 1943.

11 I. F. Gottwald, "Tests on Air Supported Course Gyros," Archive 16/17, Foreign Document Evaluation Branch, Ordnance Research and Development Center, Aberdeen Proving Ground, Md., 1943.

12 G. F. Midwood, "Tests on an Air Lubricated Thrust Bearing," Aero Technical Memo No. 5, Royal Aircraft Establishment, Farnborough, England, 1947.

13 P. M. Mueller, "Air Lubricated Bearings," *Product Engineering*, vol. 22, no. 8, 1951, pp. 112–115.

14 Sasaki, et al., "On the Effects of a Restrictor Before the Air-Hole of an Air-Lubricated Bearing," *Journal of the Japan Society of Mechanical Engineers*, vol. 20, 1954, pp. 105–108.

15 F. R. Archibald, "A Look at Hydrostatic Thrust Bearings," *Machine Design*, vol. 25, no. 9, 1953, pp. 170–175.

16 T. L. Corey, C. M. Tyler, H. H. Rowand, Jr., and E. M. Kipp, "Behavior of Air in the Hydrostatic Lubrication of Loaded Spherical Bearings," Trans. ASME, vol. 78, 1956, pp. 893–898.

17 L. Licht, D. D. Fuller, and B. Sternlicht, "Self-Excited Vibrations of an Air-Lubricated Thrust Bearing," Trans. ASME, vol. 80, 1958, p. 411.

18 P. M. Mueller, "Air Turbine Driven Spindles for Internal Grinding Machines," *Product Engineering*, vol. 23, no. 3, 1952, pp. 160–163.

19 "Bearings for Gyroscope Rotors," *The Engineer*, vol. 194, 1952, p. 651.

20 W. J. Harrison, "The Hydrodynamical Theory of Lubrication With Special Reference to Air as a Lubricant," *Trans. Cambridge Philosophical Society*, vol. 22, 1913, pp. 39–54.

21 W. J. Harrison, "The Hydrodynamical Theory of Lubrication of a Cylindrical Bearing Under Variable Load and of Pivot Bearings," *Trans. Cambridge Philosophical Society*, vol. 22, 1913, p. 373.

22 D. D. Fuller, "Air Bearings—Low Friction," *Lubrication Engineering*, vol. 9, December, 1953, pp. 298–301.

23 J. D. Pigott and E. F. Macks, "Air Bearing Studies at Normal and Elevated Temperatures," *Lubrication Engineering*, vol. 10, February, 1954, pp. 29–33.

24 J. M. Slater, "Gyroscopes for Inertial Navigators," *Mechanical Engineering*, vol. 79, 1957, pp. 832–857.

25 "Piezo-Electric Pick-Up Provides Accurate Vibration Measurement," *Design News*, October 1, 1957, pp. 52–53.

26 R. E. Randall, "Thermodynamic Properties of Air," TR-57-8, Arnold Engineering and Development Center, Gas Dynamics Facility, Department of the Air Force, Washington, D. C., August, 1957.

27 S. K. Grinnell, "Flow of a Compressible Fluid in a Thin Passage," Trans. ASME, vol. 78, 1956, pp. 765–771.

28 A. H. Shapiro, "The Dynamics and Thermodynamics of Compressible Fluid Flow," The Ronald Press Company, New York, N. Y., vols. I and II.

29 B. Blaschitz, "Development of Design Information for Externally Pressurized Air Bearings," thesis, Mechanical Engineering Department, M.I.T., Cambridge, Mass., 1956.

30 H. F. Brubach, "Some Laboratory Applications of the Low Friction Properties of the Dry Hypodermic Syringe," *Review of Scientific Instruments*, vol. 18, 1947, pp. 363–366.

31 W. Froessel, "Journal Bearings With Hydrodynamic Lubrication," *Stahl und Eisen*, vol. 71, 1951, pp. 125–128.

32 J. W. Beams, "High Rotational Speeds," *Journal of Applied Physics*, vol. 8, 1937, pp. 795–806.

33 G. S. Perkins, P. R. Vogt, and R. R. Weber, "Double-Ended Journal Air Bearing," U. S. Patent No. 2,597,371, 1952.

34 E. R. Penick, "Bearing," U. S. Patent No. 1,906,715, 1933.

35 L. F. Carter, "Air Supported Gyro," U. S. Patent No. 2,000,-896, 1937.

36 W. J. Abbot, Jr., "Air-Lubricated Bearings," U. S. Patent No. 1,337,742, 1920.

37 M. Wildmann, discussion on paper by J. S. Ausman, p. 1224.

38 J. S. Ausman, "Fluid Dynamic Theory of Gas-Lubricated Bearings," Trans. ASME, vol. 79, 1957, p. 1218.

39 B. Sternlicht and R. C. Elwell, "Theoretical and Experimental Analysis of Hydrodynamic Gas-Lubricated Journal Bearings," Trans. ASME, vol. 80, 1958, p. 865.

DISCUSSION

W. A. Gross[3]

The author has presented a clear discussion of the externally pressurized circular-plate thrust bearing which is orifice compensated. He has made a unique contribution in conducting careful experiments to verify the known equations for this type of flow.

A word about the limitations involved is in order. Inasmuch as fluid inertia terms have been neglected, the equations lose validity in the region of the inlet hole as the inlet pressure is increased or as the film thickness is increased. In addition, the existence of sonic velocity at the inlet radius R_0, followed by supersonic velocities, and eventually shock waves was first recognized by Deuker and Wojtech,[4] and has since been analyzed by others. Since the expansion occurs so rapidly in the inlet section, the flow there is more nearly adiabatic whereas throughout the remainder of the space between the two surfaces it approaches isothermal.

The effect of fluid inertia is of great importance for externally pressurized bearings, not only because of the modifications in the equation of fluid motion, but also because it can induce turbulence. For example, transition from laminar flow can occur with Reynolds numbers as low as 550 based upon the film thickness and average film velocity. The applicability of these limitations must be assessed before the equations in this paper are used.

Although the paper concentrates upon the orifice compensated bearing, as illustrated in Fig. 1, the pressure and load results as given in Section 3 depend only upon the pressure at the inlet section. For example, the left half of Fig. 3 shows a configuration which is compensated only by the change of film thickness around the periphery of the inlet hole. Because of the absence of a trapped air volume this configuration has good stability characteristics.

This discusser has conducted tests on externally pressurized flat-plate thrust bearings by fixing the plate which contains the inlet hole and moving a plate containing a one-mil diameter pressure sensing hole so that pressure at any radial position may be measured. The small pressure sensing hole is necessary in order to detect the large pressure gradients which can occur in the vicinity of the inlet hole. The pressures can fall below ambient pressure in a distance of a few mils. Too much modification of the flow, as well as effectively averaging the pressure, occurs if the pressure sensing holes are large.

Author's Closure

I appreciate the comments of Dr. W. A. Gross.

As far as the limitations of the analytical treatment chosen in the paper are concerned, it is the opinion of the author that it is not only valid as applied to bearings which are of interest to instrumentation but also to many other practical applications of externally pressurized gas bearings.

The assumptions made in the analysis are that the flow is in the laminar regime throughout the film, that inertia forces are negligibly small compared with viscous forces and that the gas expands isothermally. The very good correlation of the experimental and theoretical data is proof that these assumptions are fully justi-

---

[3] Member of Research Staff, Applied Mechanics, IBM Research Laboratory, San Jose, Calif. Mem. ASME.

[4] "Ecoulement Radial d'un Fluide Visqueux Entre Deux Disques Très Rapprochés; Théorie du Palier a l'Air," *Revue Générale de l'Hydraulique*, vol. 17, pp. 227–234, 285–294.

fied in the case of orifice regulated hydrostatic bearings used as pivot axis supports in inertial and similar instruments which operate with clearances of approximately 1.5 mil and less, orifice diameters of about 4 mil and supply pressures up to 50 psig.

The effects of fluid inertia, turbulent flow, and shock waves are undoubtedly of considerable academic interest; however, as far as practical applications are concerned, the author cannot agree that it is of great importance. As Comolet[5] and others have shown, the load carrying capacity approaches zero or can even become negative when critical values of the Reynolds and Mach numbers are exceeded; the bearing, therefore, loses its usefulness completely. Clearances of 4 to 20 mil and more, which have been used by several authors to demonstrate these abnormal effects, at high supply pressures and excessively large flow rates, are hardly of interest to the designer of bearings for practical applications who is concerned with satisfactory load carrying capacity, maximum possible stiffness, and economy of gas consumption.

---

[5] Raymond Comolet, "Ecoulement d'un Fluid Entre Deux Plans Parallels. Contribution a l'Etude de Buttees d'Air," Service de Documentation et d'Information de l'Aeronautique, Paris, France.