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EQUIPMENT, METHODS AND TECHNIQUES

A BIBLIOGRAPHY ON GAS LUBRICATED BEARINGS—REVISED

Interim Report

By
Eugene B. Sciulli

September 15, 1959

Laboratories for Research and Development
Franklin Institute
Philadelphia, Pennsylvania

UNITED STATES ATOMIC ENERGY COMMISSION
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FOREWORD

This bibliography was prepared at The Franklin Institute Laboratories for Research and Development under a program of research on gas lubricated bearings supported jointly by agencies of the Department of Defense, Atomic Energy Commission, Maritime Administration and National Aeronautics and Space Administration and administered by the Office of Naval Research.

The author wishes to express his appreciation to all those who have contributed bibliographies on gas bearings, called attention to new references, provided copies of difficult to obtain articles, or otherwise made his task easier.

Other technical reports issued under this program are:

I-A2049-1 "A Bibliography on Gas-Lubricated Bearings" by Eugene B. Sciulli, Dec. 1, 1957.

I-A2049-2 "The Influence of the Molecular Mean Free Path on the Performance of Hydrodynamic Gas Lubricated Bearings" by Albert Burgdorfer, June 1958.

I-A2049-3 "Annual Report ONR Project A-2049" by Dudley D. Fuller, July 15, 1958.

I-A2049-4 "A Study of the Stability of Externally Pressurized Gas Bearings" by Lazar Licht and Harold G. Elrod, November 1958.

I-A2049-5 "A Derivation of the Basic Equations for Hydrodynamic Lubrication With A Fluid Having Constant Properties" by Harold G. Elrod, April 1959.

CONTENTS

INTRODUCTION

This work is a revision and expansion of a bibliography issued in December 1957, as The Franklin Institute Laboratories Interim Report I-A2049-1. The present compilation contains 290 applicable references, more than twice the number of its predecessor.

Wherever possible a resumé in English of each reference is included. In most cases the abstracts were taken verbatim from the author, translation being made when required. When necessary or desirable, resumés were prepared or revised by FIL staff members.

Five indexes are provided. The Yearly and Corporate Name Indexes are the same as in the previous bibliography with, of course, the addition of the new references. The Subject Index, however, has been changed. The new Subject Index contains thirteen descriptively worded categories or headings specifically chosen to cover the many varieties and types of gas lubricated bearings. Of the other two indexes, one lists all the patents in numerical order and the other lists the country of origin of the reference when that country is other than the United States.

Every effort has been made to make this a comprehensive listing of all references published prior to July 1, 1959 which deal directly or indirectly with gas lubricated bearings. The author would be grateful if any omissions are called to his attention.

REFERENCES AND ABSTRACTS

1
ABBOTT, W. G., JR., "Gas-Lubricated Bearing," U. S. Patent 1 337 742, issued 1920.

The externally-pressurized gas bearing patented is designed with complementary tapering bearing surfaces. These could be conical bearing surfaces, spherical surfaces or other similar forms of bearing surface of which one member is convex and the other concave. The inventor claims that the bearing will withstand a much greater axial thrust or load and also a greater side pressure or side thrust than cylindrical and plane surfaces.

2
ABBOTT, W. G., JR., "Device for Utilizing Fluid Under Pressure for Lubricating Relatively Movable Elements," U. S. Patent 1 185 571, issued 1916.

The patent is for externally pressurized, gas-lubricated, rotating and reciprocating type bearings. For descriptive purposes, these devices are assumed to be used in a spinning mechanism such as is employed in the textile industry.

3
ADAMS, C. R., "The Step Bearing: A New Concept in Air Lubrication," Product Engineering, Vol. 29, No. 50, Design Issue Dec. 8, 1958.

Consisting of only two parts, bearings like the one described are rugged and inexpensive. They can be operated with air, gas, water, or mercury at high or low temperatures and speeds. (Auth)
These bearings are characterized by an extremely small sill length. The article itself appears to be rather sketchy with much information missing.

4
"Air Bearing Levels Dividing Table," Product Engineering, Vol. 27, April, 1956, pp. 156-157.

Master code wheels for angle digitizers made by Baldwin Piano Company require angular graduations to an accuracy not attainable with mechanical dividing engines. Photographic, electronic and mechanical principles, combined in a machine with the dividing table leveled to one wavelength of light, produce the required accuracy. (Auth)
The story, told in four pictures with titles, reveals that externally-pressurized air bearings made of glass were used in the system.

5
"Air Bearing Vibration Machine," Material Laboratory, New York, Brooklyn 1, N.Y., Technical Review 1956, pp. 4-7.

Mention is made of a device to help evaluate the mechanical characteristics of electron tubes and other equipment. This includes the mechanical reproductions of random noise excitation. For this purpose the test equipment (vibration machine) must have no resonances in the frequency band of interest and it must also meet other rather stringent conditions. It was found that a vibration machine incorporating air bearings could fulfill most, if not all the necessary requirements. (See SCHNEE).

6
"Air Lubricated Bearings - Some Pros and Cons About Them," Power Transmission Design, Vol. 1, No. 5, May 1959.

This article abstracts some of the material from Chapter 9 of the book, "Theory and Practice of Lubrication for Engineers," Ref. 100.

7
"Air Lubricates Grinder Head Bearing," Machine Design, Vol. 24, No. 6, June 1952, p. 138.

News item describing a small grinder that has air lubricated bearings. Built in two models, by Pratt and Whitney, the units have speed ranges from 35000 to 50000 rpm and 60000 to 100000 rpm. Air requirements range from 25 to 36 cfm.

8
"Air Lubricated Michell Bearing," Engineering, Vol. 116, No. 3007, Aug. 17, 1923, p. 203

Brief article mentioning that Kingsbury constructed a model air lubricated thrust bearing.

9
"Air Lubricated Thrust Bearing," Library of Congress, PB 117 333, (Appendix B.)

Included in a Materials Testing Report from NRL is an appendix containing mention of two air-lubricated bearings (6 and 8-inch diameter) which were used as part of the test equipment. No other information either experimental, theoretical, or design is given in this report.

10
"Air Replaces Oil for Bearing Lubrication," Aminco Laboratory News, Sept. 1958, p. 10.

This is a short, 200 word, news item which notes that many gases can be used as lubricants in either self-acting (hydrodynamic) or externally-pressurized (hydrostatic) bearing applications.

11
"An Air Thrust Bearing," Mill and Factory, Vol. 54, No. 3, Mar. 1954, p. 139.

Short article on the use of an air lubricated thrust bearing. (Same device discussed in "Cushion of Air Serves as Thrust Bearing.)

12
ANNEN, R., "Fluid Support Bearing," U. S. Patent 2 684 272, issued 1954.

The object of this invention is to provide a bearing of the fluid supported type (externally pressurized) wherein the automatic centering of the movable body is improved. In the journal bearing version, inclined spring-like fingers form the axial extremities of the pressure chambers. When the chamber pressure increases the fingers move outward cutting down the effective area through which the fluid can flow. Conversely, a shaft displacement causes some "leakage" areas to become smaller, choking off part of the flow and permitting chamber pressure to build up. Meanwhile, diametrically opposite, the escape area and flow increase and result in a lowering of chamber pressure. The response of the system is said to be so rapid that an immediate, automatic "centering" of the journal is achieved.

ANONYMOUS (4) (5) (6) (7) (8) (9) (10) (11) (74) (79) (93) (101) (102) (103) (104) (105) (106) (107) (142) (143) (176) (182) (251)

ANSCOTT, W., (51)

13
ARMSTRONG-SIDDELEY, "Gas Bearing Applications," Reactor Component Division, Armstrong Siddeley Motors Ltd., Coventry, England, Feb. 1958.

Avertising literature of a commercial device (gas pump) which employs gas lubricated bearings.

14
ARTOBOLENSKI, I. I., S. A. SCHEINBERG, "High Speed Sliding Bearing Using Air as a Lubricant," (In Russian) Machine Construction Newsletter, No. 8, U.S.S.R. 1950, pp. 5-12.

The following items are covered in separate chapters;

1. Principles governing aerodynamic bearings.
2. Structure of a supercentrifuge and its basic elements.
3. Method of designing bearings.
4. Basic properties of gaseous lubricants.

Conclusion: The main application of gas bearings is in cases of high speeds of revolution. It is difficult to define speed limits for these devices; while light loads can be supported at lower speeds, the higher rpm limit is generally set by the strength of the material or stability of the rotor.

Because of the availability of lubricant (air) and the possibility of operating at higher speeds, there promises to be numerous applications of gas bearings. (Auth)

15
AUSMAN, J. S., M. WILDMANN, "How to Design Hydrodynamic Gas Bearings," Product Engineering 28, No. 25, 1957, pp. 103-106.

The fundamental principles of hydrodynamic gas bearings are discussed. Charts and equations are given for designing a hydrodynamic gas bearing.

16
AUSMAN, J. S., "The Finite Gas Lubricated Journal Bearing," Paper 22, Hydrodynamic Lubrication, Conference on Lubrication and Wear, London, 1st-3rd Oct. 1957, The Institution of Mechanical Engineers, 1 Birdcage Walk, London, S.W. 1.

A first-order perturbation solution is obtained for hydrodynamic, gas-lubricated, journal bearings of finite width. It permits determination of end-flow factors on bearings operating at small eccentricity ratios. In comparisons with experimental data, it is shown that these end-flow factors may be used with Katto and Soda's infinite-width journal bearing solution to predict load-eccentricity characteristics on actual bearings. The agreement with experimental data is better when an adiabatic rather than an isothermal pressure-density relationship is assumed. (Auth)

This is an extension of the author's previous work. Here again third order terms are not included in the solution (see Wildman) and the question of convergence is not investigated.

The agreement of the experimental results of other authors with these theoretical adiabatic curves is remarkably good. If this agreement is a true relationship and the agreement is enhanced by the "end flow factors" being added to Katto and Soda's solution, then the author has made a significant contribution to the gas bearing field.

17
AUSMAN. J. S., "The Fluid Dynamic Theory of Gas Lubricated Bearings," Trans. ASME, Vol. 79, No. 6, Aug. 1957 pp. 1218-1224.

A differential equation for the pressure distribution in gas-lubricated slider bearings is derived from the basic equations of fluid mechanics. The equation is an extension of Harrison's gas-bearing equation in that the infinite width and isothermal restrictions have been removed. A perturbation solution is proposed and is carried out for the special case of an infinitely wide, self-lubricating (hydrodynamic) journal bearing. Comparisons with numerical solutions to Harrison's equation indicate that the first three terms in the series solution are sufficient to determine the pressure distribution and bearing load with reasonable accuracy. (Auth)

The author's approach, making use of a series solution for a differential equation is by no means unique in mathematics. Yet, the application of it to the equations of hydrodynamic lubrication with compressible fluids has attracted considerable attention.

In this paper the question of convergence of the series solution for the pressure distribution was not considered and only the first three terms of the series were used; that is, terms of third order and higher were neglected. The expression for load-carrying capacity is said to give good results for eccentricity ratios of 1/2 or less, but greater accuracy can be obtained and higher values of eccentricity employed if additional terms are used in the proposed solution.

The author's curves of theoretical pressure distribution, radial

stiffness and angle between load and deflection appear to be in good quantitative agreement with the curves obtained from Harrison's work.

18
BARBEZAT, A., "Device to Balance Thrust in Turbines," U. S. Patent 1 030 153, issued 1912.

Dummy piston device which employs steam to balance the thrust load in a turbine.

BARFIELD, B. F., (274)

19
BARRICK, P. L., J. A. BRENNAN, D. B. CHELTON, K. B. MARTIN, "Literature Survey of Bearings, Friction, Wear and Lubrication Pertinent to Cryogenic Applications," NBS Report 6018 Unpublished, NBS Boulder Laboratories, Boulder, Colo.

Since this report is unpublished it is not generally available. However, only Section 2.2 "Gas Lubrication" is of interest and all applicable references from that source are included in this bibliography.

20
BARWELL, F. T., "Lubrication of Bearings," Butterworths Scientific Publications, London, 1950. "Air Lubrication," pp. 113, 222-225.

Contains only a brief mention of the use of air as a lubricant. Cites Gerard and Shires.

21
BATES, M. F., "Resetting Means for Air Borne Gyroscopes," U. S. Patent 2 200 976, issued 1940.

Air under pressure is used to float the casing of a gyroscope so that it can oscillate about a horizontal axis.

22
BEAMS, J. W., "High Rotational Speeds," Journal Applied Physics, Vol. 8, 1937, pp. 797-804.

The paper contains a rather impressive list of references which deal primarily with centrifuges. The discussion which follows includes the abstract of this paper and also most of those it references.

It appears that following the work of Henriot and Huguenard, it became possible to produce relatively low cost centrifuges which made use of an air-driven turbine and air-lubricated bearings. However, the centrifuge has since evolved into an electrically driven rotor with bearings that use lubricants other than gases.

In the centrifuge literature, the theoretical aspects of gas bearing design is conspicuous by its absence and one senses that the bearings were built mostly by "cut and try." If any formal design methods were applied to the bearings of these centrifuges, details of them have either not come to light or have not been published. There is some mention made of the design of the turbine rotor and nozzles and the relative angles between them, but the amount of information given is rather limited.

23
BECKER, H. I., "Air Bearing Graphite Lining (porous)," U. S. Patent 2 627 443, issued 1953.

The subject of this patent is an oil free, porous, graphitized, sleeve bearing which uses externally pressurized gas as a lubricant. The advantages of this bearing stem from the low frictional characteristics of the carbon material.

24
BECKER, H. I., "Air Bearing Graphite Lining (porous)," U. S. Patent 2 645 534, issued 1953.

An externally-pressurized bearing is described. In this device the gas is distributed inside a hollow metal chamber to the outer side of a porous, graphitized carbon liner (bearing) through which it passes and acts to support the load. Applications shown include journal bearings and cup (spherical seat) bearings of various design and use.

25
BIBBINS, R. E., "Compass," U. S. Patent 1 385 423, issued 1921.

A compass which comprises a base cup adapted to permit a supply of air to pass therethrough to the chamber of said cup, a floating vessel adapted and shaped to rest in said base cup when stationary and to float therein when raised by the supporting air, a removable and adjustable cover for said vessel, and a ball adapted to be located inside said vessel when covered and to spin freely and effectively therein when, and as, acted upon by the air fed to said vessel through said base cup. (Official Gazette)

26
BIDWELL, E. C., "Work Holding and Clamping Mechanism for Centerless Grinding Machines," U. S. Patent 2 754 641, issued 1956.

This invention provides means for holding a work piece clamped against a rotating driver, such means comprising a piston movable in one axial direction to clamp the work piece and in the opposite direction to unclamp the work piece, and inside the piston a rotable work clamping member, and utilizing fluid (gas) pressure to form thrust and journal bearings between the piston and member with means independent of the journal bearing function for controlling the thrust bearing pressure so as to clamp the work piece or permit its release as by spring means. (Auth)

27
BILD, C. F., P. F. VIAL, "A Simple High-Speed Air Spinner for Centrifugal Testing of Small Mechanical Devices," Trans. ASME, Vol. 75, May, 1953 pp. 515-519. Discussion by O. C. Brewster.

A centrifuge was developed for the purpose of testing the functioning of mechanical and electromechanical devices while these devices were spinning up to 100 rps. A typical device is a clock mechanism, in which parts of considerable mass shift position during test.

The discussion of the paper by Brewster is considered by many to be of great interest.

28
BLIZARD, R. B., "Bearing," U. S. Patent 2 695 199, issued 1954.

A bearing open at one side comprising interfitting surfaces, means for supplying lubricant under pressure between said surfaces at spaced regions, and suction means for withdrawing lubricant therefrom at a point opposite said open side and intermediate the points of introduction of said pressure lubricant. (Official Gazette)

29
BLOKH, E. L., "Techenie Vlazkogo Gaza Dvumia Dvizhushchimisia Parallel'nymitsilindricheskimi Poverkhnostiami Proizvol'noi Formi (Study of the Flow of Viscous Gas Between Two Parallel Cylindrical Surfaces of Arbitrary Form)," Prikl. Mat. i Mekh. 1956, pp. 116-119.

Study of the flow of viscous gas between two parallel cylindrical surfaces of arbitrary form. The motion of gas is assumed to be caused by the rotation of the surfaces of which the inner is taken to be stationary. It is shown that for this type of motion, the ratio of the forces of resistance for viscous gas and viscous fluid is not affected by the configuration of the cross section of cylinders. Two numerical examples considered include the flow of viscous gas between two parallel planes and the flow between two co-focal elliptical cylinders. (Review-AERONAUTICAL ENGINEERING - 1956).
This paper was not available for review. It is possible that this paper is not related to gas lubricant bearings.

30
BOEKER, G., D. D. FULLER, C. F. KAYAN, "Gas Lubricated Bearings, A Critical Survey," WADC Technical Report 58-495. ASTIA No. AD 216 356. Also available through Office of Technical Services.

The authors, in this report, take a long critical look into some of the literature on gas bearings. The work is broken down into three parts as follows:

Part 1 - "General Hydrodynamic Theory and Hydrodynamic or Self-Acting Bearings,"

The purpose of Part 1 of this report is to summarize the work on the hydrodynamic types of gas-lubricated thrust and journal bearings with their attendant problems such as self-excited shaft vibrations.
In the belief that a measure of skepticism is a real stimulant to progress, the author has adopted such an attitude towards some of this work.

Part 2 - "Air Lubricated Hydrostatic or Externally - Pressurized Bearings,"

The literature on externally-pressurized bearings is critically reviewed. An effort has been made to present a broad picture of what is known in terms of analysis, design and performance of these bearings. Emphasis has been given to those areas where further information is definitely needed.

Part 3 - "Feasibility Study on the Determination of Pressure Distribution in Hydrostatic Gas - Flow Bearings via Electrical Analogy,"

The purpose of this part of the report is to investigate the feasibility of representing the gas-flow through the various components of a gas-lubricated bearing by means of a simulation electrical analogy circuit, such that at various points throughout the system, pressures may be determined by the analogy method, thus on this basis making prediction of bearing performance possible. Inasmuch as the objective is to explore the possibilities of a practical procedure, the proposal utilizes characteristic and representative flow relationships, whose form necessarily dictate the requirements of a solution.

31
BOLSTER, W., "Multiple Gyro Air Borne Compass," U. S. Patent 2 262 232, issued 1941.

Complementary spherical members separated on air film for universally supporting a central sphere for turning about a vertical axis and oscillating about both horizontal axes. Appropriate passages are employed for suppling air.

BOLSTER, W., (50)

BOOSER, E. R., (277)

32
BOTTLE, D. W., "Note on an Air Supported Bearing," Royal Aircraft Establishment, Aero. Tech. Memo No. 6, 1948.

(Paper not available for review as of July 1, 1959.)

33
BOYD, G. A., "Oil Burner," U. S. Patent 2 177 053, issued 1939.

The patent is for a new fuel burner comprising a rotor having a coaxially disposed cup therein for receiving fuel to be atomized by centrifugal force and is particularly characterized by the fact that the rotor is entirely supported on a film of air during normal operation thus eliminating metallic friction. (Auth)

BRENNAN, J. A., (19)

34
BREWER, A. F., "Gaseous Lubrication," Lubrication Engineering, Vol. 13, No. 4, Apr. 1957, p. 189.

Brief article on use of gases as lubricants.

35
BREWSTER, O. C., "High Speed Rotor Using Gas-Lubricated Bearings to Get Away From Whip," U. S. Patent 2 603 539, issued 1952.

As a means for minimizing whip in a high speed rotor using gas-lubricated bearings, the inventor recommends the introduction of a lateral gas pressure on the rotor at one side of its axis. The patent is issued for the rotor.

BREWSTER, O. C. (27)

36
BRIX, V. H., "Shaft Stability in Gas Film Bearings," Engineering 187, Feb. 6, 1959, pp. 178-182.

The author, discussing self-acting bearings, notes that they have an inherent weakness manifested in a tendency to cause the shaft to "whirl" or to precess bodily within the bearing clearance, thus making them greatly sensitive to unbalance and dynamic disturbances of various kinds. In this work he describes the results of tests made, not to change designs, but to control the manufacturing parameters so as to make the best of the existing scheme. Experimental results on whirl are given in the form of curves.

37
BRIX, V. H., "Synchronous Whirling of Shafts in Plain (Gas) Bearings," IGR-R.C.A. 176, IGR-RB/R-261, 18 June 1956, United Kingdom Atomic Energy Authority, Capenhurst Works, Chester, England.

The report begins with a dynamical theory of a shaft vibrating in two bearings, paying special attention to the values of bearing film stiffnesses and their linearity.

Several experiments are then described, which were drawn from a fairly comprehensive investigation of the whirling problem and the collateral question of balancing.

The theoretical analysis is then applied to the experimental results with a fair amount of agreement in many cases. A further theoretical estimate, extended to the case of a shaft in an oil lubricated gearbox which was known to whirl, adds some more evidence of the possible usefulness of the approach.

The report concludes by illustrating several shaft-bearing assemblies with their comparative lowest critical whirling speeds, as estimated by the formulae developed. (Auth)

Since the question of dynamic instability in bearings increases in importance as rotational speeds increase, the author's report should be of great interest. The term "half-speed whirl" is probably familiar to many readers but this is only one of many types of instability which have now been separately identified. The author makes a theoretical analysis of simple (cylindrical) synchronous whirl and conical synchronous whirl. Experimental tests are discussed and the results compared with the theoretical ones. Suggestions are made on steps to take to reduce synchronous whirl to a minimum.

38
BROWN, E. C., "Development of a High Efficiency, Air Lubricated Journal Bearing," Royal Aircraft Establishment Tech. Note Aero. 2107, June 1951.

Modifications to the air lubricated drag and side-force bearings of the virtual center balance in the R.A.E., No. 2, 11-1/2 x 8-1/2 ft, wind tunnel have resulted in a very substantial increase in their load carrying capacity. A total of eight bearings were affected and all are now working at load coefficients (Maximum load carried/ (Projected area of bearing) x (Air supply pressure)) of between 0.77 and 0.86 compared with normally accepted values of 0.3 - 0.4 for this type of bearing. (Auth)

An appendix contains some suggestions for the applications of the principles involved to the design of complete journal bearings.

Journal bearings, (180°), air lubricated by a series of jets distributed mainly on the periphery and center line of the bearings, were modified and their load carrying capacity increased. The modification consisted of (1) lapping the mating surfaces to improve the finish and cutting down the clearances and (2) forming a shallow cavity in the outer shell of the bearings. The cavity covered an area within the boundaries of the outer ring of jets and was "ventilated" (pressurized) through the existing jets on the center line.

39
BRUBACH, H. F., "Some Laboratory Applications of the Low Friction Properties of the Dry Hypodermic Syringe," <u>The Review of Scientific Instruments</u>, Vol. 18, May 1947, pp. 363-366.

The principle of rotating either the barrel or plunger of a dry hypodermic syringe to produce a low friction gas lubricated bearing is described. The application of this principle to accurate measurement of gas volume at very low pressure heads, and further applications to other instruments operating at low pressure heads is indicated. Horizontal motion of the plunger was produced in a rotating syringe barrel with pressures as low as 0.6 dynes per cm^2. (Auth)

This paper awakens one to a possible source and the relatively low cost of this type of device that can be used as a precision air bearing. The applications that were made of these syringes appear to be practical as well as novel. No theoretical treatment is given for the bearing described.

40
BRUGGER, R. G., "Air Bearing," U. S. Patent 2 695 198, issued 1954.

The invention is a "push-pull" type of bearing which may be used in devices such as gyroscopes. As designed it eliminates the need for "opposed" bearings. The method used is similar in a sense to that used by Gerard. In Gerard's invention, oil drawn from one chamber is pressurized and used in another chamber to support the load.

Here the fluid used is a gas and all the chambers or pockets are on one end or side of the bearing. The loadcarrying pockets are pressurized as before but the "sump" chamber is evacuated. The resulting pressure differential acts to hold the surfaces from separating. This restriction to motion has the same effect as the "opposite bearing. By proper balancing of sizes and pressures it should be possible to achieve a stiff bearing if desired.

41
BRUNNER, R.K., J. M. HARKER, K. E. HAUGHTON, A. G. OSTERLUND, "A Gas Film Lubrication Study, Part III: Experimental Investigation of Pivoted Slider Bearings," IBM Journal of Research and Development, Vol. 3, No. 3, July 1959, pp. 260-274.

The results of experimental measurements on pivoted slider bearings are presented, the experimental methods are described, and the experimental data is compared with data obtained from a numerical solution of the Reynolds differential equation for a compressible fluid. (Auth)
See W. A. Gross and W. A. Michael for other papers in this group.

42
BRUNZEL, N., "Pressure Lubricating Bearing," U. S. Patent 2 756 114, issued 1956.

Externally pressurized gas-lubricated bearings are described in this patent. Suggested uses are in ultra centrifuges. It is also pointed out that these bearings do not require extended periods of relative motion between parts so that they can be used for "to and fro" movements such as occur in compressor pistons, regulating valve shafts, and the like.

43
BRUNZEL, N., "Druckluftgeschmierte Gleitlager (Querlager) (Externally - Pressurized Air Lubricated Journal Bearings)," VDI - Berichte, Bd 20, 1957, pp. 123-131.

Hydrostatic journal bearings with circumferential supply slots are discussed. When the slot width is too large the shaft does not float unless a restriction is used. A range of restriction sizes is given as a function of film thickness. Laminar flow is assumed and the incompressible fluid equations are used. A Bernoulli pressure drop is assumed to occur between the inlet chamber and the bearing clearance. An expression involving hydraulic radius is used to derive equations for pressure distribution. For analysis purposes the bearing is split into an upper and lower region and the crossflow between regions considered. The results of theory and experiment are found to be in qualitative agreement. The bearing stability characteristics are analyzed and a critical rotation speed determined.

44
BUCK, W. E., "High Speed Turbine - Driven Rotating Mirrors," The Review of Scientific Instruments, Vol. 25, No. 2, Feb. 1954.

A rotating mirror is the basic element in the highest-speed cameras of both the framing and sweeping image types. The factor of merit of these cameras is determined mainly by the peripheral speed of the mirror. The turbine drive described here will spin the best-quality steel mirror up to its bursting speed. Flat mirrors with faces 17.5 mm wide by 21 mm perpendicular to the rotational axis are operated regularly at 10,000 rps. A camera designed to use these turbines and to take pictures at the rate of 3,500,000 frames per second, with an exposure time of 0.1 sec, is illustrated. (Auth)

Buck was not able to operate with air-bearings at much over 3000 rps. However, with liquid lubrication he was able to attain rotational speeds of 13500 rps. No information is given on the design or development of the air bearings.

45
BUDD, A. V., "Rotary Engine," U. S. Patent 915 549, issued 1909.

In this invention a pressurized fluid is used to support a vertical load. The same fluid impinging on "buckets" is used to impart rotation to the supported member. The fluid used may be oil, water, steam or other gas.

46
BURGDORFER, A., "The Influence of the Molecular Mean Free Path on the Performance of Hydrodynamic Gas Lubricated Bearings," The Franklin Institute-Laboratories Interim Report I-A2049-2, Contract Nonr 2342(00) Task NR 097-343. Also AECU 3771 from Office of Technical Services. Also Journal of Basic Engineering Trans. ASME Mar. 1959, Vol. 80, Series D, No. 1, pp. 94-100. ASME Paper No. 58-LUB-7.

A modified Reynolds equation is derived for gas-lubricated hydrodynamic bearings operating under "slip-flow" conditions. Closed analytical solutions are given for a Rayleigh-type step-bearing and an inclined plane slider bearing for the case of two-dimensional flow.

The influence of the molecular mean free path on the performance of bearings of arbitrary form is obtained by means of a small parameter perturbation technique. (Auth)

The author presents one item of study on the fundamental aspects of bearing lubrication. The work is directly applicable to certain conditions of gas bearing operation including the use of gases such as hydrogen and helium.

47
CARTER, L. F., "Air Supported Gyroscope," U. S. Patent 2 086 896, issued 1937.

The gyroscope described uses spherical shaped air bearings in which the air is caused to flow by lowering the pressure (exhausting) through the opening which is normally used for the inlet.

48
CARTER, L. F., "Air Borne Artificial Horizon," U. S. Patent 2 086 897, issued 1937.

A toroidal (doughnut-shaped) air-lubricated bearing forms part of the air-borne artificial horizon patented. Air flow to exert the torque required to right the gyroscope when necessary is controlled by the motion of a pendulum which is part of the device.

49
CARTER, L. F., "Air Borne Directional Gyroscope," U. S. Patent 2 086 898, issued 1937.

The gyroscope which is the patented item makes use of an air drive and air support. The air is exhausted from between the bearing surfaces rather than being forced in under pressure. The bearings used are shaped in the form of sections of toroids.

50
CARTER, L. F., W. BOLSTER, "Air Borne Gyrocompass," U. S. Patent 2 095 313, issued 1937.

A "heavy" (200 pound) gyrocompass is supported on an externally pressurized gas lubricated, spherical bearing. Pressurized air is also used for damping, and torque restoring purposes. A standby mechanical system of bearings is provided in the event that the air supply should fail.

51
CARTER, L. F., W. ANSCOTT, "Gyrovertical," U. S. Patent 2 133 809, issued 1938.

In a gyrovertical, a rotor, a rotor bearing casing supporting said rotor and air borne spherical bearing means for supporting said casing for freedom about all three principal axes. (Official Gazette)

52
CHARRON, M. E., "Role Lubrifiant de L'Air dans le Frottement des Solides. Frottement dans le Vide (The Role of Air as a Lubricant in the Friction of Solids. Friction in a Vacuum)," Academie des Science, Session 11, April 1910, pp. 906-908.

The author notes from experiments that the friction between relatively moving surfaces decreases as speed increases until a certain "critical velocity" is reached whereupon the friction becomes constant. This is attributed to the presence of an air layer which acts as a lubricating film. When the same experiment was performed in a vacuum, the coefficient of friction was found to be independent of speed.

CHELTON, D. B., (19)

CHERUBIM, J. L., (89)

53
CHIRONIS, N., "Research Focuses on Gas Bearings," Product Engineering Nov. 25, 1957, pp. 100-102.

The article gives a summary as of Nov. 1957, of the program of gas bearing research conducted at the Franklin Institute Laboratories under Contract Nonr-2342(00) Task NR 097-343.

54
CHRISTOPHERSON, D. G., "A Review of Hydrodynamic Lubrication," Proc. Inst. Mech. Eng. Conf. on Lube and Wear, London 1957, "Air Bearings," p. 11.

A brief mention of air lubricated bearings made in reviewing the papers by Ausman and Cole and Kerr presented at the same conference.

55
COLE, J. A., J. KERR, "Observations on the Performance of Air Lubricated Bearings," Paper 95, Hydrodynamic Lubrication, Conference on Lubrication and Wear, London, 1st-3rd October 1957, The Institution of Mechanical Engineers, 1 Birdcage Walk, London, SW 1.

Experiments have been made on self-acting air bearings with clearance ratios in the region of 0.001, running at speeds up to 60,000 rev/min. The results indicate that loads of about 1 lb/in^2 (0.07 kg/cm^2) per 1000 rev/min can be carried. At low loads, corresponding to calculated eccentricity ratios below 0.2, half-speed whirl occurs. Circumferential pressure distributions have been measured in the bearing mid-plane and show reasonable agreement with available theory. Water condensation has been found to occur under certain conditions in the bearing, but the amount is small and does not seem to affect bearing operation. (Auth)

The author discusses briefly the advantages and disadvantages of gas-lubrication of hydrodynamically operating bearings, pointing out that, in general, the gas lubricated bearing is more difficult to analyze theoretically. The test bearing bushings were made of glass. An induction motor was used to drive the steel shaft. The main bearings of the test shaft were rubber "o" ring mounted porous bronze, externally pressurized bearings of the type described by Montgomery. With the glass bushes the author was able to visually observe the phenomena occurring within the bearing. Thus he could see moisture condensing in the bearing film and the effect of humidity in the atmosphere. However, because of the poor thermal properties of the glass, temperature distribution within the air film was probably different from that observed. After noting that the temperature differences were relatively small the author states that his experiments support the assumption of an isothermal region in the bearing.

The author's film pressure distribution (at the center-line of the bearing) are especially interesting when the positive pressure region is compared with the theoretical results given by Katto and Soda's solution. (The author uses a factor of 1.5 in his calculations to account for the differences in analysis between finite and infinite width bearings. In comparing the negative pressure regions, however, the author finds experimentally that changes in speed, clearance or load have little effect. The theory of Katto and Soda shows relatively large changes in negative pressure due to changes in load.

In discussing the stability aspects of his bearing the author notes that vibrations were sometimes set up at frequencies of 1/2, 1/4 or 1/6 shaft speed. However, these vibrations died out on increase in speed. In this respect they differed from true whirl (1/2 speed).

56
COMOLET, R., "Ecoulement D'un Fluide Entre Deux Plans Paralleles Contribution A L'Etude des Butees D'Air (Flow of a Fluid Between Two Parallel Plates Contribution to the Study of Air Shock in Bearings)," Publications Scientifiques et Techniques de L'Air No. 334, Sept. 1957, (83 p. 24 fig.) Translated by J. Cherubim and Y. Gagne. Available from Stratos Div. of Fairchild with prior approval of author.

The author conducts a systematic study of the two-dimensional flow of a viscous liquid in longitudinal or radial movement between two fixed parallel planes, the law of transformation being of the polytropic type $\frac{P}{\rho^{m}} = C^{te}$.

This study shows a certain generality since it takes into account forces of inertia whose effects are surprising enough when it concerns divergence from radial flow. The formulas obtained permit the deduction of some results already known in the simplest cases.

Experimental testing completes the theoretical study, and it defines the sphere of application of the proposed formulas. For a radially divergent flow, the flow is laminar and isothermal as long as the local Reynolds' number is less than 550.

57
COMOLET, R., "Ecoulement Radial d'un Fluide Compressible Visqueux Entre Deux Plans Parallels (Radial Flow of a Compressible Viscous Fluid between Two Parallel Planes)," Comptes Rendus, Academy of Sciences, Paris, France, Vol. 235, No. 20, Nov. 17, 1952, pp. 1190-1193.

When there is a relatively high pressure drop between the externally pressurized bearing recess and the bearing edge (ambient), the effects of compressibility are important as is the velocity of flow, the transfer of heat is difficult and the law of transformation tends toward the adiabatic ($n = \gamma$).

58
COMOLET, R., "Etude Experimentale d'un Ecoulement Radial de Fluide Visqueux Entre Deux Plans Paralleles, (Experimental Study of Radial Flow of a Viscous Fluid between Two Parallel Planes)," Comptes Rendus Academy of Sciences, Paris, France, Vol. 235, Dec. 1, 1952, pp. 1366-1369. Translated by A. Talis; Edited by E. B. Sciulli, Franklin Institute-Laboratories, Phila., Pa., Sept. 1957.

This is a short article containing experimental verification of a theoretical analysis for the radial flow of a viscous fluid between two parallel plates. The theoretical analysis was developed in a previous paper. The results show that the flow is isothermal, proportional to the cube of the clearance height between the plates and also dependent on the bearing dimensions. The author also shows that the surface roughness of the plates must be considered in determining the clearance height.

59
CONSTANTINESCU, V. N., "Asupra Unor Proprietati Si Solutii la Limita ale Ecuatililor Lubrificatiei cu Gaze (On Certain Properties of the Equations of Gas Lubrication and the Solution for a Limiting Case)," Comunicarile Academiei R.P.R., Mechanica Aplicata, Bucharest 1955, Tomul V, Nr. 9, (Vol. 5, No. 9), pp. 1317-1321.

In this article the author deals with certain properties of the equations of gas lubrication concerning the values and the locations of the maximum and minimum of the distribution of pressures. These properties are general and apply also for lubrication with oil.

Based on these considerations, one obtains the solution of the problem of gas lubrication in the limiting case, where the relative velocity, V, of the surfaces tends to infinity (7), (11). The solution obtained is general and applies for all polytropic changes of state of the gas lubricant. Its practical application lies in the possibility of using it for calculations of bearings which operate at high but finite velocities, V, because the pressure distribution which results is close to that obtained in the limiting case examined. (Auth)

60
CONSTANTINESCU, V. N., "Consideratii Asupra Calculului Lagarelor Circulare de Alungire Infinita, Lubrificate cu Gaze (Calculations on the Infinite Length Circular (Journal) Bearing Lubricated with Gas)," Studii si Cercetari de Machanica Aplicata, Acad. R.P.R. Institutul de Mecanica Aplicata, Bucharest, 1955, Vol. 6, No. 3-4, pp. 377-400.

In the first part of this work the author determines, analytically, the pressure distribution for an infinite length circular (journal) bearing lubricated with gas. He then approximates the actual film thickness by two straight lines. He analyzes the nature (effect) of the approximations introduced and the results are compared with those obtained by other authors who have used numerical integration methods. (Auth)

61
CONSTANTINESCU, V. N., "Consideratii Asupra Calculului Lagarelor Circulare de Alungire Infinite Lubrificate cu Gaze (Study of Gas Lubricated Journal Bearings of Infinite Length)," Studii si Cercetari de Mecanica Aplicata, Bucharest 1956, Vol. 7, No. 1, pp. 81-105.

The characteristics (pressure distribution, friction moment, etc.) of infinite length gas lubricated journal bearings are determined by use of polar coordinates. The changes in these characteristics as functions of certain parameters is also studied. The results are presented in the form of curves. Suggestions to aid in the use of these curves are also given. (Auth)

62
CONSTANTINESCU, V. N., "Consideratii Asupra Calculului Lagarelor de Alungire Infinita, Lubrificate cu Gaze, Compuse din Suprafete Plane (Methods for Calculating Characteristics of Infinitely Long Slider Bearings Consisting of Plane Surfaces and Lubricated by Gas)," Studii si Cercetari de Mecanica Aplicata, Bucharest 1956, Vol. 7, No. 3.

This investigation begins by integration of the differential equation (1) for the situation in which the film thickness delta varies linearly with respect to the distance x in the direction of motion, and also for the case in which this film thickness remains constant. The solutions obtained in the second case are rigorous for isothermal conditions as well as for polytropic expansion of the lubricating gas (kappa not equal to 1). The solutions obtained for the first case are rigorous for the isothermal condition (kappa = 1) and an approximate method is indicated for determining the results for the polytropic case (kappa not equal to 1).

These results are applied to the calculation of certain types of bearings for parallel surfaces (paragraph 2), for surfaces with inclined planes (paragraph 3), and for the case in which the lubricating film has first order discontinuity (paragraph 4), and a discontinuity of the second order (paragraph 5) and also for other types of bearings (paragraph 6). The pressure distributions, as well as the general characteristics of these bearings are determined. In order to simplify the practical application of these results, they are presented in the form of graphs. The different types of bearings are also studied from the point of view of the maximum load capacity. (Auth)

The original Rumanian version of this paper contains what would ordinarily be a minor error which, however, has an effect on the results and conclusions. For the convenience of those who do not have a corrected copy available, the error and its corrections are included here.

In equation 98, $(\delta_2/\delta_1)^2$ should have been used instead of its reciprocal. This means that

$$\xi_1 = \xi_2 \left(\frac{1-\alpha}{1+\alpha}\right)^2 \frac{l_1}{l_2}$$

The incorrect ξ_1 causes an error in the third equation of 102 from which the constants are determined. (The second part of equation 104 is also incorrect.) When the constants are used in equations 94 and 96, the resulting curves in figures 24 and 25 and No. 3 of figure 26 are not correct.

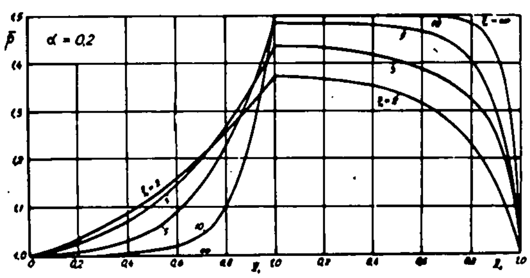

FIGURE 24.

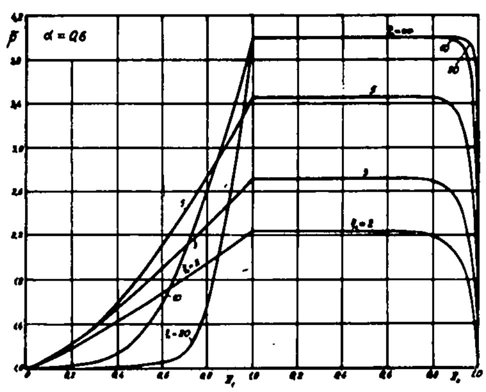

FIGURE 25.

In a letter to FIL dated 12 May 1958 the author submitted the three new figures 24, 25, 26 shown and stated as follows: "I am sending you figures 24, 25 and 26 of my article replotted by taking into consideration the necessary correction to be introduced into relation (98).

The new curves in Figures 24 and 25 seem to show an interesting fact, namely the load carrying capacity (the pressure resultant) would have a maximum value for the value obtained for $\xi_1 = 10$ the corresponding value being a little greater than the value obtained for $\xi_1 = \infty$ (because in the figures, the surface corresponding to the second step remains almost constant, while the surface corresponding to the first step is decreasing).

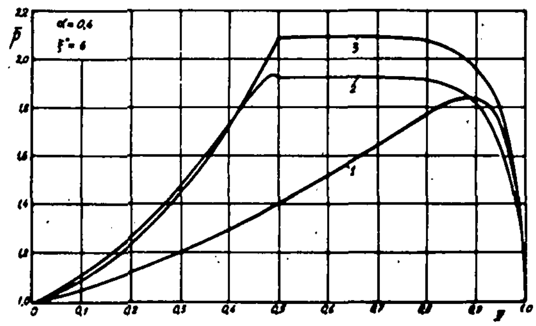

FIGURE 26.

In the Fig. 26 I have now considered $\xi^* = 6$ in order to obtain a greater difference among the curves. The result seems to be an increase of the load carrying capacity for curves 2 and 3, of about two times in comparison to curve 1. At the same time curve 3 gives a load carrying capacity greater than curve 2."

63
CONSTANTINESCU, V. N., "Contributii La Teoria Hidrodinamica A Lubrificatiei Cu Gaze (Contributions to the Hydrodynamic Theory of Gas Lubrication)," Dissertation to obtain title of scientific candidate in technical school: Academia Republicii Populare Romine Institutul de Mecanica Aplicata, Buccuresti, 1955.

The work is composed of four parts: 1) Introduction, 2) Bidimensional problem of gas lubrication, 3) Tridimensional problems of gas lubrication, 4) Final conclusion.

1. Presents the practical importance of the problem and the actual stage of the theoretical and experimental investigations in this direction. Briefly presents the general equations of gas lubrication and the various approximations used in order to simplify calculations.

2. Analyzes the previous forms attained by the differential equation for the case when motion in the lubricant layer is bidimensional. Then, analyzes some properties of this differential equation and finally, the influence of the eventual discontinuities of thickness δ upon the pressure curves. Chapter II presents some cases of exact integration of the pressure differential equation.

In Chapter III the author studies some limiting solutions of gas lubrication, namely the cases when the relative velocity between surfaces approaches either zero, or infinity. He also studies the case of motionless bearings fed under pressure.

Chapter IV presents an approximate, general method, for solving the bidimensional problem of gas lubrication.

Chapter V presents applications of the above in the calculation of various kinds of bearings.

3. Chapter VI studies the various forms of the differential equation (2.12). Thus, for the case of permanent motion, equation (2.12) is written as (19.2).

Chapter VIII presents an approximate general method of solution for $K = 1$ as well as for $K \neq 1$.

4. Presents some conclusions to the results obtained.

The paper is a summary of the original work performed by the author in order to obtain the title of Candidate. (Degree equivalent to or higher than M.S.).

64

CONSTANTINESCU, V. N., "Contributii la Teoria Lubrificatiei cu Gaze (Contributions to the Theory of Lubrication with Gas)," Travaux de la Session Generale Scientifique de la filiale de l'Academie de la R.P.R. de Cluj, 18-21, Dec. 1954.

(Paper not available for review as of July 1, 1959.)

65

CONSTANTINESCU, V. N., "Distributia Presiunilor In Lagarele de Dimensiuni Finite Lubrificate cu Gaze (Pressure Distribution in Bearings of Finite Dimensions Lubricated with Gas)," Comunicarile Academiei R.P.R. Stiinte Technice, Tomul VI, Nr. 5, (Vol. 6, No. 5), 1956, p. 377.

A successive approximation method is presented for solving the differential equation

$$\frac{\partial}{\partial x}\left(\frac{\delta^3}{\mu}\frac{\partial p^{\frac{1}{K}+1}}{\partial x}\right) + \frac{\partial}{\partial z}\left(\frac{\delta^3}{\mu}\frac{\partial p^{\frac{1}{K}+1}}{\partial z}\right) = 6V\left(\frac{1}{K}+1\right)\frac{\partial}{\partial x}\left(p^{\frac{1}{K}}\delta\right) \qquad (1)$$

for $K = 1$. The procedure can be reduced to a single iteration by the introduction of the relation

$$\frac{\partial}{\partial x}\left(\frac{\delta}{\mu}\frac{\partial p^2_{\infty}}{\partial x}\right) = 12V\frac{\partial}{\partial x}\left(p_{\infty}\delta\right) \qquad (6)$$

in the second member of equation (1) above. An analogy can be established between the manner of solving the problems of lubrication with gases and those with oils. This observation permits applying the same methods to calculate (values of) (1). The general solution is given by the expression

$$\phi = \phi_{\infty} - \phi^{*} + \alpha z \qquad (9)$$

At the end of the paper is indicated a method of solving equation (1) for $K \neq 1$, the solution of that equation for $K = 1$ being known. (Auth)

66
CONSTANTINESCU, V. N., "Lubrificatia Suprafetelor Sferice (Lubrication of Spherical Surfaces)," Comunicarile Academiei R.P.R., Bucharest 1956, Tomul 4, Nr. 4 (Vol. 4, No. 4).

Spherical coordinates are employed to resolve the equations of lubrication for the motion of spherical surfaces considering the viscosity to be variable. For the usual limiting conditions the solutions are obtained in closed form which facilitates the calculations for pressure distribution and friction moments. A method of solving the problem is also given for the general case. (Auth)

67
CONSTANTINESCU, V. N., "Repartitia de Presiuni In Lagarele de Alungire Infinite Lubrificate cu Gaze (Pressure Distribution in Infinite Length Slider Bearings Lubricated with Gas)," Comunicarile Acad. R.P.R., Bucharest, Vol. 6, No. 2, 1955, pp. 377-383.

In the case of the infinite length bearing, the general equation (1) is reducible to the first order equation (2) which with the assumption of an isothermal transformation has the appearance of (6). One can find an exact general solution to (6) for plane bearings (fig. 1), which permits obtaining, after using substitutions (10) and (13), the differential equations with separable variables (16). The appearance of the solutions differ; being given by equations (21), (23), or (24) depending on whether conditions (18), (19) or (20) are satisfied, as functions of the value of the relative velocity between the two surfaces. The region defined by equation (19) is a critical region. The regions defined by equations (21) and (24) are analogous to the subsonic and supersonic regions in the flow of gases.

When considering journal bearings (fig. 2) one may use with sufficient accuracy the results obtained for plane bearings; providing that the radial clearance, between the journal and bushing, and the eccentricity of the bearing, e, are small, the variation of lubricant film thickness is very close to two straight lines, AB and BC (fig. 3). (Auth)

68
CONSTANTINESCU, V. N., "Scurgerea Laminara a Gazelar in Straturi Subtire (The Laminar Flow of Gases in Thin Films)," Comunicarile Academiei R.P.R. Bucharest 1956, Vol. 6, No. 2, pp. 281-284.

In this note, a study is made of laminar flow of a gas between two stationary surfaces when the separation of the surfaces is small relative to the other dimensions. (Auth)

69
CONSTANTINESCU, V. N., "Sur le Probleme Tridimensionnel de la Lubrification Aux Gaz (On the Three-Dimensional Problem of Lubrication with Gases)," Revue de Mechanique Applique (Lubrification), Acad. R.P.R., Bucharest 1956, Tome 1, No. 2 (Vol. 1, No. 2), pp. 123-138. Translated by J.R. Dere and W. A. Gross, IBM Research Laboratory, San Jose, California. Available from John Crerar Library.

The purpose of this study is to present some theoretical considerations on the three dimensional problem of the lubrication with gases.

In the first paragraph, we give the general solutions of the problem for journal bearings at rest under pressure and for both extreme assumptions, $V \rightarrow 0$ and $V \rightarrow \infty$.

In the second paragraph we suggest an approximate general method which may furnish the solution of three dimensional problem of lubrication with gases in the hypothesis of an isothermal evolution of the lubricant gas $\chi = 1$ as well as for $\chi \neq 1$.

These considerations are applied in the third paragraph for the calculation of pressure distribution in circular bearings. (Auth)

70
CONSTANTINESCU, V. N., "Sur la Theorie des Paliers a Gaz (On the Theory of Gas Bearings)," Revue de Mecanique Appliquee, Vol. 1, No. 1, 1956, pp. 141-155, Academia Republicii Populare Romine Institutul de Mecanica Aplicata, Bucharest, Romania. Translated by W. A. Gross, IBM Corp. Available from John Crerar Library.

A development is given for solving the problem of circular bearings of infinite extent, lubricated by gas, based on approximating the variation of clearance of the lubricant by two straight lines.

The method proposed allows one to obtain analytic expressions for the characteristic quantities of interest in bearings.

The results are compared to calculations and experimental investigations of other authors and good agreement is obtained. (Auth)

There is currently world wide interest in the theoretical analysis of compressible hydrodynamic film lubrication of bearings. Although more generally useful theoretical developments have appeared in Japan, Great Britain, and the United States, it is well to be aware of developments elsewhere.

Constantinescu has solved an approximation to the isothermal gaseous lubricated journal bearing. He has used exactly the method of Harrison, which the latter published in 1913. Constantinescu has, however, been more thorough in his treatment, and has made comparisons with experimental results recently published in the Soviet Union.

71
COREY, T. L., H. H. ROWAND, JR., E. M. KIPP, C. M. TYLER, JR., "Behavior of Air in Hydrostatic Lubrication of Loaded Spherical Bearings," Trans. ASME, Vol. 78, No. 5, July 1956, pp. 893-898.

Some experimental data have been obtained relating the load bearing capacity of air films of various thicknesses and operating at different pressures and rates of flow for 2-, 4-, and 6-in. spherical-type bearings. Semiempirical equations have been developed for calculation of, (a) minimum air pressure as a function of load, (b) minimum flow of air as a function of pressure, and (c) bearing lift as a function of air pressure. (Auth)

Rather complete sets of experimental performance characteristics data are presented in graphical form for externally pressurized spherical thrust-type bearings. One of the parameters affecting the minimum pressure-load relationship is found to be the included angle of the spherical seat. While sufficient information is given to enable one to determine the size sphere and pressures required to support given loads, extrapolation of the data beyond the experimental ranges is not recommended according to the authors.

72
CREWDSON, E., "Improvements in and Relating to Bearings or Journals," Great Britain Patent 548 363, issued 1942.

The use of an externally pressurized gas lubricated bearing is suggested as an inexpensive means for reducing friction.

73
CURRIE, R. B., T. P. ZURFLIEH, "The Design of Equipment for Non-Rotating Testing of Pool-Type Pressurized Gas Bearings," Sc.B. Thesis MIT, Cambridge, Mass., Jan. 14, 1957.

The design of a test apparatus for determining the effects of pool geometry on the load stiffness and stability characteristics of a pool-type pressurized gas bearing is considered. Various sub-problems, especially those concerned with generating the pools, varying their size, and dimensional accuracy, are discussed and several possible solutions investigated. A final design is synthesized, incorporating the optimum solutions to the various sub-problems. Anticipated performance of the apparatus for various parameter values is calculated. (Auth)

The design information and other suggestions given may be useful. However, the section entitled "Performance Calculations" does not seem to measure up to the standards previously set. The theory taken from Richardson's work is a bit sketchy and there is insufficient discussion of the curves presented.

74
"Cushion of Air Serves as Thrust Bearing," <u>Compressed Air Magazine</u>, Vol. 59, No. 7, July 1954, p. 205.

Brief article mentioning that an industrial concern employs an air thrust bearing in place of conventional thrust bearing.

75
DE FERRANTI, "Air Bearing for High Speeds," Great Britain Patent 930 851, issued 1909.

In textile machinery certain vertical members are subjected to high rotative speeds while having little or no radial load applied. The problem here is to separate moving surfaces with as little loss in power as possible. Low viscosity gaseous lubricants are rather ideal for this purpose. However the inventor effects a substantial increase in the efficiency of the bearing by interposing one or more running bearing parts between the stationary and the highest speed rotating part of the bearing. The weights of all moving parts are supported by air.

76
DE HAVILLAND, "Gas Circulators for Radioactive Circuits," The De Havilland Engine Company Limited, Leavesden Hertfordshire, England.

A four page piece of advertising literature on a commercial device employing gas lubricated bearings.

77
"Detroit's Newest Creation Rides on Air," Providence Journal, April 7, 1958.

A short news item concerning the air supported glide devices made by Ford Motor Company. (See Jay).

78
DEUKER, E. A., H. WOJTECH, "Ecoulement Radial d'un Fluide Visqueux Entre Deux Disques tres Rapproaches. Theorie du Palier a Air (Radial Flow of a Viscous Fluid between Two Disks very Close Together; Theory of the Thrust Bearing with Air as a Lubricant)," Revue Generale de L'Hydraulique, Vol. 17, 1951, pp. 228-238. Translated by L. C. Stephens; Edited by F. A. Raven, Library of Congress, PB112987t.

The paper deals with the flow of viscous fluids between narrowly spaced parallel disks. The momentum term, which is generally neglected, is included in this analysis. By consecutive changes of variables the equations are transformed to an expression which can be integrated graphically. The authors choose instead to make a second series of substitutions which results in equations of the Abelian type which can also be graphed. From the family of resulting curves a solution for the pressure profile in the bearing can be obtained. Both the compressible and incompressible cases are considered in this paper. For the compressible case the author states that, in general one may assume $\frac{P}{\rho^m} = c$ where m varies along the radius. The equations are simplified, however, by assuming that the flow approaches the isentropic at small radial distances from the entry hole and is isothermal over the major portion of the annular region. Conditions at entry of Mach one or less are discussed.

Deuker and Wojtech make a valuable contribution to a subject considered by other authors, (Willis, Welanetz, Paivanas and Robinson). The ambiguous use of certain symbols is rather confusing and this, along with the lack of assumptions or other justification for omitting terms from the original Navier Stokes equations, tends to slow the reader. The derivation is slightly faulty and Comolet calls attention to this as well as to the ambiguity of notation. The experimentally determined curves of pressure profile do not agree as well with either the isentropic or isothermal curves as they agree with each other. The choice of scale for these curves may lead to the conclusion that the deviation between experimental and theoretical results are not significant.

79
"Development of Hermetically Sealed Centrifugal Pump Unit for Liquid Metals." TID 5143, Library of Congress.

Reference is made to some gas-pressurized bearing tests made on a hydrostatic bearing designed for liquid sodium. Although the load could be supported, considerable vibration was experienced. Attempts were made to eliminate these vibrations but these were abandoned without success.

Only pages 45, 46 and Figures 25, 41, 42, 43, 44 may be directly applicable to the gas-lubricated bearing field.

80
DOWTY, "Gas Bearing Compressors," Dowty Nucleonics Ltd., Brockhampton Park, Andoversford, England.

Advertising literature for commercial nuclear engineering equipment.

81
DRESCHER, H., "Gleitlager Mit Lufschmierung (Sliding Bearings with Air Lubrication)," V.D.I. Zeit, Vol. 95, No. 35, Dec. 11, 1953, pp. 1182-1190. BuShips Translation 549, also referenced as AEC Translation 3495 available Library of Congress or John Crerar Library. Abstract in Engineers Digest, Vol. 15, No. 3, Mar. 1954, pp. 103-107.

This is a very interesting and enlightening paper dealing with the analysis of hydrodynamic journal and thrust bearings operating on air. The author clearly indicates the assets and liabilities of such bearings. Such bearings are desirable for high temperature work as temperature has little effect on the viscosity of a gas. They are helpful where contamination from ordinary lubricants must be avoided. Their use also results in exceedingly low friction even at high speeds. These bearings are of course limited in load-carrying capacity and a reasonable maximum value is about 5 psi. Clearances are necessarily small so that dust and dirt contamination must be prevented to avoid seizure. Also hydrodynamic whirl is a matter of consideration because air bearings frequently develop this condition as do lightly loaded oil lubricated bearings. The author discusses these various aspects of air bearing performance and presents experimental data on friction, load-carrying capacity of stable bearing designs, and eccentricity locus for a plain journal bearing and for a recessed stable design of bearing. He describes several applications to electric motors that have proved to be very reliable and satisfactory.

DUNCAN, R. W., (133).

82
EDELSTEIN, M. I., "The Characteristics of a Hemispherical Air Bearing at High Rotational Speeds." Curtiss-Wright Corp. Report No. R-48-19, October 19, 1948, AF W33-038ac-14161, Project MX 772. ASTIA - ATI 159 532.

The characteristics are discussed of a sphere rotating at high angular velocities in a hemispherical air bearing. It is used as a position gyroscope.

Theoretical values of friction are reconciled with experimental data. (Auth)

The author uses a modification of a theory developed by Wagner* to find the friction in the bearing and claims excellent agreement between theory and experiment, providing an additional factor amounting to 33% of the calculated friction is included. This is by no means as arbitrary as it sounds since frictional torques of less than one gm-cm are being considered. In all, some six gas-inlet designs were investigated. With one of these (center-hole), vibration was encountered at 4800 rpm. Stability was achieved by use of additional inlet holes. When using hydrogen as the fluid, the vibration phenomenon was encountered at 12000 rpm even when the design included other inlet openings in addition to the center hole.

The experimenters were not able to attain the desired high rotational speeds with an electric motor drive. Although they finally used the equivalent of an air turbine to spin the rotor at a faster rate, the data for these runs are not included.

The experimental work presented seems to be rather thorough but for the low speeds only. Extensions of this work are contained in other reports prepared at Curtiss-Wright Corp.

83

EDELSTEIN, M., A. KRAUSZ, T. WEDGE, D. FOLEY, D. MAXWELL, W. HORTON, "The Development of a Gas Supported Rotating Sphere for Use as a Stable Element," Curtiss Wright Corp., Element Report No. R-49-22. Also ASTIA ATI 65-474.

It was originally proposed to investigate the feasibility of utilizing a gas bearing to support a spherical gyroscope rotor. Based on the conclusions of this investigation a low drift gyroscope was to be designed, constructed and tested.

This report contains a discussion of the theoretical background, design criteria, and the favorable experimental data of a novel two-stage gyroscope for use as a stable reference for guided missiles or conventional aircraft. (Auth)

This is a rather complete report with about half of it devoted to the air bearing. The bearing analysis assumes the fluid to be incompressible and makes use of a power series to effect a solution for, div (ε^3 grad P) = 0, the fundamental differential equation for the flow. This method follows that employed by Dr. Lummig of MIT and is somewhat similar to the perturbation method Ausman used a few years later. However, the equations in this report are a bit more complicated since the authors of this paper were dealing with a sphere.

84

EGLI, A., "The Leakage of Gases through Narrow Channels," Journal of Applied Mechanics, Trans. ASME, Vol. 4, No. 2, June 1937, pp. A 63-A 67.

In this paper a rational theory is developed as a basis for calculating the flow of gases (compressible fluids) through narrow channels. For the most important case the solution of the general flow equation is given in graphical form which shows the relation between mass flow, pressure drop, and channel resistance.

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*Wagner, C., "Air Friction in Gaps of Gyro," Tech. Report GS-ORD No. 35, Ft. Bliss, Texas.

Tests of the leakage of air and steam through the narrow clearance between a valve stem and bushing afford a practical demonstration of the use of the theory. Formulas are derived for the calculation of the leakage of gases through reamed bushings on ground stems. Expressions for the leakage of liquids (incompressible fluids) are obtained as special cases of the gas formulas. (Auth)

The author's contribution on the leakage in labyrinth-type seals may also prove applicable to end-leakage in gas-lubricated journal bearings, especially those which are externally pressurized.

EISENSTADT, R., (158)

85
ELROD, H. G., "A Derivation of the Basis Equation for Gas-Lubricated Slider Bearings," Tech. Memo Jan. 11, 1958, Friction and Lubrication, Franklin Institute Laboratories, Philadelphia.

The purpose of this memorandum is to derive the differential equations describing the fluid-dynamical phenomena in a gas-lubricated slider bearing. Only a preliminary attack is made on the general problem of gas lubrication, but the development presented indicates that the small-parameter technique employed for fluids having constant properties, can also be readily used for gases as well. To retain simplicity in this preliminary work, side leakage in the bearing is neglected, and the specific heats, thermal conductivity and viscosity of the gas are treated as constant. (Auth)

An analytical derivation is given. The author arrives at the equation for pressure similar to that used by Harrison. It is a bit more general than Harrison's expression in that the heating effect can be included by use of a small parameter. However, the actual integration is not shown; the author merely stating that a more complicated differential equation for pressure would result.

86
ELROD, H. G., "A Derivation of the Basic Equations for Hydrodynamic Lubrication with a Fluid Having Constant Properties," The Franklin Institute Laboratories Interim Report I-A2049-5, April 1959, Contract Nonr-2342(00), Task NR 097-343.

In this report small parameter techniques are used to derive Reynolds' lubrication equations, and refinements thereof, from the full Navier-Stokes equation, for fluids having constant properties. An effort has been made to retain vigor in the development comparable to that used in present-day boundary-layer developments. Analytical techniques similar to those employed here have been adapted to the derivation of equations applicable to fluids having pressure and temperature-dependent properties, such as gases. The results will be presented in a subsequent report.

To derive the differential equations for flow in a curved film of arbitrary thickness requires the use of general tensor analysis. The mathematical manipulations are somewhat involved, but one of the results -- a refined

Reynolds' equation -- can be simply written for a journal or slipper bearing as follows:

$$\frac{\partial}{\partial x}\left\{h^3\left(1-\frac{h}{D}\right)\frac{\partial p}{\partial x}\right\} + \frac{\partial}{\partial z}\left\{h^3\left(1+\frac{h}{D}\right)\frac{\partial p}{\partial x}\right\} = 6\mu U \frac{\partial}{\partial x}\left[h\left(1-\frac{h}{3D}\right)\right\}$$

Here: D = shaft diameter (infinite for a slipper bearing)
h = film thickness
p = fluid pressure
U = shaft surface velocity
x = distance around shaft in direction of rotation
z = distance parallel to shaft axis
μ = fluid viscosity

The error of the above differential equation is of the order of $(h/L)^2$, where L is the film length in the direction x. In all but the most unusual of applications, both h/L and h/D are exceedingly small for real bearings. Thus, the present analysis justifies the applicability of Reynolds' equation for the constant property fluid. (Auth)

ELROD, H. G. (161)

ELWOOD, R. C. (247)

EMMI, J. (255)

87
FARRAND, W. A., "An Air-Floating Disk Magnetic Memory Unit," Datamation, Nov. - Dec. 1957 pp. 38-41.

Mention is made of an air lubricated hydrodynamic thrust type bearing and its application to a computer component. The sketches and description given are adequate for this article. However, there is probably insufficient theory or design data presented to be of great value to persons working in the bearing field.

88
FIRTH, D., "Electric Dynamometer of High Precision Air Lubricated Trunnion Bearings Employed," Engineering, Vol. 179, May 20, 1955, pp. 628-630.

A high precision swinging-frame electric dynamometer has been developed for measuring the efficiency of hydraulic machinery. It is accurate to within ± 0.1 per cent of full scale torque and is reasonably portable. Novel features include pneumatic trunnion bearings, hydraulic torque measurement, and electronic speed control to within 0.1 per cent over a wide range. The development of the design is described and design features for larger dynamometers are suggested. (Auth)

89
FISCHER, G. K., J. L. CHERUBIM. D. D. FULLER, "Some Instabilities and Operating Characteristics of High Speed Gas Lubricated Journal

Bearings," ASME Paper 58-A-231.

Various factors influencing the stable operation of high speed rotors on gas lubricated journal bearings have been isolated such as; critical speed, unbalance, film stiffness, whirl, damping, and air hammer. Experimental data are given for a number of bearings to illustrate the effects of these factors on operation of gas lubricated bearings and correlation to mathematical analysis. The isolation and understanding of these factors have been due primarily to the instrumentation developed. Rotor assemblies on 1/2" and 3/4" diameter shafts have been successfully run on hydrostatic and hydrodynamic air bearings at speeds up to 165,000 rpm. (Auth)

FOLEY, D., (83)

90
FORD, G. W. K., D. M. HARRIS, D. PANTALL, "Principles and Applications of Hydrodynamic-Type Gas Bearings," A.E.R.E. ED/R 1662, Revised Version of A.E.R.E.E/R 1140, Harwell Berks, Sept. 1955. Proceedings of the Institution of Mechanical Engineers, Vol. 171, No. 2, 1957, pp. 93-113. Discussion pp. 113-128, "Gas-Lubricated Bearing." Machinery Market n 2923, 2924, Nov. 23, 1956, pp. 27-30; Nov. 30, 1956, pp. 26, 28 and 30.

The first reference contains the original data and curves and is more complete than the second reference. The third reference is little more than an abstract.

In this paper are described an experimental investigation of properties and some developments in the utilization of hydrodynamic-type gas-lubricated bearings, of both journal and thrust types, as distinct from hydrostatic bearings. Two specific developments are described, the one a pump for circulating carbon dioxide gas at 100 lb. per sq. in. gauge and 150 deg. C. through a loop in a nuclear reactor, the other a gas-bearing motor driving a pump for molten radioactive bismuth, the whole within a hermetically-sealed container. The simple machining requirements and special design principles are described. The performance of gas bearings may be predicted from normal liquid bearing theory if the loading is so small that the pressure rise within the bearing is a small fraction (for example, 10 per cent) of the ambient pressure. For higher pressure ratios compressibility effects must be taken into account. The experimental results and techniques used are reported, those for plain journal bearings embracing a wide range of working conditions and absolute size including compressible flow operation. An explanation of the physical reasons for the change in performance in compressible flow bearings is given. The dynamic instability sometimes encountered in journal bearings and methods of avoiding it are also discussed. (Auth)

This is a somewhat critical review of hydrodynamic gas-lubricated bearings which includes a discussion of the differences between gas and liquid lubrication from both the theoretical and practical viewpoints. On the subject of hydrodynamic gas bearings the paper contains much enlightening information, for example, the relatively high loads that can be carried, the "large" permissible clearances, and the class of surface finishes that can be employed.

The authors, in this paper, present various curves of theoretical and experimental results for journal bearings. They also show some photos and sketches of test equipment. Their discussions also include short sections on half-speed whirl, several types of thrust bearings and applications of gas bearings.

91
FORTESCUE, P., "The Derivation of a Generalized Chart for Viscosity Plate Performance," Atomic Energy Research Establishment, ED/M 21, 1955.

(Paper not available for review (classified) as of July 1, 1959.)

92
FRANKEL, S. R., "An Analysis of a Simple Hydrostatic Gas Bearing Including Compressibility Effects," M.S. Thesis, Mechanical Engineering, Drexel Institute of Technology, Phila., Pa., June 1958.

The use of a gas as a lubricant in bearings has increased in the past few years because of the need to supply a reliable lubricant under a wide range of ambient conditions. This paper is restricted to an investigation of a simple, nonrotating, hydrostatic gas thrust bearing in which air acts as the lubricant. In this analysis the compressibility effects are included among other design parameters, such as film thickness, load carrying capacity, and supply pressure, for subsonic flow conditions. (Auth)

The author, using a series solution, derives an equation for the load carrying capacity of an externally pressurized circular thrust bearing. The customary assumptions of isothermal flow in the bearing gap and isentropic flow through the entrance restriction are made. Differences between experimental and theoretical load carrying capacities exemplified by their respective pressure profiles as shown on graphs included by the author, are laid primarily to the lack of stiffness of the bearing plates and the inability to fully account for the flow condition at the restriction.

93
FRANKLIN INSTITUTE, "FIL to Build Gas Lubrication Science," Laboratory Report, Vol. 5, No. 2-3, Dec. 1956-Mar. 1957, p. 5. The Institute News, Vol. 22, Mar. 1958, p. 3. Journal Franklin Institute, Vol. 265, Mar. 1958, pp. 243-244. Laboratory Report, Vol. 3, Sept. 1954, p.3.

Contains various items of news and general information about a program of gas bearing research jointly sponsored by eleven departments of the U. S. Government which come under AEC, Dept. of Defense, Maritime Adm. and NASA. The program is administered by ONR.

94
FREDRICKSON, J., "Bearing for Car-Axle," U. S. Patent 1 067 727, issued 1913.

The inventor proposes air supported pistons to carry the load on

railroad journal bearings. For this purpose the familiar partial bearing is replaced by a large block with an opening in it for the journal. Pressurized air, under the engineer's control, enters a chamber formed by the journal, the bearing block, and a vertical piston located in the block, and perpendicular to the journal. As the piston is raised the weight on the arch bar is raised with it. Actual lubrication is accomplished by a lubricating material (not specified) in contact with the lower surface of the journal.

95
FULLER, D. D., "A Survey of Journal Bearing Literature," ASLE, Chicago, 1958. Published by American Society of Lubrication Engineers, 1958 "Gas Lubricated Bearings," pp. 87-89.

The author, in reviewing journal bearing literature, discusses gas lubricated bearings. Most applicable references up to Dec. 31, 1954 are included in this bibliography.

96
FULLER, D. D., "Air Bearings-Low Friction," Lubrication Engineering Vol. 9, No. 6, Dec. 1953, pp. 298-301.

In this paper, the author, speaking of the possible and probable applications of air bearings, describes a few designs including a step bearing for an ultra-centrifuge.

This work by Fuller is a revision of the paper, "Low Friction Properties of Air-Lubricated Bearings." However, it also includes an additional numerical example. This material is also found in his text book.

97
FULLER, D. D., "Air Lubricated Bearings," Mach. Des., Apr. 1953, pp. 272, 273, 381, 384, 386.

Brief article containing same information presented in author's paper, "Low Friction Properties of Air Lubricated Bearings."

98
FULLER, D. D., "Annual Report ONR Project A2049, "The Franklin Institute Labs Interim Report I-A2049-3, July 15, 1958, Contract Nonr-2342(00), Task NR 097-343, AECU 3773, OTS.

This is a summary report on the activities of the research program conducted under Contract Nonr-2342(00), "Research on Gas Lubricated Bearings," for the first year of effort April 1, 1957 to April 1, 1958.

99
FULLER, D. D., "Low Friction Properties of Air-Lubricated Bearings," Trans. N.Y. Academy of Sciences, Series II, Vol. 15, No. 4, Feb. 1953, pp. 93-99.

The author speaks of the benefits of air bearings and starting from the relationship $F = \mu A \frac{dv}{dy}$ shows, mathematically, the low friction

losses for such a bearing. Quoting Brubach, low cost air bearings made from hypodermic syringes are described. Also described is the model of the famous air-lubricated Kingsbury thrust bearing.

Appropriate equations are given for hydrostatic step bearings and drawings are shown of this and other types of air-lubricated bearings including one used in an ultra-centrifuge. Noting that the compressibility of the gas must be considered for high loads, the author derives applicable relations for the step-bearing starting from Euler's equation for steady, one dimensional flow with friction.

100
FULLER, D. D., "Theory and Practice of Lubrication for Engineers," John Wiley & Sons, Inc., 1956, pp. 287-305.

The author includes a brief history of air bearings and mentions their advantages and disadvantages. Numerical examples are used for designing self-acting and externally pressurized bearings. At the time this was written, no other textbook contained as much information on gas bearings.

FULLER, D. D., (30)(89)(160)(162).

101
"Gas Bearing for High Pressure Helium Turbine," NP 3683, Classified, AEC.

The only information available comes from "The Reactor Handbook, Volume 2 Engineering" published by McGraw Hill. Page 472 shows a drawing of this bearing and on page 475 is noted the following:

A gas bearing (as well as a combination thrust and journal bearing) is shown in Fig. 3.6.11. The journal bearing consists of four pockets, as shown in section "AA", to which high-pressure gas is admitted through individual orifices, and from which the gas is discharged through the annular clearance space between the sides of the pockets and the shaft. Since the leakage area from each pocket depends upon shaft position, any transverse shift of the shaft will alter the gas pressure in the pocket and provide a restoring force to recenter the shaft. The thrust bearing operates on the same principle, except that the annular pockets are continuous and the gas is discharged through the clearance areas at the inner and outer diameters of the bearing.

102
"Gas Bearings, JPL CBS No. 63," Combined Bimonthly Summary No. 63, Jet Propulsion Laboratory, Cal. Tech., Pasadena, Calif., ORDCIT Project, Contract No. DA-04-495, ORD. 18, Dept. Army, Ord. Corps.

This is a resume of the work being conducted on hydrostatic gas bearings at Jet Propulsion Laboratory. It includes mention of their analytical and experimental studies and a brief discussion of their test rig. The entire resume takes less than two pages and, therefore, one should not expect to find any detailed account of the work done. (See other reports from same source.)

103
"Gas Bearings, JPL CBS No. 66," Combined Bimonthly Summary No. 66, Jet Propulsion Lab., Cal. Tech., Pasadena, Calif. ORDCIT Project, Contract No. DA-04-495-ORD 18, Dept. Army, Ord. Corps.

A thorough study of the existing literature and patents on hydrostatic bearings is now in progress. The purpose of this search is to establish the state of the art and to explore areas for fruitful research and development efforts. The design of gas bearings for specific applications would be greatly facilitated by a comprehensive theory which would permit the prediction of the behavior of such bearings under varying load and environmental conditions. (Auth)

104
"Gas Bearings JPL Summary No. CBS 67," Combined Bimonthly Summary No. 67, Jet Propulsion Lab., Calif. Inst. of Tech., Pasadena, Calif., Oct. 15, 1958, ORDCIT Project Contract No. DA-04-495, ORD 18, Dept. Army, Ord. Corps.

Externally pressurized, multi-orifice, gas lubricated, semi-cylindrical journal bearings were studied as part of a long range program on gas bearings.

105
"Gas Bearings, JPL Letter Report No. 3," Letter Report No. 3, Jet Propulsion Lab., Cal. Tech., Pasadena, Calif., ORDCIT Project, Contract No. DA-04-495-ORD 18, Dept. Army, Ord. Corps.

Previous issues of these letter reports were not numbered.

This report contains excerpts from Combined Bimonthly Summary No. 68 and deals with semi cylindrical and complete journal bearings. As in all reports of this group, curves of experimental and theoretical results are given.

106
"Gas Bearings, JPL Letter Report No. 4," Jet Propulsion Lab. Cal. Tech. Pasadena, Calif., Feb. 18, 1959, NASA Contract No. NAS w-6.

The work covered deals with the load carrying capacity, clearance, and gas flows of externally pressurized gas lubricated journal bearings.

107
"Gas Lubricated Bearings-Design, Manufacture, Applications," Engineering, Nov. 2, 1956.

Gas lubrication, which has recently undergone considerable development under the stimulus of the atomic energy programs, may well have applications to half a dozen other branches of engineering, and this is borne in mind by the authors of a paper "Principles and Applications of Hydrodynamic-Type Gas Bearings," presented at the Institution of Mechanical Engineers on October 26. The authors, Mr. G. W. K. Ford, Mr. D. M. Harris and Mr. D. Pantall, are all members of the United Kingdom Atomic Energy Authority.

The call for gas bearings arose from the need to install moving parts within enclosed gas circuits where contamination of the gas is undesirable, the parts themselves are largely inaccessible and the formation of oxide films is impossible; this occurs in gas-cooled reactors such as those at Calder Hall. In addition, pumps for liquid metals, which may be at high temperatures, require a lubricant that does not deteriorate under the action of heat and will not contaminate the metals being pumped; bismuth, which may serve as a solvent for nuclear fuels in future reactors, is chosen by the authors as an example. However, high temperatures, gas circuits, inaccessibility, particulate matter in suspension, and the need to exclude contaminating materials are requirements not unique to atomic engineering. To place gas bearings in the context of other applications, the authors outline their features and limitations, and name some other fields of engineering-machine tools and chemical industry for example-in which they may be used. The paper is concerned mainly with hydrodynamic as distinct from hydrostatic bearings and covers both thrust and journal types. Parts of it are reprinted below, but specialized data and calculations are omitted. (Auth)

108
GERARD, P. L., "Combined Fluid Bearing and Mechanical Bearing for Gas Turbine Engines," U. S. Patent 2 623 353, issued 1952.

In a gas turbine application, the inventor uses rolling element bearings as an auxillary "standby system" since failure in the gas bearing external pressurization system is always a possibility.

109
GERARD,P.L., H. SERRANNE, "Fluid Bearing," U. S. Patent 2 660 484, issued 1953.

The inventor notes the disadvantage incurred by the use of a large volume recess when employing externally pressurized gaseous lubricants. His suggestion is to use grooves to outline various geometrics having the same area and perimeter as the chosen recess. The effect of this change is to reduce the tendency towards vibration.

110
GERARD, P. L., "Fluid Pressure Bearing," U. S. Patent 2 634 176, issued 1953.

When a rotating rotor becomes unbalanced through loss of a turbine blade or other cause, the centrifugal forces set up carry it close to the bearing walls and the shaft performs a kind of "whirl". To combat this potentially dangerous condition, the inventor places a one way valve in the path of the orifice leading to each bearing recess. When the shaft approaches a recess, the fluid escape area is decreased. The pressure in the chamber builds up, causing the one way valve to close and preventing leakage except through the decreasing escape areas. Since the pressure continues to build up, the necessary counterbalancing force is thus set up.

The patent mentions water as the fluid to be used. Sixsmith uses a somewhat similar system for gases but with a restriction placed in the path of flow through the evacuation chambers.

111
GERARD, P.L.,"Improvement in Fluid Bearings," Great Britain Patent 685 871, issued 1952.

The device described is a modification to improve the performance of a gas bearing. It consists of mounting a self-aligning rolling element bearing on a shaft and using a sleeve, press-fit on the outer race, to act as the journal member of a gas lubricated bearing. In the event of a lubricant failure through overload or other cause, the outer race of the rolling element bearing is restrained but the inner race and shaft are free to rotate.

112
GERARD, P.L.,"Le Palier Fluide (The Fluid Bearing)," Memoires de la Societe des Ingenieurs Civils de France, Vol. 102, No. 2, Feb. 1949, pp. 106-134. Translated by A. Talis, Edited by E. B. Sciulli, Franklin Institute-Laboratories, Phila., Pa., Sept. 1957. Note: This same reference appears under similar title in other publications.

The reference contains a short history of externally-pressurized fluid bearings, noting their advantages and also some of their shortcomings. Mention is made of several well-known devices which employ these bearings and a list given of possible applications to other machines. Under the advantages, Gerard notes the low, almost zero, starting friction one gets with these bearings, and the relatively low power requirements for their operation. In an extract from Planiol's work is included a comparison of the coefficients of friction of rolling element bearings (1.5×10^{-3}), hydrodynamic bearings (1.1×10^{-3}), precision watch jewel bearings (0.2) and a pressurized air-lubricated bearing (2.6×10^{-6}).

A brief mathematical treatment, using the electric analogy, is given to the flow of fluids through two constrictions in series. The effect of various parameters such as chambers, flow, etc. are treated theoretically and appropriate curves and tables shown.

The main purpose of the paper is to describe Gerard's multipad versions of the fluid bearing which have a "self-centering ability." A description is even given of a rather drastic test of this ability in which a grinding wheel is deliberately unbalanced in order to observe the behavior of the bearing. Despite the strong vibrations transmitted to the grinding machine, the results of the grinding remained fairly good, indicating that the axis of the grinding spindle had turned (true) about an axis of rotation off-center by 0.02 mm. (In this demonstration oil was used as the lubricant.)

113
GESSNER, E., "Nomograph for Designing Gas Nozzles and Orifices," Product Engineering, Oct. 1956, pp. 141-143.

This nomogram solves problems relating to nozzles and orifices used as flow controlling devices for compressible fluids. Pressure drop can be found if the weight of flow and diameter are known for a particular upstream pressure. While drawn up for aircraft and missile problems, with flow correction for gases other than dry air, the nomogram may be applied to air conditioning and industrial problems.

Basis of nomogram is flow weight equation representing thermodynamic relationships for the ideal situation, and corrections are added for various non-ideal configurations. A coefficient accounts for relative difference in efficiency between nozzles and orifices. (Auth)

While it is true that this paper does not deal with gas bearings as such, it does contain usable information concerning nozzles and orifices which are an integral part of most externally pressurized gas bearings. While the theory and the requisite equations are available in many textbooks, nomographs of this type are not. The nomograph is included for its value as a convenient labor saving device.

GOGLIA, M. J. (274)

114
GOTTWALD, F., R. VIEWEG, "Berechnungen und Modellversuche an Wasser - und Luftlagern (Calculations and Model Tests on Water and Air Bearings)," Zeit. Angew, Physik, II Band, Heft II, 1950, pp. 437-443.

Most of the contents of this paper are contained in other papers by Gottwald which have been translated into English. Some of the other papers contain entire paragraphs lifted bodily from this one.

115
GOTTWALD, F., "Computations and Measurements on the Air Bearing," Archive 16/15, Foreign Document Evaluation Branch, Ordnance Research and Development Center, Aberdeen Proving Ground, Md., 1943.

An analysis for a conical bearing with compressibility taken into consideration, shows that no substantial difficulties arise when air is used as the lubricant instead of water; the load capacity even increases at a minor rate. The volume of air flow is smaller than the value resulting from an estimation using the viscosity ratio between air and water. The regulating orifices or capillaries used for bearing stabilization may have practically the same dimensions as in water bearings. Practicable operating conditions are obtained when the bearing air pressure is divided between regulating point and housing gap in the ratio 1 : 1.

The bearing supply pressure must be adjusted to the external pressure. For constant load the relative pressure drop must also be constant if the same bearing gap is to be obtained. With decreasing external pressure the volume of flow remains practically constant, whereas the necessary air mass flow is respectively decreased.

A few measurements on a test bearing confirmed the correctness of the computations. (Auth)

This is but a part of a report on bearing devices. The work was done in Germany during World War II.

116
GOTTWALD, F., "Proposal for an Air Supported Course Gyroscope," Archive 16/16, Foreign Document Evaluation Branch, Ordnance Research and Development Center, Aberdeen Proving Ground, Md., 1943.

After a critical discussion of the use of different kinds of bearings for the suspension of gyros, an arrangement is suggested which has small friction since it is an air bearing, and furthermore which avoids the unbalanced moments caused by bearing clearance. (Auth)
This report contains the reasons for building an experimental model (course) gyroscope which is air supported. Previous work by the same author leading up to this decision was also a part of this investigation of low-friction bearing devices.

117
GOTTWALD, F., "Tests on Air Supported Course Gyroscope," Archive 16/17, Foreign Document Evaluation Branch, Ordnance Research and Development Center, Aberdeen Proving Ground, Md., 1943.

In a previous report, the author proposed an air-supported ball (course) gyroscope to be provided with a compensated universal suspension. Subsequently, experimental models were built and tested. This report covers those tests and gives the conditions under which the gyro maintains the prescribed precession limit. Although the author determined that the use of this type of device was feasible, he did not complete his work at this time. Since this is only one of a series of reports, it contains only a relatively small amount of information.

118
GOTTWALD, F., "Wasser-Luftlager mit Druckshmirung (Water Bearings and Air Bearings with Pressure Lubrication)," BuShips Translation 593, Office of Technical Services, PB 121405.

This paper covers part of the work this author did during World War II. Here the author summarizes the feasibility study on externally-pressurized water and air lubricated bearings. As in his previous work, the author suggests that air-lubricated bearings can be used in gyroscope compasses.

119
GRANEEK, M., H. L. WUNSCH, "Testing the Performance of Precision Ball Bearings." The Engineer, Vol. 178, Nov. 26, 1954, pp. 695-697.

Little information is available on the performance of high-precision ball bearings of small diameter when operating at very high speeds. A machine has, therefore, been developed which provides a continuous measurement of frictional torque at speeds up to 50,000 r.p.m. of small bearings under defined axial and radial loadings. This article is primarily concerned with the development of the testing machine. But the ultimate object in view is the correlation of the dimensional accuracy of the bearings with overall performance. The torque-speed characteristics of particular types of bearing will also be investigated. (Auth)

The authors describe a test machine which uses externally-pressurized air bearings. These include two main journal bearings and a thrust bearing for the test shaft as well as two journal and two thrust bearings for the drive motor. Exhaust air from the motor bearings, passed over the stator laminations, aids in cooling. One other air bearing, a hydrostatic "floating" bearing, is used to apply the radial loads. Because of its designed purpose the test shaft had to be dynamically balanced to a high degree of accuracy. Maximum test speeds of 50000 rpm were attained with the unit. Although the bearings are described, there is insufficient information given, theoretical or otherwise, to permit designing them.

120
GRINNELL, S. K., "A Study of Pressurized Air Bearing Design - Steady Loading - No Rotation," M.S. Thesis, 1954. MIT Department of Mechanical Engineering, Cambridge, Mass.

In one phase of the investigation simulation is used to determine the optimum ratios for design parameters used in air journal bearing design, minimizing mass flow rate and maximizing stiffness and load-carrying ability.

The pressure distribution and mass flow rate for one dimensional compressible fluid flow between closely spaced flat plates were studied as a basis preliminary to an understanding of the flow in a bearing.

Theoretical expressions for the pressure distribution and mass flow rate are developed analytically and verified experimentally. The simple Hagen-Poiseuille capillary flow theory was found to be good for predicting the pressure distribution if the flow path length to height ratio is greater than 1000. For smaller values the one dimensional compressible flow with friction theory of Shapiro correlates well with experimental mass flow rate, friction factor and pressure distribution. (Auth)

This 112 page thesis represents an extensive amount of work; among its contents are 41 illustrations, 11 appendices and numerous references all applicable to the subject chosen. Theoretical analyses are made for one-dimensional flow of a compressible fluid between flat plates, constant area flow of a perfect gas with friction and capillary type flow with and without momentum effects included. The design of test equipment and instrumentation are discussed and the results compared with the work of other authors where possible.

121
GRINNEL, S. K., H. H. RICHARDSON, "Design Study of a Hydrostatic Gas Bearing with Inherent Orifice Compensation," Trans. ASME, Vol. 79, No. 1, Jan. 1957, pp. 11-22. ASME Paper 55-A-177.

A hydrostatic gas bearing can provide shaft support with very low friction in high-speed devices such as centrifuges and gyroscopes and in precision static devices such as dynamometers. For comparable load conditions, the friction torque required to rotate a hydrostatic bearing is from 100 to 10000 times less than the friction torque required to rotate ball or hydrodynamic oil bearings. This paper presents information directly applicable to designs with optimum performance characteristics for hydrostatic gas bearings with inherent orifice compensation. An analytical and experimental study of a simplified model of the basic unit of which the bearing is composed and a similar study of a complete journal bearing lead to a readily usable design procedure for the hydrostatic gas bearing. The load capacity, or stiffness, and weight flow rate predicted by the design procedure are verified within 10 and 20 per cent, respectively, by experimental results obtained with an optimized bearing. (Auth)

A brief review of hydrostatic bearing development is first given and then three configurations are described after which the principles of operation of the authors' bearing are discussed. The simplifying assumptions made for analysis purposes were such that it became possible to build a simulation model consisting of square, flat, parallel plates with a single air inlet hole in one of them. The experimental results obtained with this rig are shown graphically in the text for the paper.

The analysis of the complete, full multipad bearing is made on the basis of one dimensional, laminar, isothermal, compressible flow. The resulting equations are then converted to yield dimensionless parameters with which to evaluate bearing performance. The authors do not recommend extrapolation beyond the range of the parameters covered in the simulation.

122
GRINNELL, S. K., "Flow of a Compressible Fluid in Thin Passages," Trans. ASME, Vol. 78, No. 4, May 1956, pp. 765-771.

Pressure distribution and weight-flow rate can be predicted for laminar compressible-fluid flow in a thin passage by use of the methods presented in this paper. A simplified method can be used readily when the fluid forces due to viscous action predominate over those due to acceleration of the fluid. A more complicated trial-and-error method seems to be required for larger passages where, though the flow may be laminar, the momentum effects due to acceleration of the compressible fluid are appreciable. An experimental apparatus was used to examine the validity of the analytical work. Experimental pressure distributions agree within a maximum deviation of 10% with the theoretical distributions predicted by both the comprehensive and simplified theories. Experimental weight-flow rates agree within a maximum deviation of 50% with predictions of the simplified theory. Dimensionless plots of pressure distribution are presented with experimental curves of flow rate versus pressure ratio for various ratios of passage length, L, to passage height h. These plots, together with simple equations, have been prepared for direct use by the designer. (Auth

Much of the work included here is contained in the author's MS Thesis. Hughes points out in the discussion at the end of the paper that for the flow of a compressible fluid in thin passages, an adiabatic treatment yields results identical with the isothermal solution, and, in fact, the adiabatic treatment shows that the isothermal solution is the only possible one compatible with energy conservation.

123
GROSS, W. A., "A Gas Film Lubrication Study, Part 1: Some Theoretical Analyses of Slider Bearings," IBM Journal of Research and Development, Vol. 3, No. 3, July 1959, pp. 237-249.

The Reynolds differential equation describing flow in a compressible lubricating film is developed. Important characteristics of such films are determined directly from the Reynolds equation. Pressure, load, velocity, and geometry characteristics are presented for many compressible slider bearing films based upon computer solutions of a Reynolds difference equation as derived in a companion report. Another companion report cites experimental verification of computer solutions and describes experimental techniques. (Auth)

Parts II and III of this study are authored by W. A. Michael and R. K. Brunner et al., respectively.

124
GROSS, W. A., "Film Lubrication, IV Compressible Lubrication of Infinitely Long Slider and Journal Bearings," IBM Research Paper, RJ-RR-117-4, June 25, 1958.

This is the fourth of a series of reports which deal with the theoretical aspects of hydrodynamic (self-acting) film lubrication. The aim is to aid understanding of the properties of gas lubrication. (Auth)

This rather short paragraph introduces a 105 page paper which lists 24 references including ones by W. Froessel, A. G. M. Michell, A. A. Raimondi and J. Boyd, G. I. Taylor, Y. Katto and N. Soda, V. N. Constantinescu and others. The work of these men is woven into a smooth, well developed comprehensive technical paper covering many phases of gas lubricated bearings.

125
HAGEN, G. I., "Air Floating, A New Principle in Magnetic Recording of Information," Computers and Automation, Vol. 2, No. 8, Nov. 1953, pp. 23-25.

(Not available for review as of July 1, 1959.)

126
HAGEN, H. W., "Bau und Berechnung Luflgelagerter Wellon (Design and Construction of Shafts Supported on Air Bearings)," Dissertation Technische Hochschule, Aachen, Germany, 1951.

The need for air lubricated bearings in modern technology is stressed. Early work on the theory involved is reviewed along with the few practical applications which had been made in this field up to 1948. Limitations of these early models are discussed. The principles of air lubrication are outlined in detail.

The author describes a bearing which he constructed to carry out a determination of its load capacity. In this section he treats only radial bearings - the principles underlying their use and the calculation of static load capacities. Calculations of the theoretical maximum of the load capacity are made both rigorously and by a simpler method utilizing an analytical approximation. These calculations are made under the assumption that the axle is weighted so that it is exactly tangent to the bearing casing. Since this is true only of ideal geometrical bodies, a planimetric method is described which takes waves and roughness on the surface structure of the parts into consideration. The results indicate that a calculation of the load capacity made by this method is approximately 20% lower than theoretical because of deviation of axle and bearing casing from the ideal form.

A method is next described for calculating the load capacity for any axle displacement by means of analytical approximation. These equations do not give the maximum load capacity, but they do allow the load capacity to be calculated as a function of axle displacement.

In making the calculations above, it was assumed that the weighting force caused a displacement parallel to the axle. This is generally true if two air lubricated bearings are used with a fairly large distance between them. However, in some cases it is more practical to use a single air lubricated bearing as a radial bearing. In such a case the weighting force is no longer in the middle, and this causes the axle to rock (tip) in the bearing casing. A method is presented for calculating this rocking (tipping) moment by analytical approximation. The result obtained theoretically agrees well with the value determined experimentally.

The total load capacity is made up of both static and dynamic elements. The dynamic load capacity can be calculated in the same manner as the hydrodynamic load capacity, taking into consideration the differences in physical constants between oil and air, especially the compressibility of the latter.

In the next section the principles of axial bearings are considered and their construction is described. Calculations are made to determine their load capacity and "value coefficient".

The use of air lubricated bearings in practice is described, along with methods to determine their coefficient of friction and their vibration. The relative merits of employing high-frequency motors or gas turbines to drive the axles are considered. One-and two-bearing polishing machines constructed by the author are described. From experiments conducted on them, both as polishers and borers, the author concludes that their usefulness has been established. Further improvements are suggested and other possibilities for the use of air lubricated bearings are considered.

127
HANDEN, D., "An Investigation of Air-Lubricated Shoes for High Density Magnetic Drum Head Applications," IBM Research Report No. RC-4, Jan. 1, 1957.

(Paper not available for review as of July 1, 1959)

128
HANSEN, P.D., "Flow of a Compressible Fluid in a Thin Passage," DACL Res. Memo No. 7401-2 MIT, Cambridge, Mass., 1957.

This work was classified as of July 1, 1959 and therefore unobtainable for review purposes.

129
HANSEN, S., "Fluid Bearing Mount," U. S. Patent 2 710 234, issued 1955.

A plurality of air pads are used to support the sphere for a stabalized platform. Pressurized air is supplied to some of the pads, and the other pads are evacuated. The "push-pull" effect keeps the sphere in the desired position. Extensions of the patent include changes in configuration from a sphere to truncated cones and eventually flat surfaces.

HARKER, J. M. (41)

HARRIS, D. M. (90)

130
HARRISON, W. J., "The Hydrodynamical Theory of Lubrication with Special Reference to Air as a Lubricant," <u>Trans-Cambridge Phil. Society</u>, Vol. 22, 1913, pp. 39-54.

The paper is made up of two sections, the first of which deals with the hydrodynamics of incompressible fluids. Here, Harrison, in attempting to simplify the work of Reynolds and Petroff, limits his analysis to the case of a complete cylindrical bearing (of infinite length). Making the usual assumptions, he arrives at equations identical to Sommerfeld's with somewhat less effort. Analyzing the forces (and moments) in the system he shows or concludes that Kingsbury, with the air-bearing, erred by measuring the friction on the journal and saying it was that of the bearing. From his derived expressions, Harrison then calculates the pressure distribution in Kingsbury's air bearing and compares the results with the experimental data. It was this comparison which pointed out the need to consider the compressibility of the gas lubricant.

The second section of the paper contains the derivation of the equations of hydrodynamics considering the compressibility of the lubricant. (The flow is assumed to be isothermal.) These equations are then applied to the cylindrical journal bearing and integrated numerically by Runge's method (not shown). In a series of curves (for three speeds) it is shown that the new equations predict Kingsbury's experimental results much more accurately than do the equations neglecting compressibility. An analysis is also included for the case of compressible fluids between inclined planes. The conclusion drawn from Harrison's work is that for high rotational velocities, the compressibility of air should be included in the analysis of hydrodynamic bearings.

A classic, with more than just historical value, this paper contains the original work on the use of compressible fluids as lubricants.

HAUGHTON, K. E., (41)

131
HEICHERT, H. S., "Air as a Lubricant," <u>Engineering News</u> Mar. 8, 1900, pp. 158-159.

Brief article describing the work of Kingsbury in 1897.

132
HEINRICH, G., "The Aerodynamic Bearing," (In German), Machinenbau µ Waemewirtschaft 7, 199-35 (1952). H.28368 (HU) A.E.R.E. Harwell, Nov. 1956. In U.S., 7168 AEC tr 2920. Translated by R. Todd.

The double sided, annular tracked bearing was dealt with and formulae for the average bearing pressure and the energy necessary for the compressor were derived. By means of a numerical example, it was shown how the quantities corresponding to a minimum energy requirement are determined. (Auth)

133
HENRIOT, E., E. HUGUENARD, "Les Grandes Vitesses Angulaires (High Rotational Speeds (Air Lubricated Top)), Revue Generale des Sciences Pures et Appliquees, Tome 38, No. 20, Oct. 1927, pp. 565-569. Le Journal de Physique et le Radium, Series VI, Tome VIII, Nov. 1927, No. 11, pp. 433. Also "Sur la Realisation de Tres Grandes Vitesses de Rotation, (On the Realization of High Rotational Speeds)," Comptes Rendus Vol. 180, May 11, 1925, pp. 1389-1392. (Presented at Session of April 6, 1925.)

The paper describes the development of an air-driven centrifuge in the course of which it became necessary to use an air bearing to reduce the friction sufficiently to attain high rotational speeds. According to Gerard, Huguenard, the co-author, was the inventor of the air-driven, air-bearing supported turbine.

134
"High Speed Air Bearing," National Research Development Corp. Bul., No. 9, Mar. 1957.

The NRDC Bulletin contains periodic reviews of inventions for industry. This particular issue mentions the bearings developed by Sixsmith.

135
HIRAYAMA, N., "Research on a Pneumatic Journal Bearing," (In Japanese) Trans. J.S.M.E., Vol. 19, No. 78, 1953, pp. 13-16.

Assuming the fluid incompressible and viscous, the flow pattern in the bearing clearance of a practical pneumatic journal bearing is analyzed theoretically and pressure distributions are calculated. The plausibility is confirmed by experiments. (Auth)

136
HIRN, G., "Etudes sur les principaux phenomenes que presentent les frottements mediats et sur les diverses manieres de determiner la valeur mecanique des matieres employees au graissage des machines (Study of the Principle Phenomena which are shown by Friction Media and on the Manner of Determining the Mechanical Value (Viscosity) cf Substances used as Lubricants for Machines)," Bulletin de la Societe Industrielle de Mulhouse, Tome 26, No. 129, 1854, pp. 188-277.

Mr. Hirn, speaking before an assembly, told how he found the "fluidity," i.e., the reciprocal of viscosity, to be that property of an oil or grease which determines its lubricating qualities and the relative coefficients of friction. It is this paper that mentions for perhaps the first time in print that almost anything, including air, can be used as a lubricant.

A rather lengthy dissertation, it is included here primarily because of its historic value.

137
HOFFER, F. W., "Automatic Fluid Pressure Balancing System," U. S. Patent 2 449 297, issued 1948.

This is a rather lengthy patent which extolls the virtues of externally pressurized bearings, in particular those which embody the inventor's suggestion to use "balancing zones" and "isolating grooves". A number of geometries or configurations are shown to which this zone and groove design can be applied. The term fluid is used continuously and pressures of 5000 psi are spoken of which generally indicates liquid lubricants. However, the inventor does not restrict himself and does make a number of specific mentions of using gaseous lubricants.

Like most patents, this contains no mathematical analyses or treatment. The discussion does contain many good practical design ideas among which are the use of orifice and the bearing sills to restrict or control the flow.

138
HONESS, W. T., "Air Bearing Thrust and Radial Supporting Bearing," U. S. Patent 2 617 696, issued 1952.

The inventor uses air as the lubricant in both thrust and radial support bearings for an air driven turbine. The inventor claims that because of the air bearings the unit can operate at high temperatures.

HORTON, W. (83)

139
HUGHES, W. F., J. F. OSTERLE, "Heat Transfer Effects in Hydrostatic Thrust Bearing Lubrication," <u>Trans</u>. <u>ASME</u>, Vol. 79, No. 6, Aug. 1957, pp. 1225-1228.

The limiting isothermal and adiabatic operating conditions of the hydrostatic thrust bearing have been investigated recently. However, the actual performance of such bearings is characterized by an intermediate situation in which heat transfer occurs in the lubricant and bearings. In this paper a simplified model is constructed for such intermediate situation, and it is found that the bearing performance is essentially isothermal at an elevated temperature. Expressions are derived for the temperature distribution, and the results of numerical examples are compared with isothermal and adiabatic calculations. Compressible and incompressible lubricants are considered. (Auth)

140
HUGHES, W. F., J. F. OSTERLE, "Temperature Effects in Hydrostatic Thrust-Bearing Lubrication," ASME Paper No. 56-LUB-11.

The hydrostatic thrust bearing is analyzed under adiabatic flow conditions for both an incompressible (oil) and a compressible (air) lubricant. Expressions for the pressure and temperature distributions, load capacity, and frictional torque are obtained. For the incompressible case the load capacity undergoes appreciable deviation from the isothermal behavior with variations in angular velocity. However, for the compressible lubricant, the load capacity differs only slightly from isothermal behavior and is nearly constant with variations in angular velocity. (Auth)

HUGHES, W. F. (186)

HUGUÉNARD, E., (133)

141
HUTCHINS, E. E., "Tests on the Pump Unit for the Mk I Uranium-Bismuth Loop (BERO), "AERE R/M 24, 1957, UKAEA Harwell, Berkshire, England.

This memorandum describes tests carried out to determine the characteristics of the centrifugal, induction-driven pump unit, built into the Mk I Uranium-Bismuth Loop which is to operate in BERO. Reference is also made to the apparatus employed for making the tests. (Auth)

Gas lubricated bearings were employed but there is little more than mention of them made in this report.

142
"Investigates Air as Bearing Lubricant," Soc Auto Eng. Jour., Vol. 61, No. 11, Nov. 1953, p. 108.

Short abstract of paper by D. McKinley on Kingsbury thrust bearing.

143
JAY, D. J., H. W. PEITHMAN, "An Analog Study of Levapad Stability," ASME Paper No. 58-A-287.

A set of non-linear differential equations was derived to describe the self-excited vibration of an early levapad type. These equations were solved on the department electronic analog computer. The theoretical solution which included a non-linear damping term in the equation of motion agreed favorably with the experimental results of the Levapad I type for the one set of conditions considered. The study demonstrated the manner in which the relationship of the various parameters produced a self excited condition and indicated how a system might be designed to eliminate the vibration. (Auth)

144
JAY, D. J., "Levapads for High Speed Tracks," Fourth Annual Supersonic Track Symposium, Sept. 1957, (Presented by Ford Motor Co.)

The article describes a proposed application of hydrostatic gas lubrication to the sliding pads of a supersonic test track. The term "levapad" is the name the author uses for the more familiar recess bearing; also called pad or pool bearing in the literature. (Additional information is contained in a technical paper by Jay and Peithman.)

145
JOHNSTON, T. J., "Frictionless Bearing for Electric Motors," U.S. Patent 816 330, issued 1906.

A rather elementary form of bearing is described in which jets of pressurized air impinge upon a flat surface supporting it against gravity while permitting it to rotate. Pressure at the plate, and therefore load-carrying capacity, is a function of the separation distance. The proper distance is therefore automatically maintained.

146
JUNG, K., "Bearing for Accurately Running Shafts Using Ball Bearings," U. S. Patent 1 893 995, issued 1933.

The play in ball bearings may be taken up or adjusted by axially moving one of the ball races. The inventor substitutes an externally pressurized gas bearing for the mechanical devices normally used to effect the movement.

147
JUNGGREN, O., "Combined Thrust and Guide Bearing," U. S. Patent 947 392, issued 1910.

A description is given of an externally pressurized bearing system which can use steam as the lubricant.

148
KAESTLE, A., "Skiing on Air," Popular Science, June 1959, p. 240.

Compressed air jetted from small containers provides a cushion between skis and snow, lessening friction and increasing the speed of the run. (Auth)

No other information is available.

149
KATTO, Y., N. SODA, "Theory of Lubrication by Compressible Fluid with Special Reference to Air Bearings," 1952 Proc. Second Japanese National Congress on Applied Mechanics, National Committee for Theoretical and Applied Mechanics, May 1953, pp. 267 - 270.

By considering the pressure in a bearing to be a continuous and periodic function with period equal to 2π and the total mass of air contained in the bearing clearance to be constant, these authors were able to mathematically manipulate the equation $\frac{dp}{dx} = \frac{6\eta U}{h^3} (h - \frac{k}{p})$ and arrive at a form of solution.

Conversions were then made to dimensionless forms and the results plotted. From their curves, one can find the position of the journal center (and also the friction coefficient), given the mean load and the velocity of the journal. The pressure distribution in the bearing can be found by making substitutions in the appropriate equation.

This appears to be a logical method of attack. However, the authors present no experimental verification of their theory.

KAYAN, C. F., (30)

150
KEMP, J. F., "Centrifugal Manometer," ASME Paper No. 58-A-111

The operating principles and mechanical construction of a micromanometer which utilizes air in lieu of a liquid as working fluid, are described. Some of the noteworthy features of the instrument include its high sensitivity and accuracy, quick response, wide range, and ease of manipulation. Differential pressures of the order of 5×10^{-3}mm water gage can be measured with an error of 1 per cent under normal laboratory conditions. The maximum range of the prototype described is 25mm water gage, and the corresponding error at this value amounts to about 0.25 per cent. (Auth)

KERR, J. (55)

KHARITONOV, A. M., (231)

151
KINGSBURY, A. "Experiments with an Air Lubricated Journal," Journal American Society Naval Engineering, Vol. IX, 1897, pp. 267-292. Also Journal Worchester Poly Inst., Mar. 1900 - not readily available and probably abstracted only

In one of the first carefully controlled and reported experiments of this type, Professor Kingsbury measured point of nearest approach (and attitude) of journal and bearing, friction, and pressure distribution as functions of speed and load. He also noted the points at which wear took place. One of the conclusions drawn is the necessity of clearances between shaft and bearing in order for them to operate. Suggestions are also made on where best to introduce the lubricant. These suggestions are based on the existence of negative pressures in the bearing.

One of the famous contributors to the subject of bearings, Professor Kingsbury by this paper stimulated considerable interest in gas-lubricated bearings. His knowledge of the practical side of engineering is evidenced in the design of his test rig and instrumentation. The results which were only in fair quantitative agreement with the work of Towers and Reynolds were later explained by Harrison who considered the compressibility of the gas.

KIPP, E. M. (71)

152
KIRKPATRICK, J. G., "Hydraulic Thrust Bearing," U. S. Patent 2 523 310, issued 1950.

This invention has for its primary object the provision of a thrust bearing for rotating shafts wherein the bearing will be free floating and wherin metal to metal contact upon the thrust surfaces of the bearing is prevented by the interposition of a fluid medium under pressure. (Auth)

The inventor states that gaseous lubricants may be used.

153
KLAHN, E., "Apparatus for Minimizing Friction and Vibration of Rotor Elements." U. S. Patent Re 20305 (Original No. 2 054 055), issued 1937.

The device described is perculiarly adapted for accomplishing the practically perfect balancing of rotors such, for example, as propellors, fly wheels, shafts, armatures, gyroscopes, turbine rotors, etc., as well as scale arms and the like. (Auth)

Externally pressurized air is supplied to a stationary shaft which has a longitudinal pocket cut into it. The practically frictionless support enables the movable member to be precisely balanced. The use of additional pockets is suggested to trap the air and thus provide a cushion against vibrations. Provisions are also made to cause rotative motion of the part to be balanced.

154
KLAHN, E., "Art of Sustaining Bodies in Space," U. S. Patent 1 629 577, issued 1927.

In a gyroscope: a rotatable support member having an upper bowl position; and a free, spherical member adapted to rest and to rotate therein and solely air supported during rotation. (Official Gazette)

155
KOCHI, K. C., "Characteristics of a Self-Lubricated Stepped Thrust Pad of Infinite Width with Compressible Lubricant," Journal of Basic Engineering, Trans. ASME, Vol. 81, Series D, No. 2, June 1959, pp. 135-146. ASME Paper No. 58-A-1941.

Harrison's equation for the pressure in a gas-lubricated bearing of infinite width is solved for a thrust pad with stepped configuration. Analytic expressions for the pressure and load are developed. Numerical results are presented graphically. The analytic expressions together with the numerical data permit most of those characteristics of the stepped pad of practical interest to be completely determinable. Determination of optimum design parameters is given by a pair of graphs. (Auth)

156
KOENDERS, M. A., "A Survey of Hydrodynamic and Hydrostatic Lubricated Bearings," APEX 390, OTS, US Dept. of Commerce, Wash., D.C.

A search of the unclassified literature and General Electric reports has been made with reference to the use of air as the lubricating fluid in hydrostatic and hydrodynamic bearing applications. (Auth)

This publication is in essence the state of the art as the author found it. Being rather concise (25 pages) it serves to familiarize the newcomer to the field with what has been done. All applicable references from this work have been included in this bibliography.

KONDO, (225)

157
KOWASKI, Y., "Seimitsukiakai (On the Air-Lubricated Bearings)," Journal Society Precision Machinery of Japan, Vol. 13, No. 5,6,7, pp. 39-44, No. 152,153,154, May-July 1947.

An analysis based on Reynolds' theory is given for an air-lubricated spherical bearing. The results of the analysis are then extended to the case in which the moving part of the bearing takes the form of a circular disk. The theoretical work is supplemented with experimental results.

KRAUSZ, A., (83)

158
KREITH, F., R. EISENSTADT, "Pressure Drop and Flow Characteristics of Short Capillary Tubes at Low Reynolds Numbers," Trans. ASME, Vol. 79, No. 5, July 1957, pp. 1070-1078.

The pressure drop and flow characteristics of short capillary tubes have been investigated experimentally for length-to-diameter ratios varying from 0.45 to 18 at diameter Reynolds numbers ranging from 8 to 1500. In the range of the dimensionless modulus $(L\mu)/(VD^2\rho)$ from 4×10^{-3} to 3×10^{-1}, the experimental data agree within 15 per cent with a mathematical theory by Langhaar. At a value of $(L\mu)/(VD^2\rho)$ of about 0.3 the experimental data approach the Poiseuille laminar-flow theory (2). For very short tubes ($L/D < 0.5$) the experimental results deviate from Langhaar's theory at values of $L\mu/VD^2\rho$ less than 4×10^{-3}, and at $L\mu/VD^2\rho$ equal to 5×10^{-4}, the pressure drop is twice as large as that predicted by Langhaar's theory. The experimental results for tubes having very short aspect ratios are in agreement with data obtained by Zucrow with short square-edged jets. It was found that the flow rate Q through a short capillary tube can be related empirically to the over-all pressure drop Δp raised to a power N. The exponent N is a function of the length-to-diameter ratio L/D varying from 0.5 at L/D equal to 0.45 to 0.91 at L/D of 18. The trend of the curve suggests an asymptotic approach to unity, the exponent for Poiseuille-type flow. The results of this study have application to: (a) Simulating flow through screens, doors, cracks, and fissures in small-scale model testing of buildings in atmospheric wind tunnels. (b) Automatic control devices where capillary tubes are used as hydraulic resistances in a larger line and in nozzle-flapper combinations. (c) Heat pumps and air-conditioning equipment where short capillary tubes are used as two-way control valves. (d) Flow through compact heat exchangers and porous materials. (Auth)

This paper does not deal with gas bearings as such. However, the use of short capillary tubes occurs quite frequently and therefore, this paper could prove of value to persons engaged in gas bearing work.

159
LEARY, W. M., D. H. TSAI, "The Measurement of Air Flow by Means of the

ASME Square-Edged Orifice with Flange Taps," Sloan Laboratory, MIT, Cambridge, Mass., 1950.

The work by these authors is included as part of a collection of contributions by various persons to a volume entitled "Aerodynamic Measurements" by Robert C. Dean, Jr. Both Leary and Tsai have written on flow metering. The reference is cited as one of the possible sources for obtaining information on flow measurements and flow measuring devices.

160
LICHT, L., D. D. FULLER, "A Preliminary Investigation of an Air-Lubricated Hydrostatic Thrust Bearing," ASME Paper 54-LUB-18, 1954.

Because of the growing interest in the lubrication of bearings with air, this investigation of a simple hydrostatic thrust bearing was undertaken. Equations are developed for load-carrying capacity, film thickness, pressure profile and volume of air required for a typical thrust bearing. Conditions leading to stability of operation are also considered. A comparison of theoretical and experimental values shows that within the limits of the test data the performance characteristics of this bearing can be predicted with good accuracy. (Auth)

The author offers a series of curves which, for his model, enable one to determine the flow and supply pressure required to carry a load at a specified film thickness. His note of bearing instability and its correction (by reducing the depth of the recess) is almost passed over. An analysis of this problem is promised in a subsequent paper.

161
LICHT, L., H. G. ELROD, "A Study of the Stability of Externally Pressurized Gas Bearings," The Franklin Institute - Laboratories Interim Report I-A2049-4, Nov. 1958. Contract Nonr-2342(00) Task NR 097-343. AECU 3913, OTS.

The subject of this paper is the stability of externally pressurized gas bearings.

The pertinent equations are linearized and the stability criteria stated in considering small deviations from the equilibrium point.

The flow in the bearing clearance is treated on a distributed rather than on a lumped parameter basis. Results thus obtained, when compared with those previously arrived at by means of a simplified analysis, show a marked divergence in the limiting values of parameters which influence the stability of the bearing.

Differences in predictions to the simplified and present analyses with regard to the permissible compression volume in the bearing interspace and the effect of varying the mass of the bearing are emphasized and discussed. (Auth)

162
LICHT, L., D. D. FULLER, B. STERNLICHT, "Self-Excited Vibrations of an Air-Lubricated Thrust Bearing," Trans. ASME Vol. 80, No. 2, Feb. 1958, pp. 411-414. ASLE Paper preprint No. 57-LC-12.

The authors attack the problem of instability in air-lubricated bearings and relate it to the air storage capacity. In a straight forward mathematical treatment backed up by experimental data they show, for a disk-type externally-pressurized air bearing with a centrally located recess, the most stable conditions occur with small recess depths (small air storage capacity), high recess pressures and minimum bearing clearances. In the course of the work they find the use of large nozzles is preferred to small ones and nozzles in general are preferred to capillaries. The work also shows that a choked condition at the nozzle leads to instability.

LILLIE, G., (252)(253)(254).

MACKS, E. F., (194)(239).

163
MANN, M., "Here Come Cars Without Wheels," Popular Science, July 1959, pp. 51-55, 194.

You'll ride low and fast on a bubble of compressed air, in fantastic new "sleds." They whoosh across fields, swamp, water-anywhere-at speeds that could match airplanes. (Auth)

The devices described do support themselves on a cushion of compressed air. Some "ride" only a fraction of an inch above the lower surface, others a few inches. ("Film thicknesses" of thirty feet or more are predicted by the people making these sleds.)

Classification of these sleds as gas bearings may be questioned. The reference is included here to note their existence. (See introduction to this bibliography.)

164
MARCO, S. M., "Rotary Nozzles for Soot Blowers and the Like," U. S. Patent 2 752 197, issued 1956.

An object of this invention is to provide a rotary soot blower nozzle so designed that all lubricants that would be detrimentally affected by high temperatures are eliminated.

The invention aims to provide an improved nozzle (for a soot blower) which may be used within the high temperature regions of a water tube boiler without requiring lubricants for the relatively moving parts which are detrimentally affected by the high temperatures (2500°F) within the furnace. The construction is such that moving parts are floatingly mounted by the cleaning medium, commonly air, which is introduced between the bearings of the relatively moving parts during the cleaning operation, and the cleaning medium is also employed to rotate the nozzle on the lance tube. (Auth)

MARTIN, K. B., (19)

MAXWELL, D., (83)

165
McBAIN, J. W., C. M. O'SULLIVAN, "The Development of the Air Driven Spinning Top as a Transparent Ultracentrifuge," Journal American Chemistry Society, 57, Dec. 1935, pp. 2631-2641.

In describing the development of a centrifuge, the problem of rotor stability is raised. Three types of rotor instability are described; precession, vertical vibration and horizontal wobble. Their causes and remedies are discussed.

As with most of the available literature on centrifuges, the topic of the gas-lubricated bearings is relegated to the background. No attempt is made to analyze the bearing problem mathematically. However, sufficient information is contained in the paper to make it a contribution to the general gas bearing problem.

166
McKINLEY, D. C., "Investigation of a Kingsbury Thrust Bearing Using Air as a Lubricant," Society Automotive Engineers Paper, Meeting, Jan. 19, 1953.

The design, development and testing of an air-lubricated Kingsbury type thrust bearing is described. The author assumes incompressible flow and computes the film thickness for two specific examples. He then briefly discusses the importance of a very good finish on bearing surfaces.

(Copies of this paper are not readily available.)

167
MICHELL, A. G. M., "Lubrication, Its Principles and Practices," Blackie, London, 1950, "Air Lubrication," pp. 168-169.

Contains a brief mention of the use of air as a lubricant.

168
MICHAEL, W. A., "A Gas Film Lubrication Study, Part II; Numerical Solution of the Reynolds Equation for Finite Slider Bearings," IBM Journal of Research and Development, Vol. 3, No. 3, July 1959, pp. 256-259.

This paper presents a finite-difference technique for obtaining approximate numerical solutions to the Reynolds partial differential equation of gas film lubrication theory. A digital computer program is described, and discretization errors and stability of the difference equations is discussed. (Auth)

See W. A. Gross and R. K. Brunner for Part I and Part III of this group.

The three papers, Parts I, II and III taken together represent an idealized attack on a gas bearing research problem. The theoretical analysis, the numerical solutions and the experimental verification complimenting each other admirably.

169
MICHEL, R. O., "Pneumatic Bearing Construction," U.S. Patent 2 756 115, issued 1956.

Gas bearings are particularly designed to accomodate vertical and thrust loads normally encountered in the mass centering of a propellor blade. The device is essentially a cantilevered shaft supported by a force couple formed by two 180° bearings near one end. A number of orifices are used as the air inlet ports in the radial bearings and, in the necessary thrust bearings.

170
MICHELSON, H., "Bearings," U. S. Patent 2 738 238, issued 1956.

An externally pressurized fluid is used on a work-holding and positioning device to support a vertical load meanwhile permitting one of the members to rotate freely and accurately about the bearing center. This is accomplished by introducing the fluid inside the spaces formed by a series of interlocking annular grooves cut into the mating bearing plates.

171
MIDWOOD, G. F., R. W. DUNCAN, "Tests on an Air Lubricated Thrust Bearing," Royal Aircraft Establishment Aero. Tech. Memorandum No. 5, Oct. 1947.

(Paper not available for review as of July 1, 1959.)

172
MOLLER, W., "Bearing," U. S. Patent 2 068 458, issued 1937.

The flow of air to the bearings is automatically controlled by the relative motion of parts in a compass.

173
MONTANY, E. R., "An Analytical Study of the Load Carrying Capacity of a Journal Type Gas Bearing," Curtiss Wright, R-48-2, Feb. 18, 1948 AF Contr. W33-038 ac - 14161, Project MX-772.

An analysis has been made of the load-carrying capacity of two types of journal gas bearings. Type 1 is a journal bearing with pressure inlet at the bottom and pressure outlet at the top. Type 2 has pressure inlets at both top and bottom and outlets at both sides. A series of charts is plotted which should prove useful in bearing design. (Auth)

The feasibility of the design of journal-type gas bearings by analytical means was investigated. The work resulted in a method of approach and a series of design charts for two simplified externally-pressurized types of journal bearing.

The analysis is for one dimensional fluid flow of a compressible perfect gas in a bearing with small shaft displacement. End flow is neglected.

174
MONTGOMERY, A. G., F. STERRY, "A Simple Air Bearing Rotor for Very High Rotational Speeds," A.E.R.E. ED/R, 1671 (1956).

A high speed rotor (of 3/4" diameter) is capable of 250,000 r.p.m.

driven by an air turbine; it runs on air-lubricated, externally supplied journal bearings, which consist of standard, sintered oil-retaining bronze bushes (with the oil extracted.) For purposes of sealing and flexibility, they are mounted on rubber 'O' rings. The thrust bearing is a single 0.020 inch diameter air jet in the middle of a flat surface. The rotor is a plain, ground cylindrical rod of tool steel with serrations milled at one end to provide a crude turbine wheel - it runs at a diametral clearance of about 0.003 inch. Bearing air consumption is about 10 c.f.m. The system could be made much smaller, both to achieve higher speeds and to economize in air consumption. (Auth)

The article itself is rather short yet quite important since the device permits attaining rather high rotational speeds. The use of the porous bronze bearing described is similar to the porous carbon graphite bearings patented by Becker.

175
MONTGOMERY, A. G., F. STERRY, TO UKAEA, "Gas Lubricated Bearings," Great Britain Patent 796 926, Nuclear Eng 4, 48, issued 1959.

When using gas lubricated bearings, instability of the rotor occurs under certain conditions, and may develop into violent back and forth movements of the rotor across the diameter of the bearing (as an oscillating piston in a double-ended cylinder.) An incipient oscillation is also present, determined by the mass of the rotor and the load/ displacement characteristic of the bearing. The clearance between rotor and bearing shell is of importance for this oscillation and, therefore, has to be kept extremely small (0.0005 in) and only very small tolerances are thus permissable. This clearance, however, can be raised to the order of 0.003 in for an 0.75 in rotor diameter by arranging the bearing sleeve to be surrounded by two rubber rings, one at each end which also act as gas seals in an annular chamber under gas pressure around the sleeve. (Nuclear Science Abstracts 13-8464.)

MORI, H., (217) (218) (219) (220) (221) (222) (223) (224) (225) (226) (227) (228) (229) (231)

MORRISON, R. B., (130)

176
"Motor which Floats on Air," New York Journal of Commerce, April 25, 1956, p.4.

Describes a commercial device manufactured by Air Glide Engineering Labs which uses gas lubricated bearings.

177
MOW, C. C., E. SAIBEL, "The Gas-Lubricated Sector Thrust Bearing," ASME Paper No. 58-LUB-5.

The object of this paper is to obtain an exact solution for a sector thrust bearing with side leakage and film variation in angular and radial direction, also taking into account the compressibility of the gas. (Auth)

The final form for the pressure expression is rather long and a computer would probably be required to obtain any significant amounts of data. The author shows the results of numerical examples in graphical form.

178
MUELLER, P. M., "Air-Lubricated Bearings," Product Engineering Annual Handbook of Product Design, 1953, pp. J2-J5. Also appeared in Product Engineering, August 1951, Vol. 22, No. 8, pp. 112-115.

Journal, thrust, and "flat" bearings lubricated with air are described in this paper and their performance characteristics are discussed. The effect of clearance on pressure distribution between bearing surfaces is shown. The flow of air in these bearings takes place through two orifices in series. (Auth)

In Mueller's system a fixed and a variable orifice are separated by an intermediate pressure chamber. The author shows the flow depends on the area of the second orifice (bearing clearance) and the pressure in the intermediate chamber. Increasing the load causes the clearance, h, to be smaller which should decrease the flow. However, if the load is to be supported, the intermediate pressure must rise. This, when it happens, causes the flow to increase and thus become proportional to the load. By using a high supply pressure the flow through the first orifice into the intermediate chamber is always choked.

Since the flow is meant to be controlled by the load at all times it appears the purpose of the first orifice is solely to provide a restricted passageway into the intermediate pressure chamber which is necessary if the flow must increase with load.

Critics of this system say the flow may increase and decrease in turn thereby causing a spring-type action. The author claims, however, that this will not and does not occur if the intermediate pressure chamber is very shallow.

179
MUELLER, P. M., "Air Turbine Driven Spindle," Product Engineering, Mar. 1952, Vol. 23, pp. 160-163.

This paper describes a simple air turbine, air lubricated bearings, and pneumatic speed governor combined in a drive for a high-speed internal grinder head unit designed to operate over a wide range of governed speed. (Auth)

This article contains sufficient design and development information to be of some value.

180
MUELLER, P.M., "Pneumatic Governor Design for High Rotational Speeds," Product Engineering, Oct. 1951, pp. 170-175.

Design of specific pneumatic governor suitable for small high speed air turbines. Detailed calculations of the size of essential components and of governor's operating characteristics. Theory of the air gage and general rules for designing a pneumatic servo-controlled system to meet a required set of conditions. (Auth)

There is little more than mention of gas bearings in this article.

181
NISHIHARA, T., Y. SUGIMOTO, "On the Theory of Lubrication in the Journal Bearings," Report 31, Tech. Repts of the Eng Res Inst. Kyota Univ., Kyoto, Japan.

The improvements in the mathematical treatment of Reynolds' hydrodynamical theory of lubrication by Sommerfeld and Gumbel have laid the path open to its practical application.

In case of cylindrical bearings, however, further investigations on certain corrections and approximations are necessary for a satisfactory agreement with experimental results. In the mathematical theory of Reynolds and Sommerfeld, the bearing length is assumed to be so great that the motion of the lubricant can be treated as two-dimensional.

It has been explained that, in actual practice, the lubricant can squeeze out through the edges. The present paper discusses the complete solution of the three-dimensional problem of lubrication in a journal bearing. (Auth)

Although the original analysis is for oil, air bearings are treated in the last sections. The conclusions state, "The results of analysis of the air bearing showed good agreement with the experimental data."

NORIMUNE, S., (288).

182
"North American Announces Use of Frictionless Air Bearings," American Helicopter, Vol. XX, No. 12, Nov. 1950, p. 17.

A short (200 word) article mentioning that air bearings are being used in components for guided missiles, etc.

183
OFFEN, A., "Laps," U. S. Patent 2 734 318, issued 1956.

The main object of the invention is to provide an improved method of, and apparatus for, internally lapping small round cylindrical holes (to 1/100 inch in diameter) especially those of great length. Exhaust air from the turbine drive passes between the spindle and bearings before being evacuated.

184
OHNO, T., O. TANIGUCHI, "Research on the Air Thrust Bearing, 1st Report," (In Japanese) Trans. JSME, Vol. 17, No. 63, 1951, pp. 31-36.

Several types of bearing have been used as air thrust bearings, but their behavior may not be the same or two different actions are combined in various ratios, namely lubrication by the air film (hydrodynamic) and that supplied by the uniform static pressure of air. In another special type the rotor is supported and also driven by the air. Under such circumstances, generally available data to design the air thrust bearing is lacking. We take up at first the type of two facing disks - one that is a stator and the other is a rotor, having a clearance with an externally supplied air film between them - and obtain some information concerning the properties of the air film, both experimentally and theoretically. (Auth)

185
OSPINA - RACINAS, E., "Pneumatic Toy," U. S. Patent 2 544 720, issued 1951.

An amusement device comprising a tube adapted for flow of a fluid jet thereout and a tubular conduit, one end of which conduit debouches into said fluid jet and is in aspirated relationship to said fluid jet so as to establish flow in said tubular conduit, the other end of said tubular conduit being in aspirating relationship to said fluid jet at a point further from the mouth of said tube than said first end. (Official Gazette)

Not much relationship to a conventional bearing. The ball being supported and raised by air, must re-enter the system through one of two openings from whence it is carried back to the starting point by the air stream.

186
OSTERLE, J. F., W. F. HUGHES, "High Speed Effects in Pneumodynamic Journal Bearing Lubrication," Applied Scientific Research, Section A, Vol. 7, No. 2-3, 1958, pp. 89-99.

The steady-state operation of gas-lubricated journal bearings is analyzed for the effect of lubricant inertia on the pressure developed in the lubricant. Numerical results are given for a 180 degree partial bearing. It is found that the inertia effect can be significant in the laminar regime. (Auth)

The authors, in a series of mathematical papers, have attempted to make refinements to the equations of lubrication as generally known so that the numerical results arrived at will be more nearly in agreement with experimental results than they have previously been. Here they deal with the case of a 2 inch diameter shaft rotating at speeds up to 200,000 rpm. They show that to neglect the effect of lubricant inertia may introduce measurable errors in load carrying capacity when the peripheral shaft speed becomes 500 ft./sec or more. The correction acts to decrease the value of load arrived at, which correction is in the right direction. An error in the determination of attitude angle is also incurred by neglecting inertia. No experimental verification is given.

OSTERLE, L. F., (139) (140)

OSTERLUND, A. G., (41)

O'SULLIVAN, C. M., (165)

187
PAIVANAS, J. A., "A Study of the Flow of Air in a Radial Diffuser," M. S. Thesis University of Buffalo, Buffalo, New York, June 1955.

The author made his investigations to acquire some understanding of the basic phenomena associated with the flow of air through a radial diffuser. Willis and Welanetz, also looked into this problem but not as thoroughly as Paivanas. A considerable amount of experimental work was done primarily at clearances of 1/8 inch. However, in some of the experiments, clearance was a variable and clearances as small as 0.003 inch were used. A one-dimensional theoretical study of the problem was made and compared to the experimental results. Agreement between theoretical and experimental results was not as good as the author would have liked it to be.

188
PANTALL, D., C. H. ROBINSON, "Gas-Lubricated Bearings in Nuclear Engineering, Part I," Nuclear Engineering, Feb. 1959, pp. 53-58.

The author summarizes briefly, the practical differences between bearings lubricated by liquids and gases with particular reference to the hydrodynamic or self-acting type. (Pressure-fed bearings form the subject of a subsequent article, Part II.) In this article the accuracy of manufacture, load calculations, eccentricity ratio, and other parameters are discussed. Some mention is also made of whirl and associated phenomena.

189
PANTALL, D., C. H. ROBINSON, "Gas-Lubricated Bearings in Nuclear Engineering, Part II," Nuclear Engineering, Mar. 1959, pp. 123-128.

This, the second article of a series of two on gas bearings, deals with hydrostatic (externally pressurized) types beginning with an analysis of the important features of plain journals and concluding with a section on thrust bearings. (Auth)

PANTALL, D., (90)

190
PEILER, K. E., "Sting-out Baffle for Glass Feeder Rotor Bearing," U. S. Patent 2 707 355, issued 1955.

The patent is for a system which will alleviate the deleterious effects of hot gases to machine parts in the making of glass. In the course of the discussion, mention is made of the use of gas bearings in glass making equipment.

PEITHMAN, H. W., (143)

191
PENICK, E. R., "Air Bearing," U. S. Patent 1 906 715, issued 1933.

The device patented is an externally-pressurized, multipad, gas-lubricated bearing employing short capillary tubes leading from a common annular distribution chamber to the various recesses.

192
PERKINS, G. S., P. R. VOGT, R. R. WEBER, "Double Ended Journal Air Bearing," U. S. Patent 2 597 371, issued 1952.

The patent is issued for a double ended journal air bearing for possible use in a gyroscope. The bearing is capable of supporting the mass while allowing only a single degree of freedom.

193
PICKELS, E. G., "A New Type of Air Bearing for Air Driven High Speed Centrifuges," The Review of Scientific Instruments, Vol. 9, Nov. 1938, pp. 358-364.

The author describes a modification to the air-lubricated bearing of a centrifuge. The changes made were relatively simple and included the addition of a perforated disk below and inside the rim of the turbine wheel. The space between the disk and rotor then forms a pocket in which the pressure to support the load is contained.

194
PIGOTT, J. D., E. F. MACKS, "Air Bearing Studies at Normal and Elevated Temperatures," NACA paper presented at American Society of Lubrication Engineers Meeting in Boston, Mass., April 1953. Published slightly abridged and without derivation of equations in Lubrication Engineering, Vol. 10, No. 1, Feb. 1954, pp. 29-33.

Experimental studies were made with a six-inch outside diameter externally-pressurized, parallel surface, nonrotating air thrust-bearing at temperatures to 1000°F. Theoretical expressions describing the air flow through the bearing and the air flow through capillary tube resistances are presented in the form of design equations and curves and are compared with experimental results over a wide range of temperatures and loads. Results show that the load capacity is increased as the operating temperature is increased. (Auth)

The paper contains a theoretical analysis of the air-lubricated bearing and the results of experiments carried out at temperatures to 1000°F. Experimental and theoretical values of film thickness and air flow do not agree very closely and the authors attribute this, in part, to physical changes in the bearing surface resulting from the extremely high temperatures. Instabilities were also noted in one of the test bearings.

While there are many references made to the possibility of using air as a lubricant at high temperatures, this is, as yet, one of the few published records of experiments carried out along these lines.

195
POTTS, L. D., "Fluid Balancing Means," U. S. Patent 2 502 173, issued 1950.

The pressurized process fluid from a cryogenic pump is bled off and fed to the radial and thrust bearings where it counterbalances the forces acting on the rotor. According to the inventor the fluid does not enter the space between the journal and graphite material bearing. At the temperatures contemplated the fluid employed is a liquid. Whether it remains as such or changes to gas in the system is not specified.

196
RAICHLE, L., G. SCHULZE, "Thrust Balancing for Vertical Shafts", U. S. Patent 2 605 147, issued 1952.

The thrust load on a vertical-rotor is balanced by causing the pressurized process fluid to act on a piston through which the shaft passes. When the load changes the motion of the shaft causes the flow path through a labyrinth system to be altered. The change in flow results in a corresponding change in pressure on the piston; thus automatically compensating for the unbalanced force.

197
RANDALL, R. E., "Thermodynamic Properties of Air: Tables and Graphs Derived from the Beattie-Bridgeman Equation of State Assuming Variable Specific Heats," ASTIA Document No. 135331.

The Beattie-Bridgeman equation of state was used to calculate several of the thermodynamic properties and flow process correction factors for air. The increase in the specific heats due to the vibration of diatomic molecules was included by assuming the molecules to be perfect harmonic oscillators. This report contains the equations used and the tabulated results of these calculations. Graphs are included to provide a general picture of the effects of temperature and pressure on the tabulated quantities. In order to illustrate the use of the tables, the calculation procedures and the results of several calculations are included. These procedures and results are for isentropic expansions and flow through normal shock waves. (Auth)

198
RASMUSSEN, R. E. H., "The Flow of Gases in Narrow Channels," NACA TM 1301 Aug. 1951.

This report deals with the measurements of the air flow, T, per second per unit of pressure difference through various channels at average pressures of from 0.00003 to 40 cm Hg. Hydrogen, oxygen, carbon dioxide, argon, and air were utilized.

The flow channels consisted of:

1. Narrow annular slits between optically plane glass plates in Christiansen prismatic devices.
2. A rectangular slit between ground and soot-blackened glass plates.
3. A cylindrical slit between coaxial cylindrical surfaces of brass.
4. A porous plate (filter plate) of sintered glass.

It was demonstrated that the flow rate T at high pressure increases linearly with the mean pressure in the channel in agreement with the laminar-flow theory. The width of the annular slits, of from about 3 to 10μ, was measured according to Christiansen's data by means of Herschel interferences; the optically obtained slit width was about 0.2μ larger than that obtained from the flow data.

At decreasing pressure, T assumes a minimum, if the mean path length is approximately equal to the slit width a; the minimum value T_{min} is approximately equal to the value obtained by Knudsen's molecule flow formula. Hence, $\lambda_{min} \simeq a$, $T_{min} \simeq T_{Kn}$; this holds for all channels with well-defined slit width and for all gases.

At further decreasing pressure, T increases again and ultimately assumes a constant value T_0, when the mean path length has become substantially greater than the length of the channel. The most accurately determined test values of T_0 are tolerably agreeable with the values obtained from Clausing's formulas by an only approximately correct application.

It was shown that the quantity $T\sqrt{M} = f_{(\lambda)}$ is approximately the same function of the mean path length for all gases for a particular channel, hence, independent of the gas. This rule may be of practical significance for determining the flow resistance of a channel for different gases within a random pressure zone.

The effect of the divergence from the cosine law on the molecule flow, identified by Knauer and Stern, was investigated. It was found that it amounts to only a few percent of the total flow.

The decrease of T from the value T_0 to T_{min} is a consequence of the collisions of the molecules.

199
RAWLINS, J. A., "Air Lubricated Thrust Bearing," U. S. Patent 2 535 454, issued 1950.

This patent is by the same inventor as 200 below. This device differs from the other in that the principle of the movable blocks, to relieve the clearance and pass off solid foreign particles, is applied to hydrodynamic, gas lubricated thrust bearings.

200
RAWLINS, J. A., "Gas Lubricated Bearing," U. S. Patent 2 511 543, issued 1950.

The patent issued describes a hydrodynamic type gas-lubricated bearing which negates the probable occurrence of failures due to dirt in the gas. This is accomplished by making the stationary block in two parts which are held by spring pressure. The excessive pressures cause the blocks to move apart. Thus foreign particles cannot become embedded and cannot therefore cause binding or scoring of the bearing surfaces.

201
REETHOF, G., "Analysis and Design of a Servomotor Operating on High-Pressure Compressed Gas," Trans. ASME, Vol. 79, No. 4, May 1957, pp. 875-885, Done at MIT - USAF Contract No. AF 33(616)-2356.

The analysis, design, and development of a high-performance gas servomechanism suitable for aircraft and missile applications is described. The flow-control valve consists of two upstream orifices of fixed areas and two differentially variable downstream orifices. The areas of the variable orifices are controlled by a simple electromagnetic actuator. The fluid motor consists of two single-acting self-lubricating pistons which actuate the rocker-arm load assembly through push rods. Design parameters were obtained from the results of an analog-computer design study. The predicted transient response agrees very well with the experimentally derived rise time of 4 millisec. (Auth)

The purpose of the paper is to demonstrate a successful approach to the design of high speed pneumatic control systems. Since gas-lubricated bearings may prove to be particularly susceptible to damage from dynamic loading, a device such as described may be of value. In any event, the analysis of flows and system characteristics are straightforward and may find application to gas lubricated bearings.

202
REINER, M., "Research on the Physics of Air Viscosity," Contr AF 61(514)-871, Library of Congress PB 122,227, (1957). Proc. Royal Soc. A., Vol. 240, 1957, pp. 173-188.

I. A Centripetal Pump Effect in Air

An instrumental arrangement is described which constitutes a centripetal air-pump. It consists of a hollow cylinder closed at the top and open at the bottom which can be brought into rotation at high speed about a vertical axis. When a receptacle filled with a heavy oil is lifted until the cylinder is partially immersed, the oil does not wet the cylinder, but an airgap is maintained between the walls of the cylinder and the oil. It can be seen that air is pumped from the outer atmosphere through this gap into the cylinder. This presupposes that the air must be in a state of stress, which includes elastic cross-stresses. It is shown that these stresses result from a stress-strain relation in which the strain is defined in Hencky's logarithmic measure. This confirms Maxwell's theory that air is an elastico viscous material possessing an elastic shear modulus, and therefore a finite time of relaxation. A rheological equation for air is proposed accordingly.

II. A Centripetal Airpump

An instrument is described consisting of two circular metal plates; one stationary, the other rotating opposite it with a very narrow gap between both. At certain high speeds the air is drawn in a centripetal direction into the gap. (Auth)

The author interprets his experimental results as being due to non-Newtonian properties in air. Taylor in discussing this paper points out that if the conclusion is correct, the Navier-Stokes equations do not adequately describe the mechanics of air flow, therefore, many of the aerodynamic investigations carried out in the past 20 years were improperly done.

Since the hydrodynamic theory of lubrication as postulated by Reynolds assumes the lubricant to be a Newtonian fluid, there is much of interest in Reiner's work and the outcome of it.

203
REYNOLDS, O., "On the Flow of Gases," Proc. of Manchester Literary and Philo. Soc., Vol. 25, 1885, pp. 55-71.

This paper contains a discussion and the correct interpretation of results noted by Wilde. The author, making use of the concept of sonic velocity at the throat of a convergent nozzle, shows that the flow of gas (air) is independent of the downstream pressure when the ratio of downstream to upstream pressure is less than a specific critical value (0.527 for air).

204
RICHARDSON, H. H., "Dynamic Analysis of Externally Pressurized Air Bearings," MIT Dept. of Mechanical Engineering M.S. Thesis, Cambridge, Mass., 1955.

A method of analyzing and understanding the dynamic characteristics of externally pressurized air bearings is presented and is applied to a specific bearing configuration.

Theoretical developments are given, leading to predictions of steady-state and dynamic characteristics of an air-journal bearing for the case when the shaft is not rotating. For the test bearing, the linearized theory, as developed, predicted within 20 percent the experimentally determined steady-state stiffness, mass flow, and dynamic response to a sinusoidal load force.

The effects of shaft rotation were studied empirically, and it was shown that the tangential slipping between the journal and sleeve surfaces produced a stabilizing effect on bearing dynamics at least up to 60,000 rpm. Thus a bearing designed to be sufficiently stable when the shaft is stationary will be more stable when the shaft is rotating.

Experimental curves of torque required to revolve an air bearing are presented for speeds up to 50,000 rpm. (Auth)

In this paper the author extends previous work (Richardson and Grinnell), to include dynamic characteristics of air bearings. In turn, this work, which includes the derivation of the "dynamic spring constant" of the bearing, leads to another contribution. Other material, suggested either by this paper or perhaps even by Richardson himself, has come from Wiese and Currie.

205
RICHARDSON, H. H., "Static and Dynamic Characteristics of Compensated Gas Bearings," Memo No. R.M. 7401-1, MIT, Cambridge, Mass., April 2, 1957, Trans ASME, Vol. 80, No. 7, Oct. 1958, pp. 1503-1509.

A static and dynamic analysis of a general configuration of a compensated gas bearing is presented for the case in which the effects of shaft rotation on performance are negligible. The equations developed can be used quantitatively, and are particularly useful in assessing the effects on static and dynamic performance of changes in design parameters such as fluid properties, compensation schemes, and geometry. To illustrate the use of the equations developed, a comparison is made between two common types of hydrostatic gas bearings - the pool bearing and the inherently compensated bearing - and a design example for a specific bearing requirement is worked. (Auth)

This is an extension of Richardson's previous work since the same equipment and original assumptions are used. This paper contains no experimental verification of the author's work, but he states that based on previous work noted above, the type of analysis used is valid. He also notes in his summary that at high values of speed the hydrodynamic effects in the fluid film can become the same order of magnitude as hydrostatic effects. (His analysis takes no account of rotational speeds.)

RICHARDSON, H. H., (121)

206
RIEGER, N. F., "Air-Lubricated Bearings: A Review of Published Work," Journal Engineering Society, Nottingham Univ., Vol. 9, 1957-8.

The author gives a concise review of work in the field of gas bearings. All of the numerous references listed are contained in this bibliography.

207
RIEGER, M. F., "An Experimental Investigation of the Pressurized Air-Lubricated Journal Bearing in the High Speed Range," Inst. Mech. Eng. 1958, Discussed Feb. 3, 1959, The Chartered Mechanical Engineer, Nov. 1958, pp. 422-423. (Summary only).

Experimental apparatus has been developed and used to study the friction characteristics of an externally pressurized air-lubricated journal bearing. The effects of variations in speed, load, diametral clearance, and inlet pressure have been studied over a wide range at high speeds. The experimental friction coefficients have been compared with those given by the well-known Petroff formula, and a reasonable degree of correlation has been found.

Bearing air consumption has been measured and a linear-relationship between air-mass flow and inlet pressure is indicated. Curves relating load-carrying capacity to various ratios of inlet pressures are included, the applied loads being carried by hydrostatic flotation in all cases.

The bearings used were plain, cylindrical bushes of diameter 1-3/8 in. and length 1-1/2 in. Compressed air was admitted through three sets of radial-inlet holes around the bush circumference, pressures being adjusted to keep the shaft and bush as close to concentric as possible. (Auth)

This report represents a comprehensive experimental investigation of the high-speed range. It has value as a guide to future designs of high-speed apparatus and as a means of verification when a full analysis of the finite, pressurized bearing is developed. (Auth - Chartered Mech. Eng.)

208
RIEGER, N. F., "The High Speed Air-Lubricated Journal Bearing," M. Eng. Sc. Thesis, Univ. of Melbourne, 1957.

(Paper not available for review as of July 1, 1959.)

209
ROBERTS, D. B., "Comparison of Experiments with Infinite Length Theory for Gas Lubricated Journal Bearings," Tech. Memo 93-69-37, North American Aviation, Los Angeles, Calif., Sept. 22, 1955.

(Technical Memorandum are prepared for internal use of North American Aviation and are not generally available.)

210
ROBINSON, C. H., F. STERRY, "The Static Strength of Pressure Fed Gas Journal Bearings, Jet Bearings," A.E.R.E. Report R/R 2642, Sept. 1958. Available British Information Services.

The operation of a jet-type hydrostatic bearing is analyzed; the analysis suggests certain parameters which are used in the presentation of experimental data. Methods of predicting the load carried by, and the flow requirements of, such a bearing are given. (Auth)

211
ROBINSON, C. H., F. STERRY, "The Strength of Pressure-Fed, Air-Lubricated Bearings," Part 1, A.E.R.E. Report ED/R-1672, Harwell, Berks, 1958.

The method of operation of an hydrostatic journal bearing is reviewed. An expression for the load carried and the gas flow from an infinitely long porous bearing is deduced, and experimental results are plotted on the basis of parameters derived from the theoretical study.

Design curves for the load and gas flow are included. (Auth)

212
ROBINSON, C. H., F. STERRY, "The Strength of Pressure-Fed, Air-Lubricated Bearings," Part II, A.E.R.E., Report ED/R-1673, Harwell, Berks, 1958.

(Paper not available for review as of July 1, 1959.)

ROBINSON, C. H., (36)(189)

213
ROBINSON, G. M., "A Special Analytical Study of Air-Lubricated Bearings for Jet Aircraft Engines," Franklin Institute Lab Final Report F-A1914, Feb. 1957, prepared for NACA under Contract NAw 6473.

Design formulae and methods for a simple step bearing were derived and bearing loads encountered in maneuvers listed in the specification MIL-E-5007A were analyzed. These analyses and formulae indicate that air-lubricated bearings may be adaptable to aircraft turbojet engines. However, large bearings, small clearances, and large volumes of air will be involved. (Auth)

This is an unpublished report for NACA having as its major objective an analytical study of the feasibility of adapting air-lubricated bearings to aircraft turbojet applications. The author derives equations for the laminar, isothermal, compressible subsonic flow of a perfect gas through a capillary, with and without momentum effects included and compares the two cases graphically. The viscous flow through thrust bearings of the flat, parallel disk type is then analyzed in a manner similar to that of Deuker and Wojtech. The flow equations which result are applied to the experimental data of Licht and Fuller and remarkable agreement (1 1/4% error) is found. The analysis and a discussion of the above are carried to simple recess type hydrostatic gas bearings.

The author includes a short section on the typical loadings to be expected on the basis of imposed specifications. This is then followed by a numerical solution for load carrying capacity and required gas flow in a bearing which might be applied. Since the hypothetical bearing was not subjected to rigorous design considerations, the author can and does discuss ways of modifying bearings to improve their performance characteristics.

As of July 1, 1959, this report was being rewritten.

214
ROUDEBUSH, W. E., "An Analysis of the Effects of Several Parameters on the Stability of An Air Lubricated Hydrostatic Thrust Bearing," National Advisory Committee for Aeronautics, TN-4095, 1957.

Equations are developed for the motion of a gas-lubricated hydrostatic thrust bearing, and solutions are obtained on a digital computer for air as the gas. Systematic investigations are made of various parameters to determine their effect on bearing stability. Bearing pad volume and rigidity appear as prime controlling factors. (Auth)

A mathematical analysis is used which permits the development of the equation of motion of the bearing. Then by actual numerical solution for particular cases the amplitudes of motion are investigated as function of time to determine if they decrease (stable condition) or increase (unstable condition) with time.

ROWAND, H. H., Jr., (71)

215
RUSTON, "Gas Bearing Circulator, Class NFB," Publication 9792 Ruston and Hornsby Ltd, Lincoln, England.

A four page piece of advertising literature on a commercial device employing gas lubricated bearings.

SAFFMAN, P. G., (256)

SAIBEL, E., (177)

216
SASAKI, R., "Research on the Air Bearing," (In Japanese) Trans. Japanese Society for the Science of Fire Arms (Kahei Gakkaishi), Vol. 37, No. 1, 1943, pp. 1-44.

Results of extensive experimentation on air lubricated bearings are given in the form of tables and graphs. (There is little or no theoretical analysis presented.) Three test rigs were employed; in the first the shaft rotates, in the second the shaft is stationary, and in the third, conical surfaces permit thrust loads to be taken (on the rig with the stationary shaft judging from sketches.) Pressure distributions were taken with one row of taps when the stationary shaft design was studied. However, with the rotatable shaft a considerable number of pressure taps arranged entirely around the bearing had to be used. Static and kinetic coefficients of friction were determined along with load carrying capacity and pressure distribution. The effect of speed on the coefficients of friction is shown in applicable curves.

This paper was published during the years of World War II in a publication which evidently has since gone out of print. As a consequence, copies of the paper are limited and not readily available. Sasaki and Mori used a pressure tap device quite similar to the one shown here. They, in their work, also make much use of the coefficient of friction in presenting their results.

217
SASAKI, T., H. MORI, and OTHERS, "Air Lubricated Bearings and Their Utilizations," (In Japanese) Journal J.S.M.E., Vol. 60, No. 463, 1957, pp. 821-827.

The Navier-Stokes equation with inertia term neglected is used to derive the expressions for pressure distribution and rate of air flow. The general formulas are given for film thickness, bearing load and flow rate for the case when film thickness remains constant. Optimum designs of air bearings are discussed. Experimental results on coefficient of friction and frictional power loss are presented.

218
SASAKI, T., H. MORI and OTHERS, "Air-Lubricated Bearings for Spinning Spindles, 1st Report," (In Japanese) Trans. Japan Soc. Mech. Engrs., Vol. 21, No. 102, 1955, pp. 131-136.

The air-lubricated bearing which operates with slight friction and little or no temperature rise because of the cooling effect of air applied to spinning spindles which usually rotate at high speeds of 8000 to 12000 rpm. In this study, as the first step of the attempt, air-lubricated bearings are applied to spinning spindles without change in design of the ordinary spinning spindle which is lubricated with oil. The performance of such air-lubricated spindles under ordinary operating conditions is compared with those of oil-lubricated spindles. Experimental results show that the frictional power of the air lubricated spindle can be reduced to about 40% of that of the oil-lubricated spindle. (Auth)

219
SASAKI, T., H. MORI and OTHERS, "Air-Lubricated Bearings for Spinning Spindles, 2nd Report," (In Japanese) Trans. J.S.M.E., Vol. 21, No. 102, 1955, pp. 137-140.

Following the research of the first report, the design of the air-lubricated bearing of the spinning spindle was modified for the intended purpose. (Originally air was used in a standard oil-lubricated spindle bearing.) The operating characteristics of the new air-bearing were determined and compared with those of the oil-lubricated and unmodified air-lubricated bearings.

The experimental results show that the frictional power (loss) for the new bearing is some 30% less than that of the oil-lubricated bearing and about 50% less than that of the unmodified air-bearing. Thus the new bearing represents a significant improvement over the earlier versions tested. (Auth)

220
SASAKI, T., H. MORI and OTHERS, "Air-Lubricated Bearings for Spinning Spindles, 3rd Report," (In Japanese) Trans. J.S.M.E., Vol. 21, No. 102, 1955, pp. 141-144.

Following the previous reports, the newly-designed spindle with a radial air-lubricated bearing and a thrust bearing made with a steel ball were investigated. Such a design of thrust bearing was chosen owing to the fact that the air-lubricated thrust bearings with conical surfaces are not sufficient to reduce the frictional power as described in the previous reports. But the design of the upper radial bearing is left the same as it was in the 2nd report, because it had good characteristics. The experimental results show that the new spindle is superior to the other spindles especially in the range of high speed rotation, and its frictional power (loss) at 12000 rpm is about 25% of that of ordinary oil-lubricated spindles, 60% of the air-lubricated spindle in the 1st report and 80% of the spindle in the 2nd report. And, moreover, by measuring the quantity of air flowing and calculating the power required to compress the air, the total power of the new spindle, that is the sum of the frictional and air-compressing power, is shown to be less than the power of the ordinary oil-lubricated spindle. This fact shows that the use of air-lubricated bearings is practical for spinning spindles. (Auth)

221
SASAKI, T., H. MORI, "Air-Lubricated Bearings with Capillary Air-Feeder Holes," Memoirs of the Faculty of Engineering, Kyoto University, Vol. XIX, No. 1, April 1957.

Capillary air-feeder holes of which each one is considered to possess the ability of two restrictions in series have been applied to air-lubricated bearings running at high speed. It has been concluded by the author that the air-lubricated bearing, having capillary air-feeder holes located in diametral symmetry, can be operated in quite a stable state and with an extremely small coefficient of friction. This friction coefficient coincides perfectly with the value calculated from Petroff's equation. (Auth)

In this article the authors consider bearings with more than one air-entry hole. The value of enlarging the capillary where it joins the bearing inner surface is discussed and the conclusion drawn that enlargement is not necessary if the proper ratio of air-entry hole radius to bearing radial clearance is used. The information presented in the paper is predominately experimental. The theoretical work is taken primarily from previous work and consists only of relatively simple mathematics with some discussion.

222
SASAKI, T., H. MORI and OTHERS, "On the Air-Lubricated Spinning Spindles, 4th Report," (In Japanese) Trans. J.S.M.E., Vol. 21, No. 102, 1955, pp. 51-54.

The experimental set-up to obtain results for this report is similar to that described in Report No. 3. Graphs are given to show the frictional power loss and power required to supply the compressed air for lubricating the spindles at various air pressures and speeds. In comparison, it is shown the total power loss (frictional loss plus power to operate air compressor) is substantially less than that of an oil-lubricated spindle. The modified design gives improvement in performance over the one in Report No. 3.

223
SASAKI, T., H. MORI, "On the Characteristics of Air-Bearing," Memoirs of the Faculty of Engineering, Kyoto University, Vol. XIII, No. 1, Jan. 1951.

This is an experimental study of some of the factors effecting the performance of externally-pressurized air bearings. In one section the authors describe three means of determining the friction in the bearing and then use one or more of these methods in their experimental program. They measure friction values for various bearing pressures for two types of air inlet holes. These data are plotted in suitable curves. For all other curves the minimum friction value, (described in 225) is used when applicable. Among the factors investigated are bearing length, speed, clearance and angle of air inlet opening. Since curves of friction versus speed at various diametral clearances are shown for both air and oil lubricated bearings, a direct comparison can be made if desired.

The second part of the paper is devoted to the determination of air flow and pressure distribution in the bearing. The bearing shell used in these experiments had pressure taps arranged every 30° around the circumference at specified distances in the axial direction. From the results the authors conclude that air flows into the bearing at the sonic velocity. This knowledge is then used to determine the air flow, the value of which agrees with that measured.

This is the authors' English version of a Japanese paper and one of the things one notes about their writing is the lack of a "summary" or "conclusions" which most of us are accustomed to. Their work appears to be quite well done with only minor bits of information missing. There is no attempt to relate the experimental results with any theory except very briefly in the case of air flow determination. The entire article could be summed up as a presentation of experimental results with insufficient written matter to exploit what was done.

224
SASAKI, T., H. MORI, "On the Characteristics of Air-Lubricated Bearing (Succeding Report)," Memoirs of the Faculty of Engineering, Kyoto University, Vol. XVI, No. II, April 1954.

The author states that it becomes possible to increase dynamic stability of the air-lubricated bearing and to reduce frictional resistance, when the air supply pressure from the air compressor and the cross-section area of the primary restrictor are properly designed and treated in relation to bearing conditions. (Auth)

This is one of a group of papers on air bearings by the same authors. In this as in other papers, they use two restrictors in series and determine the supply pressure and section areas by a minimum friction concept which is explained in detail in another paper. Since this article is related so closely with others of the group they could properly be read together.

225
SASAKI, T., H. MORI, KONDO, SATO, "On the Effects of a Restrictor before the Air-Hole of an Air-Lubricated Bearing," (In Japanese) Trans. Japan Soc. Mech. Engrs., Vol. 20, No. 90, 1954, pp. 105-108, Translated by C. Kim, Franklin Institute Laboratories, Phila., Pa., Sept. 1957.

It is generally known that the air-flow between the air-hole and the bearing clearance of the air-lubricated bearing is equivalent to the air-flow through a nozzle. In this case, when a restrictor that corresponds to the air-hole and bearing clearance is set before the air-hole, the pressure in front of the air-hole will increase or decrease with the decrease or increase of the bearing clearance, (in the same manner as the gage pressure in the high pressure type pneumatic gage), and then the eccentric motion of shaft will be controlled automatically. The effect of a restrictor before the air-hole was studied by measuring the coefficient of friction, and the optimum cross-sectional area of the restrictor. From this the air-supply pressure was determined. (Auth)

The authors' suggestion of determining the required air supply pressure on the basis of the minimum coefficient of friction is rather novel and interesting but as is pointed out, applicable primarily to systems with relatively light loads.

226
SASAKI, T., H. MORI, and OTHERS, "Research on the Air Bearing, 1st Report," (In Japanese) Trans. J.S.M.E., Vol. 17, No. 59, 1951, pp. 49-53.

Experimental results are presented on air-lubricated journal bearings; one with a radial air inlet and the other with an air inlet making an angle of 40° with a diameter of the journal. Relations between two of the four parameters: speed of journal, coefficient of friction, air pressure and bearing clearance, are plotted in graphs. In estimating the coefficient of friction Karman's formula is used to calculate the air resistance. (Auth)

227
SASAKI, T., H. MORI, and OTHERS, "Research on the Air Bearing, 2nd Report," (In Japanese) Trans. J.S.M.E., Vol. 17, No. 63, 1951, pp. 16-21.

In this report, the coefficient of air-bearing friction measured by the pendulum method and the pressure distribution investigated mainly for the state of minimum friction, are described. The coefficient of friction can be reduced to minimum on the order of 10^{-3} for each bearing load by adjusting air supply pressure and this minimum value becomes larger with decrease of bearing clearance and increase of rotating speed. The pressure is distributed almost symmetrically with respect to the line of the air inlet hole, and no influence of rotating speed and bearing length are seen for the pressure distribution. By measuring the quantity of flow and from theoretical considerations it is shown that the operating state corresponding to the minimum friction is non-eccentric rotation and the maximum air velocity at the outlet of the air inlet hole is the velocity of sound. (Auth)

228
SASAKI, T., H. MORI, and OTHERS, "Research on the High Speed Air-Bearing and on the Influence of Inlet Holes for the Air-Bearing," (In Japanese) Trans. J.S.M.E., Vol. 18, No. 74, 1952, pp. 51-56.

In the 1st and 2nd reports of research on the air-bearing, we discussed the measurement of the coefficient of air-bearing friction by the damping method with rotating disc, and the pendulum method, but the former was not suitable for high speed rotation, and the latter contained some error due to the moment caused by the air supply rubber tube. In this report, therefore, by making a newly designed balanced beam tester using a zero-setting method, we measured, accurately, the coefficient of air-bearing friction for the state of high speed rotation (12,500 rpm), and investigated the influence of bearing length and inclined angle of air inlet hole comparing it with the half (180°) air-bearing. The coefficient of air-bearing friction can easily be made of 10^{-3} order by adjusting the air supply pressure for the high speed rotation of 12,500 rpm, but then the air pressure is required to be higher. The half bearing is superior to the full-circle bearing for stability with varying bearing load, but it is inferior in terms of frictional resistance, supply pressure, and quantity of flow. (Auth)

229
SASAKI, T., H. MORI, and OTHERS, "Research on the High Speed Air-Bearing and on the Influence of Inlet Holes for the Air-Bearing," (In Japanese) Trans. J.S.M.E., Vol. 18, No. 74, 1952, pp. 56-61.

In the paper, "Research on the Air-Bearing (2nd Report)," we stated that the air-flow through air supply inlet hole has large effects upon the air-flow in the bearing clearance and consequently influences the frictional characteristics. In this paper we proceeded with the study of the air-flow just after the jetting-hole by measuring air pressure distribution under the low pressure of air supply; and varying the form and dimension of the inlet hole we inspected their influences on the frictional characteristics and the quantity of flow. Thus, it was shown that making the air supply slot longer along the axis of the shaft has more effect in reducing the frictional resistance than making the diameter of the air supply hole larger, and the flowing quantity is proportional to the product of periphery length of air hole, bearing clearance at the inlet and absolute pressure of supply air. Based upon the above considerations, we revised the formula of the air-flow for air-bearing described in the 2nd report. (Auth)

230
SASAKI, T., "Theories of Pressure Distributions, Quantities of Flow and Restrictions in Air-Lubricated Bearings," (In Japanese) Presented at Annual Meeting Japan Society of Mechanical Engineers, April 3, 1958.

For constant viscosity and film thickness Reynolds' equation reduces to Laplace's equation from which the solution for pressure distribution is obtained by using a function of a complex variable and conformal mapping. The effect of compressibility is discussed.

231
SASAKI, T., H. MORI, "Theory of Journal Air-Bearing," (In Japanese) Trans. Japan Soc. Mech. Engrs., Vol. 19, No. 86, 1953, pp. 45-48. Translated by C. Kim, Franklin Institute - Laboratories, Phila., Pa., Sept. 1957.

In the (hydrostatic) journal air-bearing, air supplied from either a single or multiple hole air-inlet, flows radially into the bearing clearance at first. It then flows longitudinally and lastly outwards from the ends of the bearing. Therefore, a three-dimensional analysis is necessary when the air-bearing is studied theoretically. In this report, analytical investigations were made for the condition of non-eccentric rotation. This is important because it corresponds to the condition of minimum friction. Then the solution of the hydrodynamic equation was obtained by considering that the air flow corresponding to the condition of non-eccentric rotation, is equivalent to the two-dimensional potential flow. The theoretically obtained results coincide moderately well with the experimental results. This solution can be applied to the case of multiple air-holes. (Auth)

In this, as in their other work, the authors proceed slowly but thoroughly. The mathematical analysis is made with the aid of a suitable transformation into the complex plane. The solution of Reynolds equation arrived at for pressure distribution is then modified to permit the use of additional inlet holes. The theoretical results agree with the experimental ones determined with a special bushing containing a sufficient number of pressure taps arranged both circumferentially and axially to give desired information.

SATO, C., (225)

232
SCHEINBERG, S. A., A. M. KHARITONOV, "Aerodinamicheskie opory dlia vysokoskorostnykh dvigatelei i turbin (Air Lubricated Bearings for High Speed Motors and Turbines)," Vestnik Mashinastroenia, Vol. 38, No. 9, Sept. 1958, pp. 14-17.

Description of a high speed rotor with air lubricated bearings successfully tested in laboratory and industrial conditions, in the latter as an internal grinding head. The head assures high quality grinding and high efficiency. Design and manufacturing details.

233
SCHEINBERG, S. A., "Gazovala Smazka Podchipnicov Scoljenia (Gas Lubrication of Sliding Bearings)," Treniei Iznos v Machinakh Izd. Akad. Nauk. USSR, 1953, Vol. 8, pp. 107-204, Translated by C. Demrich; Edited by M. Wildmann. May be available from John Crerar Library.

In the present work the fundamental problem of gas lubrication (self-acting bearings) is examined and the theory of establishment of the lubricating layer described. In Chapter I there is derived, on the basis of the study of the lubricating characteristics of gases, the equation of spatial flow of a gas lubricant. Chapter II is devoted to the solution of the problem of the lubrication of bearings of infinite length, that is, the plane problem. In Chapter III the obtained solutions are extended with the help of certain assumptions to real bearings of finite length. In Chapter IV, finally, there is described the method of calculation of gas lubrication of bearings, and its results are verified experimentally. (Auth)

234
SCHEINBERG, S. A., "Experimental Investigation of Aerodynamic (Sliding) Bearings," (In Russian) Friction and Wear in Machines, Publication No. 6, Academy of Sciences of the USSR, Institute of Machine Construction, Moscow, 1950, pp. 182-299.

The first portion of the paper explains briefly the principles of operation and design of gas bearings. Later the experimental program is discussed including the methods and apparatus for determining film thicknesses, pressures and speeds. The experiments conducted on journal and thrust bearings are then described. The results obtained in these tests are compared with those from theoretical investigations.

235
SCHEINBERG, S. A., "On the Question of Gaseous Lubrication of Rotating Shafts," (In Russian) Part 8 released April 2, 1945, pp. 175-206. The source of this paper cannot be determined. Copies are on file in the Friction and Lubrication Branch, The Franklin Institute - Laboratories, Phila., Pa.

In Chapter I the theory of the plane slider bearing is developed. In Chapter II the experimental apparatus is described, the description includes that of each individual item such as galvanometer, stroboscope etc. In Chapter III the pressure distribution in the air film is discussed.

The apparatus and arrangement of the experiment are given. In Chapter IV the method of measuring friction torque and the results of experimentation are presented. In Chapter V the load carrying ability expression for air lubricated journal bearings is derived. The seventh and last chapter deals with industrial applications of air bearings.

SCHEINBERG, S. A., (14)

236
SCHNEE, M., E. J. WOHL, "Study of Fatigue Evaluation Procedures for Electron Tubes," Lab Proj. 5032-B-3.14, Prog. Dept. 14, NE 091105, Oct. 11, 1956. Materials Lab., N. Y. Naval Shipyard, Brooklyn, N. Y.

Progress on a related Material Laboratory investigation which concerns the development of a novel shaker (in rudimentary form), permitting wide frequency range vibration and possessing little transverse sensitivity, is reported. Preliminary results indicate that 3/16" excursion of a (linear air bearing supported) 15 pound table is possible with as little as 10 watts at 10 cps. (Auth)

SCHULZE, G., (196)

237
SCIULLI, E. B., "A Bibliography on Gas Lubricated Bearings," The Franklin Institute Labs, Interim Report I-A2049-1, Dec. 1, 1957, Contract Nonr-2342(00), Task NR 097-343, ASTIA No. AD 147 733.

This bibliography is the result of an extensive survey conducted as one phase of a research program sponsored by ONR, in conjunction with other government agencies, to establish a technology for gas-lubricated bearings. The purpose of the survey was to evaluate the present state of the art and to establish a library of applicable technical papers to serve as ready references of work done in this field.

In order to include all the pertinent material available on gas-lubricated bearings it was necessary to review some literature from countries other than the United States. The bulk of this literature, primarily from England, France, Germany and Japan is obtainable in this country.

The entire contents of this report have been absorbed into the present bibliography.

SERRANNE, H., (109)

238
SERDUKE, J. J., R. O. WEBSTER, "High Speed Bearing and Turbine," U. S. Patent 2 602 632, issued 1952.

The invention is a high speed bearing and turbine with a short shaft rotor. The turbine buckets are cut in the side of the rotor so that the impinging air constitutes a stablizing force similiar to that described by Brewster.

239
SEYFFERT, M., "Air Bearing Apparatus," U.S. Patent 2 671 700, issued 1949.

This invention appertains to novel and useful improvements in devices for use in fine measurements, close tolerance working and the like. It provides gas lubrication in rotary and thrust bearings for drills, buffers, polishing, and grinding machines which operate at exceedingly high speeds. (Auth)

240
SHAW, M. C., E. F. MACKS, "Analysis and Lubrication of Bearings," McGraw Hill, N. Y., 1949, Sect. 8-13, pp. 329-332.

Contains a brief mention of gas lubricated bearings.

241
SHIRES, G. L., "Experiments with an Air Lubricated Journal Bearing," National Gas Turbine Establishment Memorandum No. M. 49, May 1949.

Using a 2-inch diameter bearing, air is introduced through either a central ring of holes or two rings of holes placed symmetrically about the center of the bearing in the axial direction. The effect of straight and flared inlet holes was determined as was the effect of diametral clearances. The holes were also connected by grooves and the effect noted. Among other variables chosen were speed (found to have a negligible effect on hydrostatic pressure distribution, up to surface speeds of 100 ft./sec) and asymmetrical loading. Measurements were also made of mass flow and pressure distribution for various radial loads.

A 4-inch diameter (static) bearing with an eccentric stub on each end of the journal was used to obtain pressure distributions. Flow streamlines are shown in two photographs taken with the aid of oil as the fluid.

242
SHIRES, G. L., "On a Type of Air Lubricated Journal Bearing," National Gas Turbine Establishment Report No. R. 61, Nov. 1949, also available as AERO Research Council Current Paper 318, London 1957.

Experimental journal bearings have been constructed which will support a radial load when supplied with air at high pressure. The principles of this type of bearing are discussed, and some of the available experimental data analysed. The results are collated in terms of a non-dimensional parameter based on the theory of viscous flow between two adjacent surfaces and by this means are extrapolated to give performance figures for bearings outside the range of the experiments. The estimated performance is then compared with that of conventional bearings, and conclusions are drawn regarding possible applications of this type of air lubrication. (Auth)

In the introduction, the author states that the theoretical solution of the load-carrying capacity of journal bearings, based on viscous flow theory, yielded values which were optimistic. It became necessary, therefore, to consider the problem in greater detail. The greatest detriment in the course of the experiments reported seemed to be complications of flow at the inlet holes. However, tests were conducted and empirical factors deduced from the data.

In the appendix the effect on the bearing of Reynolds' number, temperature, and centrifugal forces are each considered separately.

243
SHIRES, G. L., "The Viscid Flow of Air in a Narrow Slot," Memorandum No. M. 46, Dec. 1948, National Gas Turbine Establishment, Re-issued with Addendum as Aeronautical Research Council Current Paper, No. 13, 1950.

The properties of the viscous flow of air in a rectangular slot having a width large in comparison with its depth was investigated. The results of various tests are found to verify theoretical and empirical relationships between the pressure distribution in the slot, the air mass flow and temperature, and the slot dimensions. Both laminar and turbulent flow are considered. (Auth)

Flow experiments using air were performed with slots of various shapes (3) and the results expressed in the terms of the parameters λ and Re. These were then compared with the results of experiments with incompressible fluids carried out by Blasius. The author reports that for laminar flow, the value he found for the resistance coefficient, λ, compares favorably with that for incompressible fluids. However, for turbulent flow the values of λ given by Blasius are not, in general, applicable.

244
SIXSMITH, H., "Air Bearing for High Rotational Speed," <u>Machinery</u>, Vol. 90, June 21, 1957, p. 1418.

A brief article describing the bearing developed by Sixsmith.

245
SIXSMITH, H., "The Theory and Design of a Gas Lubricated Bearing of High Stability," Doctoral Thesis, Reading Univ, Reading, England.

The author designed (and later patented) a bearing having cavities leading to restricting orifices through which the gas need flow before leaving the bearing. According to the author, the pressure build-up in the pocket as the eccentric shaft approaches it is sufficient to combat the tendency of the shaft to whirl. Even at extremely high rotational speeds the shaft appears to be quite stable.

246
SLATER, J., "Gas Spin Bearings for Gyroscopes," <u>Military Systems Design</u>, May-June, 1959, pp. 138-139.

A brief discussion is given of the application of gas bearings to gyroscopes and the advantages of these bearings over rolling element bearings. The work on which this article is based is attributable primary to J. S. Ausman, M. Wildmann et al.

247
SLATER, J. M., V. A. TAUSCHER, "Zonal Ball-Air Bearing," U. S. Patent 2 617 695, issued 1952.

A zonal ball air bearing is described. The supported member "floating" between spherical seat bearings. Jeweled orifices, which are available commercially, are used in the design.

SLATER, J. M., (50)

SODA, N., (149)

248
STERNLICHT, B., R. C. ELWOOD, "Theoretical and Experimental Analysis of Hydrodynamic Gas-Lubricated Journal Bearings," Trans. ASME, Vol. 80, No. 4, May 1958, pp. 865-878.

This paper presents a numerical solution for finite width journal bearings and results of experiments conducted with air-lubricated hydrodynamic journal bearings. Comparison is made between theoretical and experimental results. Design formulas and recommendations for future studies also are included. (Auth)

From the Navier-Stokes equation and the continuity equation for compressible fluid flow, the authors write Reynolds' differential equation for hydrodynamic lubrication in two dimensions and convert it to a dimensionless form. The resulting equation is first written as a difference equation from which an expression is then obtained for the pressure at the center of any grid element, for solution on a digital computer. The authors then discuss the desirability of maintaining a general pressure-density relationship involving the exponent δ. However, to expedite calculations, this relationship is simplified by investigating only the isothermal case, $\delta = 1$. Theoretical and experimental results are presented for full journal bearings and correlation appears to be good for eccentricity ratios below 0.7. The solution of the original equation is promised for a later paper.

STERNLICHT, B., (162)

STERRY, F., (39)(174)(175)(210)(211)

249
STONE, W., "A Proposed Method for Solving Some Problems in Lubrication," Commonwealth Engineer (Australia), Vol. 9, 1921, pp. 115-122, 139-149. Available - Library of Congress.

This is a rather famous paper dealing with an experimental verification of Michell's theories of the action of thrust bearings. The apparatus was made of glass and the thrust shoes were fabricated from transparent quartz crystals. Air was the lubricant. Since the lubricating films were very thin and the angle of inclination small, they were measured by employing interference bands by passing sodium light through the apparatus. The author suggests that this method might be applied to cylindrical bearings. Considerable data are presented on speeds, loads, film thickness and angle of inclination of the blocks. Typical data show slopes varying from a minimum of 0.137 minutes to a maximum of 1.93 minutes and mean film thicknesses varying from a minimum of 113×10^{-6} cm to a maximum of 1290×10^{-6} cm. Correlation between fact and theory is good.

There is an extended discussion on aspects of instability that were observed with certain of the test blocks. The author has studied these factors extensively and presents theory and data with the hope that certain problems may be solved that are associated with the application of air or other gases to the lubrication of machinery bearings.

250
STONER, G.H., "Air Bearing Gyroscope," U.S. Patent 2 474 072, issued 1949.

The invention is for gyroscope application and eliminates the need for a gimbal ring when the spin axis requires freedom only within a cone of ± 20° from the axis of the mount. The gas, introduced through a fixed hollow shaft with a ball at its end, enters an air chamber from which some escapes through "Bernoulli passages" formed by the ball and adjacent corresponding spherical surfaces formed in the wheel or rotatable member. The balance of the gas produces the rotation by escaping to the atmosphere through properly angled propulsion jets located in the periphery of the gyroscope. The best clearances for the Bernoulli passages (bearing film thicknesses) are said to depend in part upon the particular design and the conditions of operation, and for optimum operation are best determined by experimental means.

251
SUGIMOTO, Y., "The Theory of Air Bearings," (In Japanese) Trans. JSME, Vol. 17, No. 63, 1951, pp. 12-15.

The air bearing will run without the so-called lubricant and the friction is very low. In this paper, I dealt with, from a purely theoretical point of view, the use of air to diminish the friction between bearing surfaces without any conventional lubricant.

In conclusion, air bearing is employed generally for high speed and light load.

The fundamental equation for air bearing is:

$$\frac{\partial}{\partial\theta}\left\{\rho\frac{\partial p}{\partial\theta}(\alpha+\cos\theta)^3\right\}+R^2\frac{\partial}{\partial z}\left\{\rho\frac{\partial p}{\partial z}(\alpha+\cos\theta)^3\right\}=\frac{6\lambda U}{m^2R}\frac{\partial}{\partial\theta}\left\{\rho(\alpha+\cos\theta)\right\}$$

where p is the pressure of air in bearing clearance, α is the eccentricity, ρ is the density of air, R is the radius of journal, λ is the viscosity of air, U is the linear velocity of sliding surface, mR is the distance between shaft center and bearing center, θ is the angle of coordinates, and z is the axis of coordinates. (Auth)

SUGIMOTO, Y., (181)

252
"Supersonic Compressor," Sulzer Technical Review 3, 1958, pp. 62-65.

An industrial concern, Sulzer, in Switzerland has built a high speed compressor in which the bearings are lubricated with the gas being pumped.

253
TAFT, H., G. LILLIE, "Experiments with an Externally Pressurized Air Bearing," Bryant Chucking and Grinder Co., Research and Experimental Report No. 23, Springfield, Vt., 1950.

This is the first of a series of internal reports of experimental work done at Bryant Chucking and Grinder Co. on externally pressurized air-lubricated bearings. Using two opposed, static, parallel plate, thrust type bearings, the authors investigated the effect of bearing clearance, and number of air inlet holes, as well as the length and diameter of the holes. The results are plotted as load versus deflection for various supply pressures (20 to 50 psi). The work is summarized for 50 psi in three plots of "Maximum Bearing Modulus" versus each of the variables.

254
TAFT, H., G. LILLIE, "Experiments with an Externally Pressurized Air Bearing," Bryant Chucking and Grinder Co., Research and Experimental Report No. 24, Springfield, Vt., 1950.

This is the second in a series of internal reports of experimental work done at Bryant Chucking and Grinder Company on externally pressurized air bearings. For purposes of this report a simple, single, thrust type bearing was used both with and without a recess or pressure pool. Investigation was made on the effect of internal and external resistances and pool depths. The information gained was then applied to a journal bearing, which did not function as well as was expected. A series of modifications and additional tests resulted in a bearing which appeared to give satisfactory performance.

255
TAFT, H., G. LILLIE, "Experiments with an Externally Pressurized Air Bearing," Bryant Chucking and Grinder Co., Research and Experimental Report No. 25, Springfield, Vt., 1950.

This is the third in a series of internal reports on experimental work done at Bryant Chucking and Grinder Company on externally pressurized air bearings. This report covers a series of static tests to obtain load deflection values for plotting graphs of a number of designs of cylindrical externally-pressurized air lubricated bearings for the purpose of determining approximately optimum designs for a wheelhead to be used in actual grinding tests. (Auth)

The authors tested the performance of a number of designs of pool type bearings (various pool depth and bearing lengths, etc.) using the slope of the load-deflection curves as the basis of comparisons. It would seem from their report that they were entirely satisfied that they had achieved a near optimum design of a bearing for a specified purpose.

TANIGUCHI, O., (184)

256
TAUSCHEP, V. A., J. M. SLATER, J. EMMI, "Double Ball Gyro Precession Axis Bearing," U. S. Patent 2 644 727, issued 1949.

An externally pressurized gyroscope type, spherical, gas lubricated bearing is proposed. One difference from previous bearings is the use of "high pressure" (80 psi) air.

TAUSCHER, V. A., (247)

257
TAYLOR, G. I., P. G. SAFFMAN, "Effects of Compressibility on Air Flow at Very Low Reynolds' Numbers," Journal of the Aeronautical Sciences, Vol. 24, No. 8, Aug. 1957, pp. 553-562.

This paper is a discussion of Reiner's paper, "Research on the Physics of Air Viscosity". In it, Taylor mentions the possibility of occurrence of two conditions which could have influenced Reiner's experiments.

(1) The effect of slight errors in the perpendicularity to the axis of rotation of either the stator or the rotor, and

(2) The effect of rotor vibration in the axial direction.

Taylor then goes on to show mathematically that, with an incompressible fluid between the platen, neither the tilting action nor vibration could cause a pressure rise of the magnitude which Reiner observed. On the other hand, with a compressible fluid between the plates, either the tilting action, or vibration, or a combination of the two could account for the results noted by Reiner.

A discussion "On the Reiner-Taylor-Saffman dilemma," by M.Z.V. Krywoblock, appears on pp. 915-916 of the December 1957 issue of the Journal of the Aeronautical Sciences.

258
TIPEI, N., "Consideratii Asupra Calculului Lagarelor Prin Alunecare, (Methods of Calculation for Sliding Bearings)," Bul. Stiint. Acad. R.P.R., Sectinuea de Stiinte Technice Si Chimice, 1952, 4, 3-4, 291.

(Paper not available for review as of July 1, 1959.)

259
TIPEI, N., "Ecuatiile Lubrificatiei cu Gaze (The Equations of Gas Lubrication)," Comunicarile Acad. R.P.R. Bucharest, 1954, Vol. 4, No. 11-12, pp. 699-704.

(Paper not available for review as of July 1, 1959.)

260
TIPEI, N., "Hidro-Aerodinamica Lubrificatiei (Hydro-Aerodynamic Lubrication)," Biblioteca Stiintelor Tehnice, Editura Academiei Republicii Populare Romine, Bucharest, 1957.

The bulk of this 695 page book is devoted to the development of mathematical expressions in the theory of lubrication with incompressible fluids; only the last 65 pages deal with gaseous lubricants. However, the work contained in the document is so extensive and so complete that experts in the field of lubrication consider it one of the best books on lubrication published to date.

The reader may note a similarity in titles of papers on gas bearings by Constantinescu and chapter subheadings in this book. Being a former student and presently a colleague of Tipei, Constantinescu would be expected to write and possibly extend the work already done.

The book is currently being translated from the Rumanian to English through the efforts of Dr. W. A. Gross of IBM and will be made available probably late in 1960.

261
TOPANELIAN, E., JR., "Journal Bearing," U. S. Patent 2 696 410, issued 1954.

A porous material is made to form the bearing shell and one of the mating thrust surfaces. The lubricant, either gas or liquid is forced through the porous medium which, being tortuituous, offers a high resistance to flow and the effect is the same as having an infinite number of orifices. As described, the bearing has self-centering capabilities such as orifice-type bearings would have.

TSAI, D. H., (159)

TYLER, C. M., JR., (71)

262
VANCE, M. D., "The Characteristics of a Multi-Orifice Journal Air Bearing," Curtiss Wright Corp., Report No. 49-6, also ASTIA, ATI 56 113.

A compilation has been made of experimental data illustrating the characteristics of a multi-orifice journal air-bearing relative to stiffness and load capacity. (Auth)

As the author states, this report contains experimental data. However, no firm conclusions are drawn and the paper proves to be merely a presentation of extensive data in appropriate curves. For practical purposes it appears to have value for only the type of bearing that was investigated.

263
VAN DEVENTER, J. H., "Counterbalanced Bearing," U. S. Patent 1 070 088, issued 1913.

In engines of the twin rotary type, (compressors), the impactive and expansive force of the motive fluid supplied to the engine is brought to bear at one side of the rotors. This produces an excessive lateral thrust on the rotors and causes the bearings which carry the same to wear unevenly.

The general object of this invention has been: to provide a bearing which shall utilize the pressure of the fluid supplied to the engine to counterbalance the lateral thrust caused by the fluid entering the rotors of the engine. (Auth)

The engine is adapted to be driven by steam. However, steam, compressed air, or any fluid under pressure may be used for motive power and for the bearings.

VIAL, P. F., (27)

VIEWEG, R., (114)

264
VITELLOZZI, W. J., "Report of an Investigation on Water and Steam Lubricated Bearings," EES Report, C-3229-C NS-633-008, 9 June 1950, ASTIA No. AD 147 283.

Journal bearings using steam or water for lubrication will find wide application in turbines, pumps, and other rotating machinery. The use of this type of bearing and lubricant would permit the design of exceedingly compact and reliable machinery. Immediate saving in weight and space would result through the elimination of seals, glands, lubricating oil sumps, pumps, coolers, filters, strainers, and piping.

This report covers the results of preliminary work in the development of journal bearings for service with steam or water lubrication.

To date, various materials have performed satisfactorily with water lubrication. Under steam lubrication, however, only one class of bearing material, namely, silver impregnated carbon, has shown promise of satisfactory performance.

The report concludes with the recomendation that this investigation continue, using the materials found satisfactory to permit establishment of material specifications and engineering designs. (Auth)

265
VOGELPOHL, G., "Betriebasichere Gleitlager, Berechnungsverfahren fuer Konstruktion und Beitrieb (Sliding Bearings Calculations and Design for Safe Operation)," Springer, Berlin 1958 for "Air Bearings," pp. 120-121, 128-129.

(Book not available for review as of July 1, 1959.)

VOGT, P. R., (192)

266
WALLOGREN, A. G. F., "Bearing," U. S. Patent 2 113 335, issued 1938.

A description is given of a bearing within a bearing to be used principally where inaccuracies in alignment may occur. The shaft is contained in a gas-lubricated bearing which in turn is part of a cardan ring; the entire cardan ring unit being free to move within a second bearing shell.

267
WEBER, R. R., "Investigation of Dynamic Response of Hydrodynamic Gas Bearings," U.C.L.A., MS Thesis, Los Angeles, Calif. 1952.

The author starting with the Navier-Stokes equation in vector notation, transforms it to cylindrical coordinates, makes various assumptions and introduces his boundary conditions to arrive at the equation for flow between flat parallel disks. At this point he introduces a density term and solves for the pressure distribution in the bearing showing it to be approximately linear across the sill (recess pressure to atmospheric pressure). Using this relationship, an expression for load carrying capacity is found. The equation for weight flow through the bearing is then equated to the weight flow through an orifice and after constant temperature is assumed, the film thickness is determined. The work is then applied to a discussion of opposed pad bearings.

Considering only the steady state parameters, the author imposes limits on the minumum operating gap and applies a forcing function ($X = A \cos \omega t$). The spring rate function is approximated by typical functions and the coefficients determined by a curve fitting technique. Laplace transforms are then employed, to arrive at Duffing's equation, which can be solved by a method of successive approximation.

The restrictor (orifice) is "blamed" for certain departures between theoretical and experimental data.

The author concludes from his work that the compressibility effects of the gas trapped in the bearing can be considered negligible for low frequency oscillations, and the dynamic response to oscillatory loads may be predicted on the basis of steady state characteristics.

268
WEBER, R. R., "The Analysis and Design of Hydrodynamic Gas Bearings," North American Aviation, Inc., Report AL-699, 1949, Los Angeles, Calif.

This report presents the fundamental theory of operation of single-disc pad, and journal types of gas bearing supports from the standpoint of gas consumption and load-carrying ability. An attempt has been made to illustrate the optimum or desirable values for the different bearing parameters. Two typical examples, a spherical bearing with four pads and a journal bearing, have been worked out to illustrate the design techniques which were developed. (Auth.)

The author, in a rather neatly prepared paper, carries the reader in a step process from the analysis of flow between parallel plates, eventually to the design of two types of externally pressurized gas-lubricated multipad bearings. His brief treatment of the preload effects on the spring rate of opposed bearings is made clearer by the use of suitable sketches and, as yet, has not been discussed elsewhere in the gas bearing literature.

Journal bearings are treated as a series of rectangular pads. The momentum effects are considered negligible as is the tangential flow (between pads.) Since the entrance pressure of the gas and the film thickness, h, depend on the location of the journal in the bearing, the necessary equations are derived relating bearing inlet pressure, eccentricity and angular position of the gas inlet. The load-carrying ability of the bearing is then obtained.

Having dealt with the principles of bearing operation, attention is then directed to the design considerations with emphasis being placed on minimum power required or minimum gas consumption. The two examples given, the design of a 4-pad supported sphere and the design of a journal bearing, contain numerical solutions.

WEBER, R. Ŕ., (192)

WEBSTER, R. O., (238)

WEDGE, T., (83)

269
WEIR, A., J. L. YORK, R. B. MORRISON, "Two and Three Dimensional Flow of Air through Square Edged Sonic Orifices," ASME Paper No. 54-A-112.

In this investigation, the two-dimensional flow of air through rectangular and the three-dimensional axisymmetrical flow of air through circular, square-edged sonic orifices was examined under pressure ratios ranging from 1.894 to 42.0 (upstream stagnation pressure/downstream static pressure). Mass flow measurements were made using a primary metering system, rather than another orifice or nozzle. Optical techniques were used to obtain pictures of the flow upstream, within the thickness of the orifice plate, and downstream of the orifice. Evidence is presented in this paper which indicates that square-edged sonic orifices can be treated as sonic nozzles by utilizing the concept that the air "turning the corner" of the orifice plate, in effect, makes its own nozzle. It is believed that this interpretation of experimental observations is in full agreement with established principles of aero-and thermodynamics. (Auth)

270
WEIR, J. G., "Selected Bibliography on Precision Instrument and Fluid Bearings with Annotations," Materials Report No. 48 pp 28-35, U. S. Naval Avionics Facility; Indianapolis, Indiana, 3-14-57

This bibliography is the result of an extensive survey of the entire field of precision instrument ball bearings and fluid bearings. The survey was made to evaluate the current state of the art as one phase of a bearing research program. The bibliography is intended to include all material pertinent to precision instrument ball bearings and fluid bearings. The material included on jewel bearings is less complete. (Auth)

The section on fluid bearings, pp. 28-35, contains references on gas lubricated bearings. These references are included as part of this bibliography.

271
WELANETZ, L. F., "A Suction Device Using Air Under Pressure," Journal of Applied Mechanics - Trans. ASME, Vol. 78, June 1956, pp. 269-272. Discussion March 1957.

An analysis is made of the suction holding power of a device in which a fluid flows radially outward from a central hole between two parallel circular plates. The holding power and the fluid flow rate are determined as functions of the plate separation. The effect of changing the proportions of the device is investigated. Experiments were made to check the analysis. (Auth)

Welanetz gives a more elaborate treatment to the problem first attacked by Willis in 1828. Using the general energy equation of steady flow and accounting for the various energy losses along the path, he derives the equations describing the characteristics of the device. He then attempts to verify his theory by experiments. Failure of the theoretical and experimental results to agree is attributed by the author to flow separation occurring at the transition from the small tube to the space between the plates (see Paivanas.)

In his closure, after Zaid's discussion Welanetz also notes the possibility of shock waves occurring. The effect of this and other factors such as the compressibility of air are not included here in what the author refers to as a simple theory.

272
WESTINGHOUSE, G., "Vertical Fluid Pressure Turbine," U. S. Patent 745 400, issued 1904.

In a vertically mounted steam turbine, the vertical load is supported by the pressure of atmospheric air (or compressed air). The necessary pressure differential results from a partial vacuum caused by condensing the steam used to drive the turbine.

In this design, as in many of that date, no attempt was made to "design" an externally pressurized bearing of the types generally in use today (circa 1959). In general, use was made of the load carrying ability of a constrained volume of pressurized fluid with little attention paid to flow. The other extreme was to use the push effect of change in momentum directly over the fluid issuing from a jet.

273
WHIPPLE, R. T. P., "Herringbone Pattern Thrust Bearing," A.E.R.E., T/M 29.

(Paper not available for review as of July 1, 1959.)

274
WHIPPLE, R. T. P., "Theory of the Spiral Grooved Thrust Bearing with Liquid or Gas Lubricant," Atomic Energy Research Establishment T/R. 622, 1951.

The stated object of this paper was "to calculate the thrust for the spiral groove thrust bearing, and to find the optimum shape of the grooves at low speed." This type of bearing uses constant-depth grooves cut into the surface of a circular plate to generate, hydrodynamically, a thrust-carrying pressure distribution within the bearing. The load carrying capacity is derived analytically for both incompressible and compressible flow. The theoretical work is very complicated, even with simplifying assumptions, and the text is difficult to follow because all of the steps are not indicated or made clear. Some curves are presented for a particular spiral configuration which allow the designer to predict the load carrying capacity under varying conditions of viscosity, film thickness, relative velocity, ambient pressure and bearing dimensions.

275
WHITE, F. M., JR., B. F. BARFIELD, M. J. GOGLIA, "Laminar Flow in a Uniformly Porous Channel," Journal of Applied Mechanics, Trans ASME, Vol. 25, No. 4, Dec. 1958, pp. 613-617.

Presents the general solution of the Navier-Stokes equations for flow between porous parallel plates. The assumptions made in this analysis are as follows: (a) The flow is steady, viscous, and laminar; (b) Flow conditions do not vary in the z-direction (a two-dimensional problem is prescribed), (e) The condition of uniform porosity is simulated by prescribing a constant normal, velocity at the walls. (Auth)

The use of porous materials has been considered for gas lubricated bearings. This reference is included as a possible source of contributory information.

276
WIESE, B. B., "Development of Design Information for Externally Pressurized Gas Bearings," Sc.B. Thesis, MIT, Cambridge, Mass., 1956.

By determining the effect of changing the clearance, design information is developed experimentally for a specific hydrostatic air bearing with inherent orifice compensation (see Richardson). Results of tests for bearing supply pressures to 400 psig are presented. (Auth)

The testing reported appears to be part of a broad program being carried out at the Dynamics and Control Laboratory of MIT. The data collected by the author is extensive and it should prove to be a valuable contribution.

277
WIGHTMAN, L. W., "Air-Driven Spinners," Machine Design, Vol. 20, No. 5, May 1948, pp. 121-125.

The author tells of the difficulties he experienced in building a high rotating speed machine for testing commutators. He admits rather frankly that some of the problems were solved by cut and try and others strictly by accident. In the end, an acceptable working device was evolved.

A bearing designer would do well to consider the difficulties encountered and described here.

278
WILCOCK, D. F., E. R. BOOSER, "Bearing Design and Applications," McGraw Hill, N. Y., 1957, pp. 356-366.

Contains a small amount of information on gas bearings.

279
WILCOX, R. M., "Air Bearing," U. S. Patent 2 683 635, issued 1954.

This patent contains many ideas. The inventor points out various methods by which the stability, load carrying ability and stiffness of the externally pressurized gas bearings may be improved. These methods include the use of porous materials and shaping of the bearing surfaces. While many versions of these methods are presented, the basic ideas are to provide a restriction to gas flow before it enters the space between the bearing surfaces or before it leaves the bearing surface, to divorce the supply from the film and to keep the volume of "trapped" gas to a minimum.

While there is no extensive mathematical treatment given, the discussion of theory concerning vibration of gas bearings appears to be thorough and sound. For other work on stability of hydrostatic bearings see Licht.

280
WILDE, H., "On the Velocity with which Air Rushes into a Vacuum, and on Some Other Phenomena Attending the Discharge of Atmospheres at Higher into Atmospheres of Lower Density," Proc. Manchester Literary and Phil. Soc., Vol. 25, 1885, pp. 17-34.

This is a presentation of experimental results of air-flow through a small opening. In his work the author experienced the effect of a critical pressure ratio but did not recognize it as such. Since the numerical data are relatively simple to reproduce, the paper has, perhaps, only historic value. For a more complete discussion of the experiment, and the correct interpretation of the results see the reference by Reynolds.

281
WILDMANN, M., "Experiments on Gas Lubricated Journal Bearings," ASME Paper No. 56-LUB-8.

Experiments performed on hydrodynamic gas-lubricated journal bearings are described, and results obtained are presented. During these experiments, radius, gap, length, speed, ambient pressure, and ambient gas were varied, and the effect of each variable on bearing deflection (eccentricity) and attitude angle noted. Axial and radial pressure distributions also have been obtained. (Auth)

The author approaches his problem in a critical manner, attempting to achieve utmost accuracy and precision in his experiments. Many probable sources of error are noted and their effect on the data evaluated. The experimental results are well presented in suitable curves. However, the discussion of them is rather abbreviated and some parts of the results left unexplained.

From his data, the author expects to obtain empirical relations between the various parameters affecting compressible fluid lubrication and with these predict the performance of such bearings. This work will be published in another paper.

282
WILDMANN, M., "The Behavior of Gas Lubricated Journal Bearings," M.S. Thesis, UCLA, January 1957.

A perturbation solution to the differential equation describing the behavior of a full gas-lubricated journal bearing of infinite width is obtained. An exact solution to the same differential equation for the limiting case of infinite speed is also obtained. From these solutions, expressions for load capacity, attitude angle and friction forces are derived. The expressions are then compared to expressions for a similar bearing using a non-compressible lubricant. This comparison shows that there are large differences in the behavior of bearings using compressible and non-compressible lubricants. (Auth)

In this thesis, the effect of an association between the author and Ausman is noticed in that a perturbation solution is obtained for the equation of hydrodynamic lubrication with compressible fluids. In fact, here the author carries the solution a step further and includes third order terms which Ausman neglected.

In the appendix the author carries out the perturbation solution in a step by step process for the first, second and third order solutions.

283
WILDMANN, M., "The Load Capacity and Attitude Angle of Gas Lubricated Journal Bearings," Presented June 18, 1958, ASME Semi-Annual Meeting, Detroit, Michigan.

From experiments performed on gas lubricated journal bearings, semi-empirical equations giving load capacity and attitude angle of these bearings are derived. These equations are then compared to available gas bearing theory and it is shown that for small eccentricities, the equations obtained are adequate to predict the performance of gas lubricated bearings. (Auth)

The reader should take particular note that the author is presenting semi-empirical relations. The data are taken from previous work by the same author.

WILDMANN, M., (15)

284
WILLIS, REV. R., "On the Pressure Produced on a Flat Plate when Opposed to a Stream of Air Issuing from an Orifice in a Plane Surface," Trans-Cambridge Phil. Society, Vol. 3, 1828, pp. 121-140. (Microfilm or photostat available from Library of Congress.)

The author attempts to explain the suction effect produced when air flows between two flat disks. By comparing the phenomenon taking place with that which occurred in an experiment explained by Hanksbee in 1719, he concludes that there is a rarefication (and therefore a lowering of pressure between the plates) due to the "jet" action.

This was one of the first scientific type experiments conducted on what is now termed a vaneless radial diffuser. That the problem is still of interest is evidenced by the recent paper by Welanetz.

WOHL, R. J., (236)

WOJTECH, H., (78)

285
WOOD, W. H., "Counter Balance for Journals," U. S. Patent 466 645, issued 1892.

Provision is made for automatically varying the gas pressure in a hydrostatic bearing to compensate for increased load.

286
WOODROW, J., "The Stability of Gas Bearings," A.E.R.E. E/M-35, July 11, 1950, 2 pages. Available USAEC on microcard.

In gas bearings involving divergent flow, a rise in pressure along the channel due to the Bernoulli effect, is superimposed on the pressure drop due to viscosity. Under certain conditions this leads to an unstable gas film. A preliminary investigation into this effect was made and is presented. (Nuclear Science Abstracts 13-5643.)

287
WORDSWORTH, D. V., "The Viscosity Plate Thrust Bearing," A.E.R.E., E./R. 2217, Oct. 1952.

In Part 1 of the report, the aerodynamic theory of viscosity plate bearings is considered. Taking into account as many aerodynamic effects as possible, a new method of performance prediction is developed. The method is a simple one and easily used. Results given by it agree quite well with the existing one by Whipple. However, neither of these methods predicts the experimental results within an accuracy of 30% at speeds below 9000 rpm. At higher speeds there is no correlation at all. The theoretical curves show that the thrust is a linear function of speed throughout the entire range whereas the experimental curves indicate a decided change in slope at about 10,000 rpm from which point on the thrust is nearly constant for all speeds. The author being acutely conscious of this discrepancy attempted to find an explanation for it and in Part 2 investigated the effects of centrifugal action on the gas, heating of the gas due to frictional losses, the ratio of bearing clearance to the mean free path of the gas molecules (see Burgdorfer) and finally distortion of the grooved plate under pressure load. The last of these is shown to have a considerable influence as plate deflections reach a maximum of about five times the nominal gap and moreover vary considerably with radius and around the disc. The author concludes that the theoretical methods discussed, while evidently still valid, are not applicable to the experiments conducted since they are based on constant plate clearance and unable to cope with the elastic effects noted. (Author - Paraphrased.)

288
WUNSCH, H. L., "Design Data for Flat Air Bearings," <u>Metalworking Production</u>, Sept. 26, 1958, pp. 1697-1704.

A fundamental investigation on air bearings is being carried out by the Mechanical Engineering Research Laboratory, and as a first step tests have been carried out on one form of flat air bearing. This article gives the relationships that have been derived between design parameters, and illustrates their application with a design example. (Auth)

WUNSCH, H. L., (119)

YORK, J. L., (269)

289
YOSHIRA, K., S. NORIMUNE, "Theory of Lubrication by a Compressible Fluid with Special Reference to Air Bearing," Second Japan National Congress Appl. Mech. 1952, Science Council Japan, Tokio 1953, pp. 267-270.

(Paper not available for review as of July 1, 1959.)

290
ZAID, M., Discussion of "A Suction Device Using Air Under Pressure," by Welanetz. Journal Applied Mech., Trans. ASME, Mar. 1957, pp. 156-158.

The author discussing the paper by Welanetz, notes that two pressure forces were neglected in the original analysis and proceeds to make the necessary corrections. However, his theoretical results differ from the experimental ones even more than do those by Welanetz.

Both authors agree that an even more comprehensive theory is required.

ZURFLIEH, T. P., (73)

SUBJECT INDEX

Externally Pressurized Thrust Bearings of the Spherical or Conical Types

(1) (21) (22) (24) (25) (31) (40) (47) (48)
(49) (50) (51) (71) (82) (83) (96) (102) (114)
(115) (116) (117) (118) (129) (133) (137) (155) (165)
(192) (216) (247) (250) (256) (268)

Flow in Restrictors

(12) (43) (56) (84) (98) (104) (105) (113) (115)
(121) (122) (128) (132) (158) (159) (178) (187) (196)
(198) (201) (203) (213) (216) (221) (223) (224) (225)
(226) (228) (229) (242) (243) (247) (268) (269) (275)
(280) (284) (290)

Self Acting Bearings Analysis, General

(14) (30) (46) (59) (60) (61) (62) (63) (64)
(68) (70) (85) (86) (98) (123) (124) (130) (149)
(157) (168) (173) (177) (181) (235) (248) (251) (257)
(258)

Self Acting Journal Bearings of Finite Width

(16) (36) (37) (39) (44) (55) (75) (86) (89)
(90) (110) (151) (181) (234) (248) (251) (281) (283)

Self Acting Journal Bearings of Infinite Width

(15) (17) (30) (36) (46) (55) (59) (60) (61)
(69) (70) (124) (130) (135) (149) (173) (186) (209)
(230) (232) (234) (264) (282)

Self Acting Thrust Bearings of the Pumping (Grooved) Types

(30) (274) (287)

Self Acting Thrust Bearings of the Tilting Pad, Tapered Land, Or Discontinuous Geometry Types

(8) (41) (62) (81) (85) (87) (123) (124) (142)
(155) (157) (166) (168) (177) (233) (234) (235) (249)
(258)

YEARLY INDEX

(Year of Publication)

In this index the file numbers of reference appear under the appropriate, chronologically listed, year.

1952

(7) (35) (57)
(58) (108) (111)
(132) (138) (149)
(179) (192) (196)
(228) (229) (238)
(247) (258) (267)
(287) (289)

1953

(23) (24) (27)
(81) (96) (97)
(99) (109) (110)
(125) (135) (142)
(149) (166) (178)
(194) (231) (233)
(256) (289)

1954

(11) (12) (28)
(40) (44) (64)
(71) (74) (81)
(93) (119) (120)
(160) (194) (224)
(225) (239) (259)
(261) (269) (279)

1955

(59) (60) (63)
(67) (88) (90)
(91) (121) (129)
(187) (190) (204)
(209) (218) (219)
(220) (222) (231)

1956

(4) (5) (26)
(29) (37) (42)
(61) (62) (65)
(66) (68) (69)
(70) (71) (90)
(93) (107) (113)
(122) (132) (140)
(164) (169) (170)
(174) (176) (183)
(236) (271) (276)
(281)

1957

(15) (16) (17)
(34) (43) (53)
(54) (55) (56)
(58) (73) (87)
(112) (121) (127)
(128) (134) (139)
(141) (144) (158)
(162) (201) (202)
(205) (206) (208)
(213) (214) (217)
(221) (225) (231)
(237) (242) (244)
(248) (257) (270)
(271) (278) (282)
(290)

1958

(3) (10) (13)
(19) (46) (77)
(85) (89) (92)
(93) (95) (98)
(102) (103) (104)
(105) (124) (143)
(150) (155) (161)
(162) (177) (186)
(205) (207) (210)
(211) (212) (230)
(232) (248) (252)
(265) (275) (283)
(288)

1959

(6) (30) (36)
(41) (46) (86)
(106) (123) (148)
(155) (163) (168)
(175) (188) (189)
(207) (246)

PATENTS

In this index patents of interest are tabulated in numerical order. The country of issue is the United States unless otherwise noted.

PATENT NO.	FILE NO.	YEAR	PATENTEES	TITLE
548 363*	72	1942	Crewdson, E.	Improvements in and Relating to Bearings or Journals.
685 871*	111	1952	Gerard, P.	Improvement in Fluid Bearings.
796 926*	175	1959	Montgomery, A. F. Sterry	Gas Lubricated Bearings.
RE 20 305**	153	1937	Klahn, E.	Apparatus for Minimizing Friction and Vibration of Rotor Elements.
466 645	285	1892	Wood, W. H.	Counter Balance for Journals.
754 400	272	1904	Westinghouse, G.	Vertical Fluid Pressure Turbine.
816 330	145	1906	Johnston, T. J.	Frictionless Bearing for Electric Motors.
915 549	45	1909	Budd, A. V.	Rotary Engine.
930 851	75	1909	De Ferranti, S. Z.	Air Bearing for High Speeds.
974 392	147	1910	Junggren, O.	Combined Thrust and Guide Bearing.
1 030 153	18	1912	Barbezat, A.	Device to Balance Thrust in Turbines.
1 067 727	94	1913	Fredrickson, J.	Bearing for Car-Axle.
1 070 088	263	1913	Van Deventer, J. H.	Counterbalanced Bearing.

*Issued by Great Britain.
**Reissue of U.S. Patent 2 054 055.

PATENT NO.	FILE NO.	YEAR	PATENTEES	TITLE
1 185 571	2	1916	Abbott, W. G.	Device for Utilizing Fluid Under Pressure for Lubricating Relatively Movable Elements.
1 337 742	1	1920	Abbott, W. G.	Gas-Lubricated Bearing.
1 385 423	25	1921	Bibbins, R. E.	Compass.
1 629 577	154	1927	Klahn, E.	Art of Sustaining Bodies in Space.
1 893 995	146	1933	Jung, K.	Bearing for Accurately Running Shafts Using Ball Bearings.
1 906 715	191	1933	Penick, E. R.	Air Bearing.
2 054 055	153	1937	Klahn, E.	Apparatus for Minimizing Friction and Vibration of Rotor Elements.
2 068 458	172	1937	Moller, W.	Bearing.
2 086 896	47	1937	Carter, L. F.	Air Supported Gyroscope.
2 086 897	48	1937	Carter, L. F.	Air Borne Artificial Horizon.
2 086 898	49	1937	Carter, L. F.	Air Borne Directional Gyroscope.
2 095 313	50	1937	Carter, L. F. W. Bolster	Air Borne Gyroscope.
2 113 335	266	1938	Wallgren, A. G. F.	Bearing.
2 133 809	51	1938	Carter, L. F. W. Anscott	Gyrovertical.
2 177 053	33	1939	Boyd, G. A.	Oil Burner.
2 200 976	21	1940	Bates, M. F.	Resetting Means for Air Borne Gyroscope.

PATENT NO.	FILE NO.	YEAR	PATENTEES	TITLE
2 262 232	31	1941	Bolster, W.	Multiple Gyro Air Borne Compass.
2 449 297	137	1948	Hoffer, F. W.	Automatic Fluid Pressure Balancing System.
2 474 072	250	1949	Stoner, G. H.	Air Bearing Gyroscope.
2 502 173	195	1950	Potts, L. D.	Fluid Balancing Means.
2 511 543	200	1950	Rawlins, J. A.	Gas Lubricated Bearing.
2 523 310	152	1950	Kirkpatrick, J.	Hydraulic Thrust Bearing.
2 535 454	199	1950	Rawlins, J. A.	Air Lubricated Thrust Bearing.
2 544 720	185	1951	Ospina-Racinas, E.	Pneumatic Toy
2 597 371	192	1952	Perkins, G. S. P. R. Vogt R. R. Weber	Double Ended Journal Air Bearing.
2 602 632	238	1952	Serduke, J. J. R. O. Webster	High Speed Bearing and Turbine.
2 603 539	35	1952	Brewster, O. C.	High Speed Rotor Using Gas-Lubricated Bearings to Get Away From Whip.
2 605 147	196	1952	Raichle, L. G. Schulze	Thrust Balancing for Vertical Shafts.
2 617 695	247	1952	Slater, J. M. V. A. Tauscher	Zonal Ball-Air Bearing.
2 617 696	138	1952	Honess, W. T.	Air Bearing Thrust and Radial Supporting Bearing.

PATENT NO.	FILE NO.	YEAR	PATENTEES	TITLE
2 623 353	108	1952	Gerard, P. L.	Combined Fluid Bearing and Mechanical Bearing for Gas Turbine Engines.
2 627 443	23	1953	Becker, H. I.	Air Bearing Graphite Lining (Porous).
2 634 176	110	1953	Gerard, P. L.	Fluid Pressure Bearing.
2 644 727	256	1953	Tauscher, V. A. J. M. Slater J. Emmi	Double Ball Gyro Precession Axis Bearing.
2 645 534	24	1953	Becker, H. I.	Air Bearing Graphite Lining (Porous).
2 660 484	109	1953	Gerard; P. L. H. Seranne	Fluid Bearing.
2 671 700	239	1954	Seyffert, M.	Air Bearing Apparatus.
2 683 635	279	1954	Wilcox, R. M.	Air Bearing.
2 684 272	12	1954	Annen, R.	Fluid Support Bearing.
2 695 198	40	1954	Brugger, R. G.	Air Bearing.
2 695 199	28	1954	Blizard, R. B.	Bearing.
2 696 410	261	1954	Topanelian, E. Jr.	Journal Bearing.
2 707 355	190	1955	Peiler, K. E.	Sting-out Baffle for Glass Feeder Rotor Bearing.
2 710 234	129	1955	Hansen, S.	Fluid Bearing Mount.
2 734 318	183	1956	Offen, A.	Laps.
2 738 238	170	1956	Michelson, H.	Bearings.
2 752 197	164	1956	Marco, S. M.	Rotary Nozzle for Soot Blowers and the Like.
2 754 641	26	1956	Bidwell, E. C.	Work Holding and Clamping Mechanism for Centerless Grinding Machines.

PATENT NO.	FILE NO.	YEAR	PATENTEES	TITLE
2 756 114	42	1956	Brunzel, N.	Pressure Lubricating Bearing.
2 756 115	169	1956	Michel, R. O.	Pneumatic Bearing Construction.

CORPORATE NAME INDEX

This is an alphabetical listing of the sources of the various references of the bibliography.

Product Engineering
(3) (4) (15) (53)
(113) (178) (179) (180)

Providence Journal
(77)

Publications Scientifiques et Technique de L'Air
(56)

Reading University (Great Britain)
(245)

The Review of Scientific Instruments
(39) (44) (193)

Revue Generale de L'Hydraulique (France)
(78)

Revue Generale des Sciences Pure et Appliques (France)
(133)

Rockefeller Foundation International Health Division
(193)

Royal Aircraft Establishment
(32) (38) (171)

Ruston and Hornsby Ltd. (Great Britain)
(215)

Science Council Japan
(289)

Society of Automotive Engineers Journal
(142)

Society Automotive Engineers (Paper)
(166)

Societe des Ingenieurs Civil de France
(112)

Springer (Germany)
(265)

Sulzer Technical Review (Switzerland)
(252)

Transactions American Society of Mechanical Engineers
(17) (27) (46) (71)
(121) (122) (139) (158)
(162) (201) (205) (248)

Transactions Cambridge Philosophical Society
(130) (284)

Transactions Japanese Society of Mechanical Engineers
(135) (184) (218) (220)
(222) (225) (227) (228)
(229) (231) (251)

Transactions New York Academy of Sciences
(99)

Treniei Iznos v Machinakh (USSR)
(233) (234)

United Kingdom Atomic Energy Authority
(37) (141)

University of Buffalo
(187)

University California and Los Angeles
(267) (282)

University of Melbourne
(208)

Vestnik Mashinastroenia (USSR)
(232)

VDI - Berichte (Germany)
(43)

VDI Zeit (Germany)
(81)

Wiley
(100)

Wright Air Development Center
(30)

Zeit Angew Physik (Germany)
(114)

Source Undetermined
(235)

LITERATURE ORIGINATING IN AREAS OUTSIDE OF THE UNITED STATES

In this index, referenced article file numbers appear under the name of country of origin or publication. Copies of all referenced literature are obtainable in the U. S. unless otherwise noted in the text.