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Performance of Simple Gas Foil Thrust Bearings in Air

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Abstract

Foil bearings are self-acting hydrodynamics devices used to support high speed rotating machinery. The advantages that they offer to process fluid lubricated machines include: high rotational speed capability, no auxiliary lubrication system, non-contacting high speed operation, and improved damping as compared to rigid hydrodynamic bearings. NASA has had a sporadic research program in this technology for almost 6 decades. Advances in the technology and understanding of foil journal bearings have enabled several new commercial products in recent years. These products include oil-free turbochargers for both heavy trucks and automobiles, high speed electric motors, microturbines for distributed power generation, and turbojet engines. However, the foil thrust bearing has not received a complimentary level of research and therefore has become the weak link of oil-free turbomachinery. In an effort to both provide machine designers with basic performance parameters and to elucidate the underlying physics of foil thrust bearings, NASA Glenn Research Center has completed an effort to experimentally measure the performance of simple gas foil thrust bearing in air. The database includes simple bump foil supported thrust bearings with full geometry and manufacturing techniques available to the user. Test conditions consist of air at ambient pressure and temperatures up to 500 °C and rotational speeds to 55,000 rpm. A complete set of axial load, frictional torque, and rotational speed is presented for two different compliant sub-structures and inter-pad gaps. Data obtained from commercially available foil thrust bearings both with and without active cooling is presented for comparison. A significant observation made possible by this data set is the speed—load capacity characteristic of foil thrust bearings. Whereas for the foil journal bearing the load capacity increases linearly with rotational speed, the foil thrust bearing operates in the hydrodynamic high speed limit. In this case, the load capacity is constant and in fact often decreases with speed if other factors such as thermal conditions and runner distortions are permitted to dominate the bearing performance.

1.0 Foil Thrust Bearing State of the Art

One of the earliest published works on the idea of a foil bearing, in journal bearing form and using oil as the lubricant, was published in 1953 by H. Blok of the Technical University at Delft in Holland (Ref. 1). In this work Blok describes an experimental apparatus in which a foil is wrapped around 180° of a journal and loaded via a system of weights and pulleys. The results of friction and load tests are presented with theoretical equations representing the accommodation of the foil membrane to the hydrodynamic pressure. Over the past several decades the use of foil bearings has enabled the development of many unique, high speed machines.

The benefits foil bearings offer to high speed turbomachinery can be significant. Among these benefits are reduced machine weight due to the elimination of the oil systems, removal of the traditional diameter—rotational speed limit imposed by rolling element bearings, and a synergistic use of working fluid as a lubricant enabling a contaminant free working fluid without the need for seals, filters, and ancillary subsystems. However in order to realize these benefits, foil bearing must be able to support the required machine load, provide the requisite rotordynamic stiffness and damping, and operate reliably and without burden to the machine. Excess burden to a turbomachine usually manifests itself in the detrimental use of working fluid as bleed flow to cool or pressurize specific components.

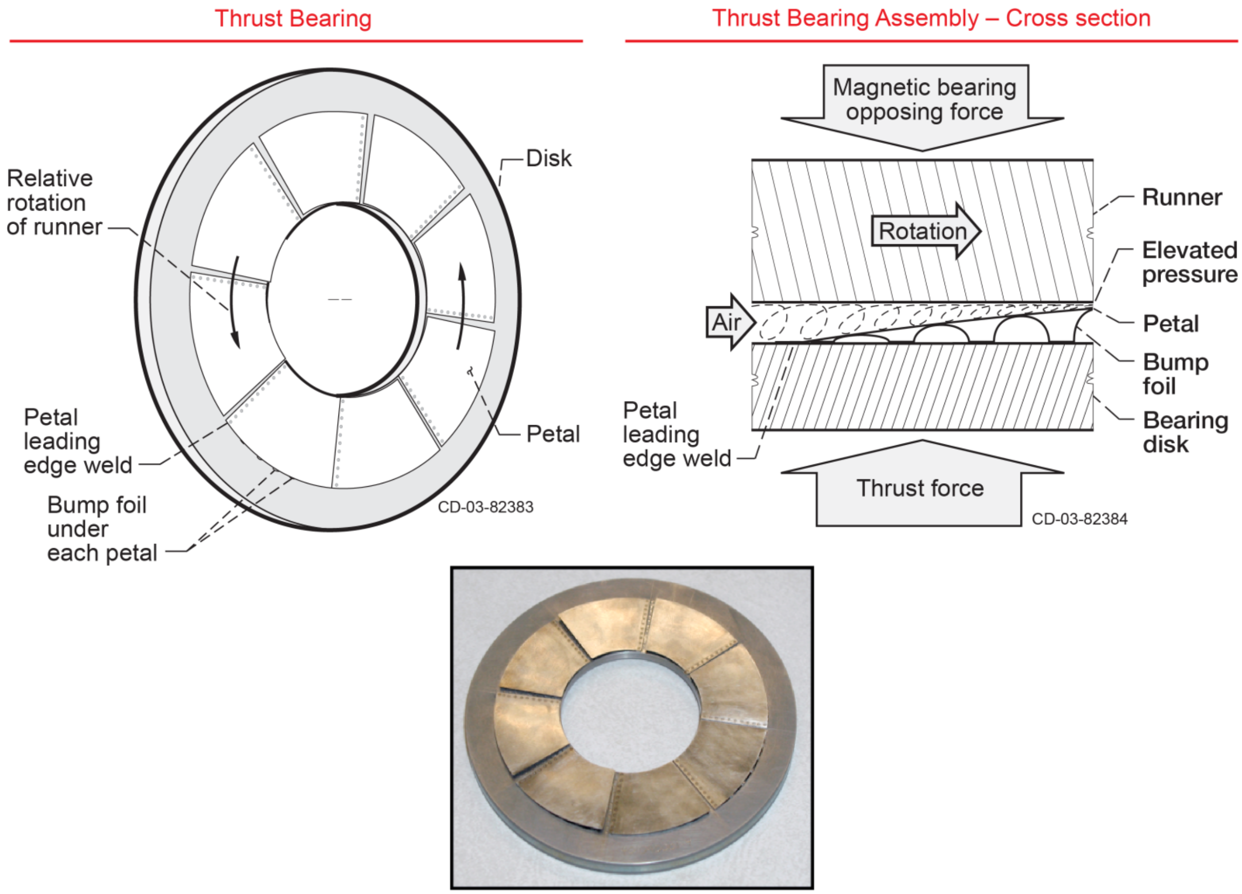

Figure 1.—Drawing and photograph of a simple foil thrust bearing.

A typical foil thrust bearing is shown in Figure 1. The bearing consists of a solid backing plate with an annulus of discrete bearing pads or petals. Each of these pads is constructed from a smooth and continuous top foil that is fixed on the leading edge and free on the remaining three edges. The backside of the top foil is supported by a compliant foundation. The hydrodynamic pressure rise is initially created by the physical contraction of the film thickness between the top foil and the thrust runner. The compliant foundation can take any number of styles and forms.

The foil thrust bearing operates in the same manner as all other hydrodynamic bearings. As viscous fluid is dragged through a converging channel the momentum given the fluid through the moving shaft is transformed into elevated pressures. Thus a significant load can be supported with a very small drag force. Theoretically the supported load to drag force ratio can reach 1000, however in practice this ratio is in the low hundreds. According to the governing Reynolds equation, all hydrodynamic lubrication follows certain behaviors such that supported load increases with absolute viscosity and decreases with the square of film thickness. Hydrodynamic behavior with respect to speed is variable. Figure 2 (Ref. 2) highlights some of the pertinent features. At low relative surface speeds the load support increases with speed and the bearing analysis can proceed in a simplified fashion with the assumptions of incompressible lubricant and zero side leakage. This proportional increase of load capacity with respect to shaft speed has given rise to the load capacity rule of thumb for foil journal bearings, DellaCorte (Ref. 3). However, as shaft speed continued to increase the load capacity reaches a limit or high-speed asymptote. This limit

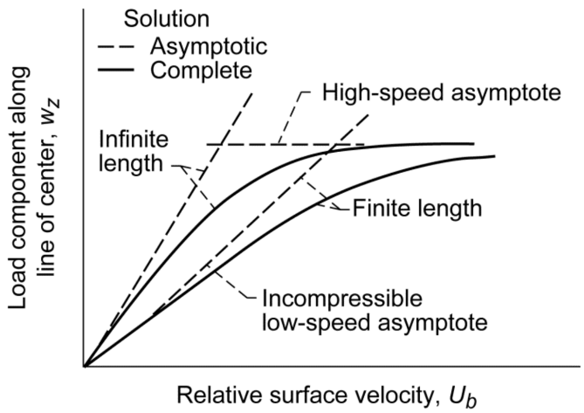

Figure 2.—Generalized behavior of hydrodynamic lubrication (Ref. 2).

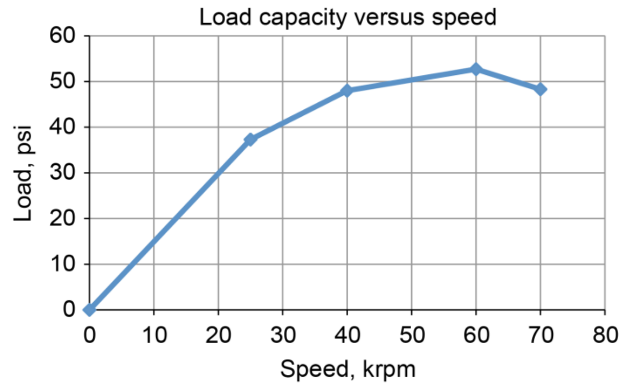

Figure 3.—Load capacity of foil thrust bearing cross plotted from data Heshmat (Ref. 4) showing high load capacity speed drop off.

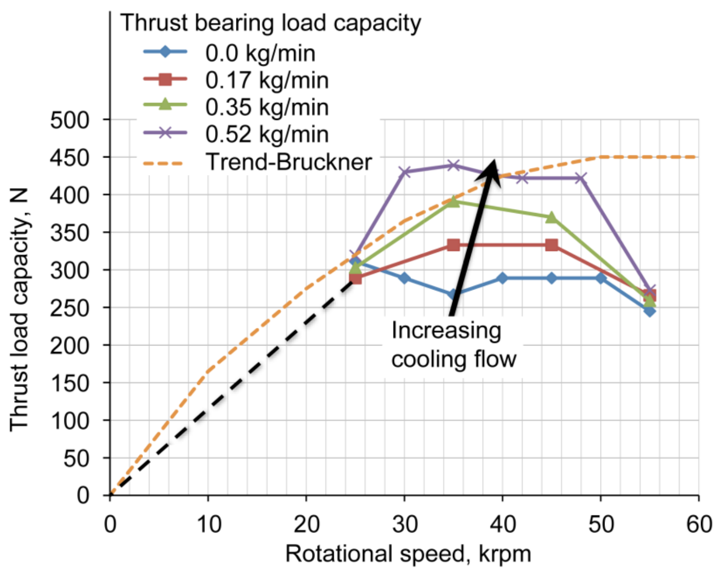

Figure 4.—Load capacity versus shaft speed graph showing high speed drop off. Data from References 5 and 6.

is experienced in foil thrust bearings. As shaft speed is further increased a region of decreasing load capacity is reached that is attributed to high rates of viscous heat generation and surface distortions of the bearing and runner. Figures 3 and 4 demonstrate this phenomenon. In Figure 3, data from Heshmat (Ref. 4) is cross plotted to generate a load capacity versus speed chart. The data shows a drop in load capacity from 60,000 to 70,000 rpm. Figure 4, obtained by plotting data published in References 5 and 6, contains load capacity data from 25,000 to 55000 rpm. The uncooled thrust bearing shows a decrease in load capacity over this speed range, while cooling is shown to enable a modest increase in load capacity. The asymptotic behavior is also shown analytically in Figure 4 as is calculated by the methods of Bruckner (Ref. 7).

The analysis of foil thrust bearings has been hampered by the lack of a self-consistent data set that includes load, torque, and speed data along with a detailed description of the bearing design. Few such data sets exist in the open literature. It is the objective of this work to provide such a database so that the understanding and analysis of foil thrust bearings can be advanced by a broad spectrum of potential users of the technology.

2.0 Experimental Method

NASA Glenn has developed two test rigs specifically designed to test the performance of single sided foil thrust bearings. The vertical thrust bearing rig is driven by a 5 kW electric motor and is capable of speeds up to 21,000 rpm. The vertical rig also has a high temperature capability where the bearing cavity temperatures can be controlled up to 800 °F. The horizontal thrust bearing rig is driven by an air turbine, has a practical speed limit of 60,000 rpm, and an ambient temperature limit. Both thrust bearing rigs utilize ambient pressure air as the lubricant and are not capable of high pressure environments. In addition to the two test rigs NASA has also developed a method to produce simple bump foil thrust bearings (Ref. 8). The design of these thrust bearings had the objective of creating research grade bearings. The intent of research grade bearings is to possess repeatable, albeit modest performances. In order to accomplish this objective the inter-pad spacing was increased, the inlet contraction was lengthened, and the compliant foundation was softened.

Two different bump foil designs have been tested to date. These two configurations are shown in Figure 5. All performance testing of these two bump foil configurations was performed without forced cooling. The tests of the first bump foil configuration are described in detail in Dickman (Ref. 9). The primary objectives of this test were threefold: to develop final manufacturing and test techniques, to quantify bearing-to-bearing variability, and to generate an open source performance database. A summary of the results is shown in Figure 6. Load and torque data is presented for shaft speeds of 14, 19, 21, and 40 krpm. At modest loads the load torque characteristic is repeatable for the three bearings that were tested. However, the load capacity showed large variability. At 21 krpm the load capacity varied from 40 to 60 lb. This variability in load capacity is typical of all foil bearings and is due to the hand-made nature of the current state of the technology.

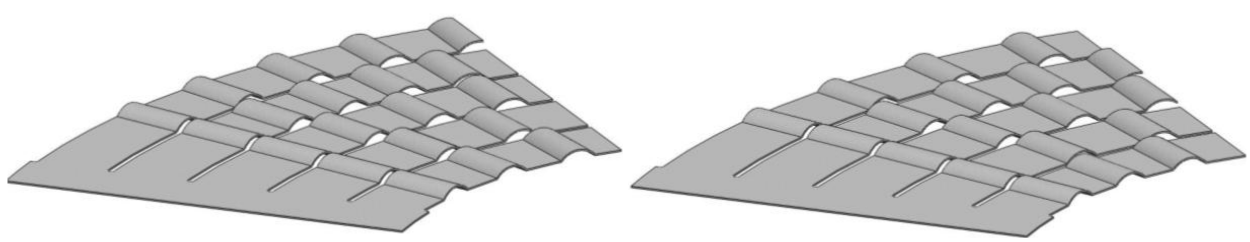

Figure 5.—Rendering of the bumpfoil configurations used for the initial open source thrust bearing test program. Bump foil tested by Dickman on left. Bump foil used in the TEE experiments on right.

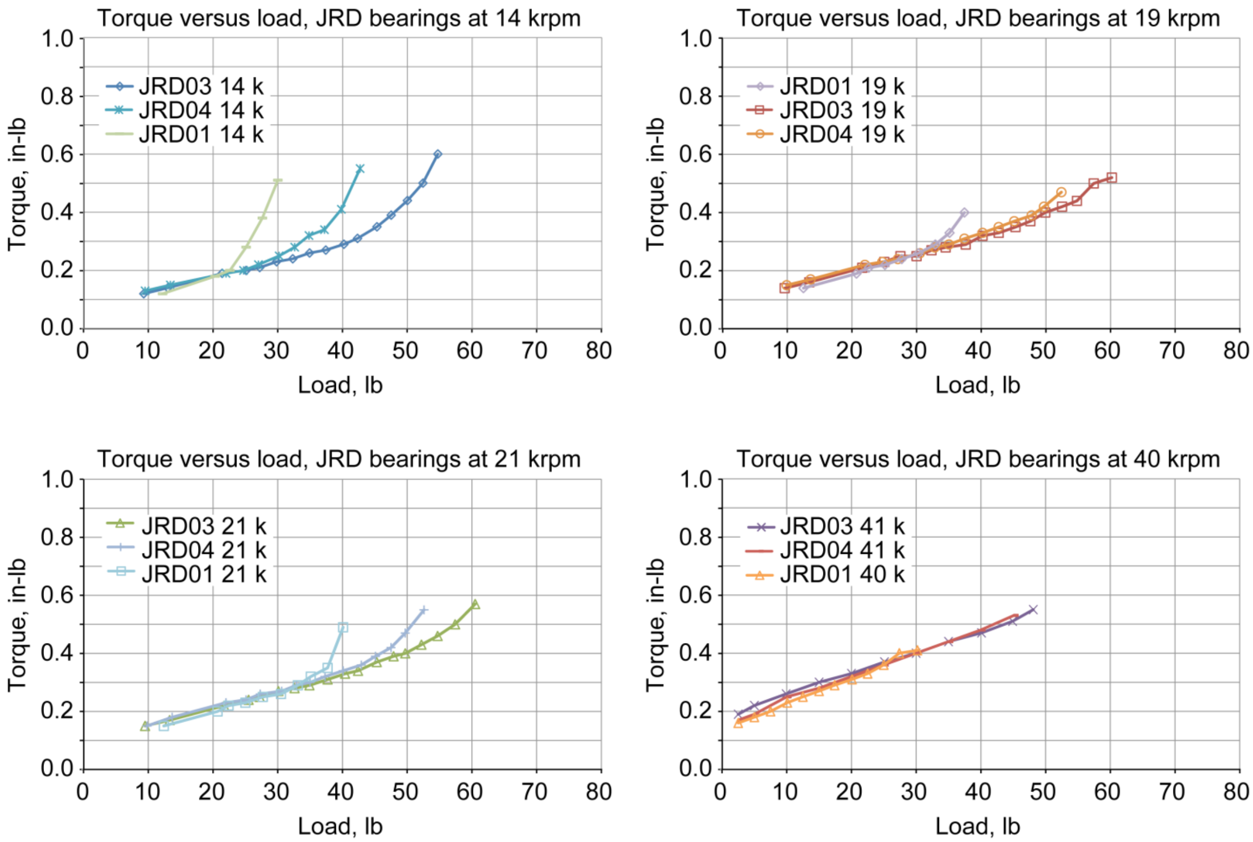

Figure 6.—Simple foil thrust bearing data from Dickman (Ref. 8).

The second bump foil configuration was tested with two different top foils in order to investigate the inter-pad separation. The bearing designated TEE01 was comprised of the original top foils having a 15° separation between leading and trailing edge. The bearing designated TEE02 used a top foil that extended to the next pad such that there was no trailing edge to leading edge separation. Data for this test is presented in Figure 7 for speeds of 19, 21, and 40 krpm. Data comparison between Figures 6 and 7 is not possible because two different bump foil configurations were used. In the later the stiffness distribution was concentrated near the inner radius of the bearing causing the bearings to underperform when compared to the Dickman data. Qualitative comparison indicates that the bearing with the larger top foil, TEE02, has higher torque at a given load and speed than that of the original configuration. Additionally, the extra pad area did not have a significant effect on the load capacity of the bearing at higher rotational speeds. Although at low speeds (14 and 19 krpm) the load capacity for TEE02 showed small increases with large increases in frictional torque.

An important and consistent observation was made from the commercial bearings tested by Dykas, the open source bearings tested by Dickman, and the open source TEE bearings were the asymptotic load capacity limit of 20 psi. This crude estimation of ultimate load capacity was obtained by calculating true loaded area from observations of witness marks following high speed load capacity tests. The total load divided by the true load area for uncooled thrust bearings appears to be consistent across different bump foil designs and tribological wear couples.

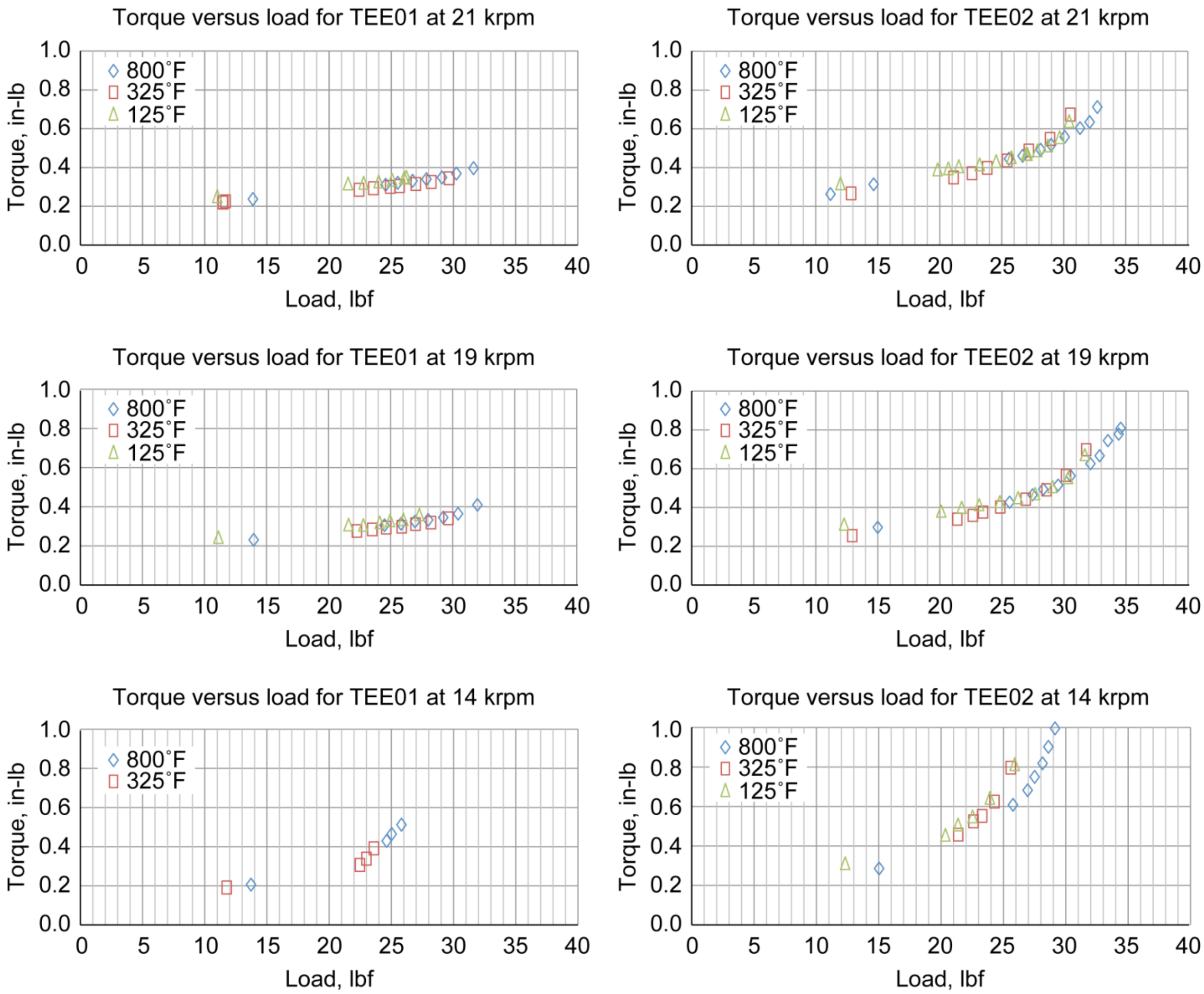

Figure 7.—Simple foil thrust bearing data from the inter-pad separation effect.

3.0 Summary and Conclusions

Analysis of existing historic foil thrust bearing data shows that unlike the journal bearing counterpart, foil thrust bearing load capacity does not increase linearly with speed. For the thrust bearing the theoretical high speed asymptote is often reached and a high speed load capacity drop-off may be encountered. The oil-free turbomachinery designer must take this into account when designing new articles of high speed rotating machinery that utilize this technology.

A preliminary database has been generated that shows robust and repeatable performance of foil thrust bearings up to ~80 percent of their load capacity. However, variability in load capacity from seemingly identical bearings is on the order of ± 25 percent. Based on witness mark observations from high speed load capacity tests the asymptotic high speed limit of foil thrust bearings operating in air appears to be 20 psi when true pad area is used. The foil thrust bearing performance database can be used by analytic model developers to validate and verify foil bearing predictive codes.

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14. ABSTRACT
Foil bearings are self-acting hydrodynamics devices used to support high speed rotating machinery. The advantages that they offer to process fluid lubricated machines include: high rotational speed capability, no auxiliary lubrication system, non-contacting high speed operation, and improved damping as compared to rigid hydrodynamic bearings. NASA has had a sporadic research program in this technology for almost 6 decades. Advances in the technology and understanding of foil journal bearings have enabled several new commercial products in recent years. These products include oil-free turbochargers for both heavy trucks and automobiles, high speed electric motors, microturbines for distributed power generation, and turbojet engines. However, the foil thrust bearing has not received a complimentary level of research and therefore has become the weak link of oil-free turbomachinery. In an effort to both provide machine designers with basic performance parameters and to elucidate the underlying physics of foil thrust bearings, NASA Glenn Research Center has completed an effort to experimentally measure the performance of simple gas foil thrust bearing in air. The database includes simple bump foil supported thrust bearings with full geometry and manufacturing techniques available to the user. Test conditions consist of air at ambient pressure and temperatures up to 500 °C and rotational speeds to 55,000 rpm. A complete set of axial load, frictional torque, and rotational speed is presented for two different compliant sub-structures and inter-pad gaps. Data obtained from commercially available foil thrust bearings both with and without active cooling is presented for comparison. A significant observation made possible by this data set is the speed-load capacity characteristic of foil thrust bearings. Whereas for the foil journal bearing the load capacity increases linearly with rotational speed, the foil thrust bearing operates in the hydrodynamic high speed limit. In this case, the load capacity is constant and in fact often decreases with speed if other factors such as thermal conditions and runner distortions are permitted to dominate the bearing performance.

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