dynamic film to break temporarily or permanently, causing an increase in the bearing-friction torque, a resulting rise in bearing operating temperature, and often a seizure of bearing and journal.

If a journal is started from rest to some finite rotational speed under conditions of high radial loading, the hydrodynamic film may be unable to build up. When this condition appears, often by reducing or removing the load while the journal continues to rotate and then gradually applying the same total load, the hydrodynamic film may be formed.

If oil is supplied to the radial oil hole on the unloaded side of a lightly or heavily loaded journal bearing at atmospheric or slightly below atmospheric pressure, the bearing generally will pump sufficient oil to perform satisfactorily and exhibit hydrodynamic lubrication characteristics.

CONCLUSIONS

From the experimental and theoretical data presented in this paper, the following conclusions are drawn:

1. The most useful means of presenting short-bearing theoretical and experimental results appear to be by the use of the \( N_{DL}/D \) versus \( h_{m}/D \) and the \( N_{DL}/V \) versus \( C_{D}/D \) curves. Bearing designers will find these particular curves useful for design and analysis.

2. The clearance-load numbers, experimental clearance-load numbers, minimum oil-film thickness-load numbers, experimental minimum oil-film thickness-load numbers, \( D/L \) load numbers, and oil-pressure load numbers are basic dimensionless quantities useful for predicting and analyzing the performance of short journal bearings. The \( T/T_{0} \) versus \( N_{A} \) and the \( q \) versus \( N_{A} \) curves are useful for predicting bearing-friction torques and oil-flow rates. It is probable that the optimum arrangement of the variables of short-journal bearing lubrication has not yet been made in order to obtain the most useful dimensionless quantity.

3. The experimental clearance-load numbers and the experimental minimum oil-film thickness-load numbers appear to be improvements on present short-bearing theories; however, additional analysis is necessary in order to determine the value of the exponent \( y \) more accurately.

4. So long as the minimum oil-film thickness is of the order of or exceeds the sum of the predominant peak surface roughnesses of the bearing and journal measured in the circumferential directions after run-in of bearing and journal, experimental bearing-friction-torque data indicate the presence of hydrodynamic film lubrication. Smaller oil-film thicknesses are indicative of marginal lubrication. Bearing-friction-torque curves indicate a rapid continuous transition from hydrodynamic to marginal lubrication conditions rather than a sharp abrupt change.

5. Although in present engineering practice most journal bearings operate at clearance-load numbers below 100, values of 100,000 and more are attainable.

6. Short journal bearings can operate successfully under conditions of marginal lubrication but with bearing-friction torques and operating temperatures exceeding those predicted by hydrodynamic lubrication considerations for a similarly sized bearing.

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Discussion

A. Bond. The writer would expect that the author's experimental results in the thin-film region depend very largely on the running-in procedure employed. The run-in methods were not described in the paper. Should their effect be as noticeable as the writer expects they are, then the initial surface-finish measurements (discussed by the author and by Prof. Oevirk) would hardly be significant for design calculations.

F. W. Oevirk. The author is to be commended for his experimental exploration into the thickness of hydrodynamic films in journal bearings. The major portion of his experimental data shows measurements of minimum film thickness less than 0.0001 in. and reaching extreme thicknesses of 0.00001 in. or less. Measurement of film thicknesses of these orders of magnitude are difficult, and the question of accuracy of measurement inevitably arises. However, the use of very short double bearings as test specimens appears logical since the effect of shaft deflection, misalignment, and waviness of bore are less apt to be disturbing variables. In view of the author's careful technique and the sensitive performance of the microformers, the order of magnitudes of film thicknesses measured appears reasonable.

The author's statement that surface roughness seems to be the limiting factor in the purely hydrodynamic performance of thin films is logical. Marginal lubrication is apparent first from a rise in friction because of the beginning of metallic contact which is accompanied by a large temperature rise. This does not mean necessarily that a breakdown of load capacity is the primary cause of failure usually signified by temperature rise but that the increase friction is the primary factor because of the rapid reduction in clearance owing to differential thermal expansion caused by the heating. The author's statement that a large clearance would be desirable under marginal conditions is logical in this regard. It would appear that purely hydrodynamic steady-state performance at minimum film thicknesses of much less than 0.00001 in. could be realized with extremely fine finishes and relatively large clearances—and with short bearings.

Perhaps a clearer picture of the influence of surface roughness on the failure of thin hydrodynamic films is apparent from Tarasov's magnifications of surface irregularities of machined surfaces. Tarasov shows that relatively few but very high peaks exist in all machined surfaces (turned, ground, lapped, superfinished) and that these peaks are much higher than the irregularities which are predominant over the major portion of the surface. Thus it is possible that a substantial film exists between the surfaces even though a friction rise becomes apparent because of the contact of the peaks. Moreover, Tarasov shows that the high peaks are of the order of from \( 41/2 \) to 10 times greater than the root-mean-square roughnesses measured with profilometers. Thus, for mating surfaces each having 1-microinch profilometer roughness, the load-carrying film thickness may be as much as \( 2 \times 1 \times 10^{-10} = 20 \) microrinches when metallic contact first begins. Run-in may reduce the height of the peaks, but this should be accomplished at high loads and low speeds to prevent high heating.
D. F. Wilcock. The author is to be commended for his painstaking experimental work which confirms so well the result of the simple theory for zero-length bearings. Efforts to induce a better correlation with the clearance-load number by making the exponent of the \( D/L \) term variable tend to reduce the results to those of an empirical relation. As the author points out, accurate results can be obtained by using the relaxation procedures of Cameron and Wood.

Rosenthal and Wilcock showed the benefits to be obtained by the use of a d-e network analyzer in obtaining more rapid solutions of Reynolds equation for bearings of finite length.

More recently, Pinkus and Wilcock have given more accurate results obtained by the use of digital computers. It would seem preferable, where the results of the simple theory are inadequate, to use solutions of Reynolds equations for finite bearings rather than to attempt correlations between experimental results and theoretical results for extreme conditions.

The substantial agreement obtained by the author between his experimental results for very short bearings and the theory for zero-length bearings lends added evidence to the writer's conviction of several years' standing that with the rapid solution of Reynolds equation for finite bearings available using computers, the amount of experimental work can be reduced sharply. Good bearing analyses can now be made by the right kind of theoretical prediction and only confirmatory experimental runs need to be carried out.

The author does not make clear what temperature is used in arriving at the oil viscosity used in correlating the results. For small bearings such as are discussed in this paper, a large amount of the heat is removed by conduction. Nevertheless, knowledge of oil flow and power loss must be utilized in arriving at the proper operating temperature. Perhaps the author can clarify this point? Similarly, the viscosity data on the oil used in the experiments are not given, and the reader must assume that careful measurements of viscosity at two or more temperatures were made and used. The SAE designation mentioned in the paper covers a rather broad range of possible viscosities.

**AUTHOR'S CLOSURE**

The author wishes to express his appreciation for the discussions given by Dr. Bondi, Professor Ocvirk, and Dr. Wilcock and to their interest in and encouragement of the continuation of related investigations.

Little as the transition from full hydrodynamic film lubrication to marginal lubrication conditions appears to begin when the minimum oil-film thickness becomes less than the sum of the predominant-peak surface roughnesses of the bearing and journal measured in the circumferential direction after run-in of bearing and journal, Dr. Bondi justifiably requests description of the run-in procedures. The new **1/4-in-diam** test bearings and journals were run in under constant journal rotational speeds of approximately 1000 rpm with continually increasing radial loading until clearance load numbers of approximately 1000 were obtained. This careful increase of loading was accompanied by a continuous monitoring of the bearing-friction torques and bearing operating temperatures in order to prevent high heat generation in the oil film effecting a large reduction of diametral clearance with subsequent scoring of bearing and/or journal. The journals then were permitted to run at clearance-load numbers of approximately 1000 for 1 hr, after which time additional run-in appeared to have little or no effect in burnishing of bearing and journal surfaces with accompanying reduction of bearing-friction torques and operating temperatures. Surface-roughness measurements of both the bearing and journal then were made, the bearing and journal were tested, and surface-roughness determinations were repeated to assure that the testing had effected no further burnishing of the mating surfaces.

The author believes that this run-in procedure results in surface roughnesses corresponding to those of commercial oil-lubricated short journal bearings which have been broken in through conventional usage, provided this break-in period was not accompanied by sufficiently high bearing operating temperatures to cause scoring of bearing and/or journal. Dr. Bondi correctly states that the initial surface-finish measurements of new bearings and journals are not very significant for design calculations unless these initial roughnesses correspond closely to those after run in. Fortunately, a bearing designer has available from experience typical roughnesses of various types of mating bearing and journal materials and surface treatments after conventional break-in conditions and it is these roughnesses that should be used in the design and analysis of short journal bearings.

Surface-roughness measurements in the circumferential direction were made on each journal and bearing axially midway between the ends of the bearing surface and for the bearing at the point estimated at the location corresponding to the position of the minimum oil-film thickness for the heaviest loading of the bearing. Root-mean-square microinch surface-roughness readings were obtained by use of a Brush surface analyzer and a profilometer. These roughnesses were translated into predominant-peak surface roughnesses by use of the methods described by Tarasov. This method was checked experimentally on several of the bearings by use of micrometer section of a plastic replica of the bearing surface and a toolmaker's microscope for direct measurement of predominant-peak surface roughness.

Thanks are due Professor Ocvirk for additional information concerning the transition from full hydrodynamic film lubrication to marginal lubrication conditions and the probable effect that the predominant-peak surface roughnesses of the bearing and journal play in this process, and for presenting some of the findings of Tarasov. It is appreciated that Professor Ocvirk amplified the point that the breakdown of load capacity of a short journal bearing operating with marginal lubrication, usually signified by a rise in bearing operating temperature, is not the primary cause of bearing failure but that the increase of function is the primary factor because of the rapid reduction of diametral clearance due to the differential thermal expansion caused by the heating.

Increasing diametral clearances of short journal bearings reduces the possibility of seizure of the bearing and journal as a result of this differential expansion and in most cases without any substantial reduction in the maximum load capacity. Reducing the predominant peak surface roughnesses of the journal and bearing surfaces reduces the limiting minimum oil-film thickness at which marginal lubrication begins.

The bearing lubricant employed throughout all investigations was Texaco SAE 20-20W D insulated motor oil. Its viscosity as determined experimentally by use of a Saybolt universal viscometer and checked by a Brookfield viscometer, was as given in Fig. 11, herewith. These viscosity determinations were made with the oil at various constant-temperature conditions and at atmospheric pressure. As Dr. Wilcock indicates, it is a difficult task to determine a single effective temperature of the oil in the bearing in order to arrive at a useful value of viscosity. The temperature and pressure in the oil film of a short journal bearing vary...
both circumferentially and axially and the viscosity of the oil varies accordingly. If a complete temperature and pressure traverse of the oil film experimentally were possible without altering the other experimental findings, then it would be a simple matter to determine an average viscosity of the oil in the oil film. Unfortunately, with the smallness of the oil-film thicknesses involved in these experimental investigations, this procedure was not possible. The following method was employed for the determination of oil viscosity in the bearing in correlating the experimental results with theoretical predictions; no attempt was made to take into account the effect of pressure upon viscosity.

A small copper-constantan thermocouple junction was placed within the bearing material at a point 1/4 in. from the actual bearing surface at the point at which the load $P$ is shown applied to the bearing in Fig. 1. The temperature indicated by the output of this junction and the viscosity data of Fig. 11 were employed to determine the viscosity of the test oil under test conditions of the bearings and journals.

Dr. Wilcock points out a probable trend in scientific investigations, that of employing computers to obtain solutions of problems rather than resorting to lengthy experimental investigations. Of course, certain conditions must be known about the problem before computers can give useful results. It is possible that in the near future, experimental investigations may be limited to the determination of the minimum information necessary for setting up a computer program and for obtaining a few confirmatory experimental runs of the computer results!

![Graph showing experimentally determined viscosity of test oil at atmospheric pressure.](image-url)