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Compliant Foil Journal Bearing Performance at Alternate Pressures and Temperatures

Robert J. Bruckner and Bernadette J. Puleo
Glenn Research Center, Cleveland, Ohio

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Robert J. Bruckner and Bernadette J. Puleo
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Abstract

An experimental test program has been conducted to determine the highly loaded performance of current generation gas foil bearings at alternate pressures and temperatures. Typically foil bearing performance has been reported at temperatures relevant to turbomachinery applications but only at an ambient pressure of one atmosphere. This dearth of data at alternate pressures has motivated the current test program. Two facilities were used in the test program, the ambient pressure rig and the high pressure rig. The test program utilized a 35 mm diameter by 27 mm long foil journal bearing having an uncoated Inconel X-750 top foil running against a shaft with a PS304 coated journal. Load capacity tests were conducted at 3, 6, 9, 12, 15, 18, and 21 krpm at temperatures from 25 to 500 °C and at pressures from 0.1 to 2.5 atmospheres. Results show an increase in load capacity with increased ambient pressure and a reduction in load capacity with increased ambient temperature. Below one-half atmosphere of ambient pressure a dramatic loss of load capacity is experienced. Additional lightly loaded foil bearing performance in nitrogen at 25 °C and up to 48 atmospheres of ambient pressure has also been reported. In the lightly loaded region of operation the power loss increases for increasing pressure at a fixed load. Knowledge of foil bearing performance at operating conditions found within potential machine applications will reduce program development risk of future foil bearing supported turbomachines.

Introduction

The discovery of the compliant foil journal bearing was initially reported by Blok and VanRussom (ref. 1) in 1953. These bearings are self-acting hydrodynamic bearings having the unique feature of a compliant surface. A representation of a compliant foil journal bearing is shown in figure 1. The main features of these bearings include a rigid sleeve (or bearing housing), a compliant foundation provided by either overlapping leaves or bump foils, the hydrodynamic surfaces of the top foil, and the rotating journal. When stationary, the top foils are preloaded against the journal, which is a departure from traditional hydrodynamic bearings that are characterized by a fixed clearance between the rotating and stationary components. However, even at relatively low rotational speeds, hydrodynamic lubrication quickly builds a gas pressure that acts against the compliant foundation and separates the two moving surfaces. This provides a low friction and maintenance-free rotor support system. These bearings can offer many advantages to high speed turbomachines. These benefits primarily arise from the elimination of an oil system and the associated weight and maintenance burden. Additional benefits may be achieved from the elimination of temperature and rotating speed limits that are found on traditional oil-lubricated bearings. The resulting rotor support system having no oil lubricated and cooled components has become known as "Oil-Free Turbomachinery".

Over the first four decades of foil bearing development these bearings were applied to several types of turbomachines. These applications were characterized by ambient pressure, low temperature, and lightly loaded conditions in centrifuges, cryogenic pumps, and aircraft air cycle machines. Recent advances in foil bearing load capacity and high temperature solid lubricant coatings have broadened the scope of potential applications. Microturbines for distributed power generation are commercially available products as are industrial oil-free compressors and blowers. Oil-free turbojet engines and turbochargers have been demonstrated, while development programs are underway to utilize foil bearings in larger aircraft engines. Future applications that are under consideration are microturbines for closed Brayton cycle power generation systems (ref. 2). One impediment to more widespread use of foil bearings in high speed turbomachines is the general lack of understanding of foil bearing performance at off-design speeds and at relevant ambient pressures and temperatures. Knowledge at both low and high pressures is necessary to provide preliminary guidance for future oil-free turbomachines. Current foil bearing size selection stems from the use of the design generation designation of DellaCorte (ref. 3). However, additional information is required, such as off-design performance, to design the optimum rotor support structure. For example, if one considers a ground-based open Brayton cycle microturbine sized for 30 kW of electrical output, the foil bearings could account for 1.6 kW of power loss. Bearings designed in such a manner could still possess adequate performance in terms of rotor support. However a more appropriate size selection based on actual ambient conditions found in the machine could reduce this power loss by an order of magnitude. Not only would this knowledge benefit the overall system thermodynamic performance, but it would also provide greater life and durability for the engine.

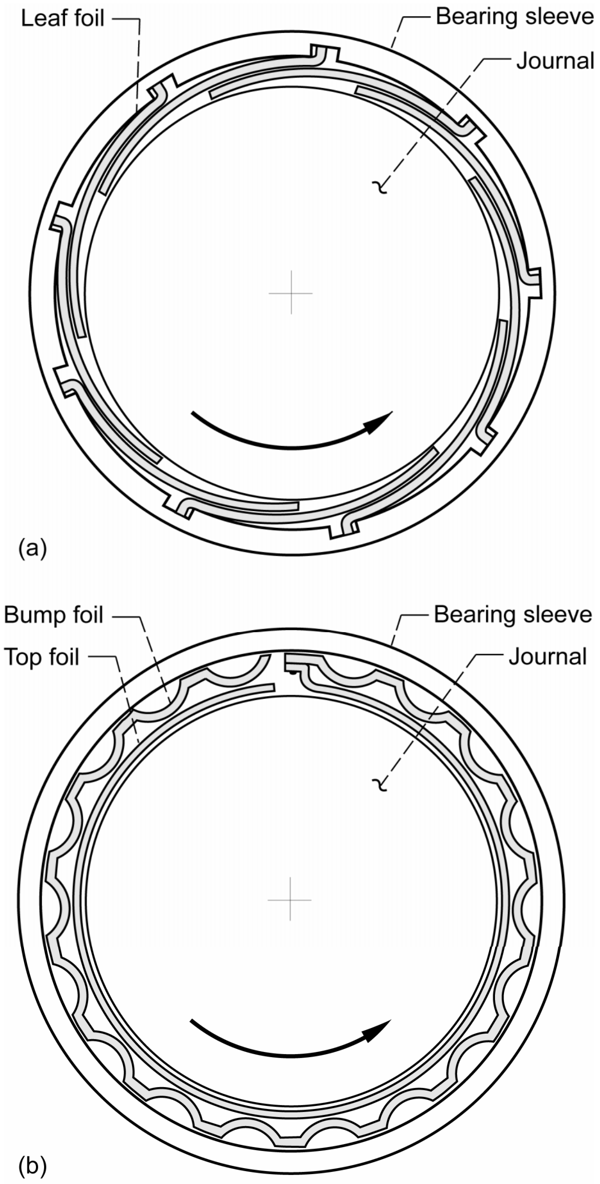

Figure 1.—Early foil bearing designs. (a) Leaf-type foil bearing. (b) Bump-type foil bearing.

Because gas foil bearing performance is a highly coupled phenomenon comprised of large structural deformations, tribology, hydrodynamics, and fluid properties an experimental approach is taken towards furthering the understanding of the effects of ambient environment on foil bearing performance. Experimental performance has been measured on two research rigs, the ambient pressure rig and the high pressure rig. Each of these rigs has a unique capability. The ambient pressure rig is capable of measuring load capacity at pressures and temperatures up to 2.5 atmospheres and 500 °C, respectively. The high pressure rig is capable of measuring lightly loaded bearing performance at pressures and speeds up to 48 atmospheres and 42,000 revolutions per minute, respectively. The experimental results presented herein can be explained through the use of the foil bearing performance map (ref. 4). The basic performance map in three dimensions plots bearing power loss versus shaft speed and unit load. In this perspective the foil bearing exhibits a proportional trend with load and a parabolic trend in speed where a power loss minimum may be identified. The performance trends found in the current test program indicate that pressure and temperature effects can best be described as a translation along the rotational speed axes on the foil bearing performance map.

Nomenclature

$\mathcal{D}$	Load capacity coefficient, mN/(mm^{3}krpm) [lbf/(in.^{3}krpm)]
W	Load supported by foil bearing, N [lbf]
D	Diameter of journal, mm [in.]
L	Length of bearing, mm [in.]
N	rotational speed, kilo-revolutions per minute (krpm)
P	ambient pressure of bearing cavity, atm
T	ambient temperature of bearing cavity, °C

Subscripts

pl	preload
t	total
dw	deadweight

Foil Bearing Description

Foil gas bearings are compliant surface, self-acting hydrodynamic bearings that use ambient gas as their working fluid or lubricant. They do not require external pressurization and are typically constructed from several layers of sheet metal foils from which they derive their name. The reader is again referred to figure 1 which shows examples of early style journal bearings. The top bearing in figure 1 is commonly referred to as an overlapping leaf design while the lower bearing is a bump foil design. These names stem from the design and architecture of the compliant layer beneath the top foil. This innermost foil, top foil, serves as the hydrodynamic surface that traps the high pressure gas film between it and the rotating shaft. Foil bearings are used in many lightly loaded, high-speed turbomachines such as compressors used for aircraft pressurization and micro-turbines. Foil gas bearings provide a means to eliminate the oil system leading to lower system weight and enhanced temperature capability. Additionally, the elimination of the oil system can lead to a maintenance-free machine. Under static conditions the top foil is preloaded against the shaft, W_{pl}, such that there is no static clearance or eccentricity between the stationary and rotating parts. This is a fundamental difference between the foil bearing and rigid hydrodynamic bearings and gives rise to additional parameters required to characterize these bearings (ref. 5). Additionally, the design generation or load capacity coefficient is a third parameter that characterizes a foil journal bearing. Dellacorte (ref. 3) identifies a design classification scheme that correlates compliant foundation complexity with bearing load capacity. A generation I design consists of a uniform stiffness foundation and is typical of early foil bearings. Generation II bearings vary the compliant foundation in one direction, for example in the axial or circumferential direction. Generation III bearings vary the compliant foundation in at least two directions. DellaCorte goes on to quantify the load capacity of foil journal bearings according to equation (1). In the steady state performance testing of foil bearings great care is taken to minimize all applied loads other than the preload and deadweight load such that the total load is known very accurately. The performance coefficient is typically 0.08, 0.19, and 0.27 mN/(mm^{3}krpm) [0.3, 0.7, and 1.0 lbf/(in.^{3}krpm)] for generation I, II, and III bearings respectively.

$$W_t = \mathcal{D}\,(L \times D)\,(D \times N) \qquad (1)$$

Where,

$$W_t = W_{pl} + W_{dw} + W_{dynamic} + W_{thermal} + \ldots$$

For the foil bearings used in this test program, typical values for friction coefficient, preload and load capacity coefficient measured at room temperature and ambient pressure are 0.45, 3.7 kPa [0.54 psi], and 0.27 mN/(mm^{3}krpm) [1.0 lbf/(in.^{3}krpm)]. The friction coefficient is quite high, especially considering that low friction is desirable for this application. This high value is caused because only materials suitable for high temperature applications are used. The foil bearings use uncoated Inconel top foils and the shaft is coated with PS304, a high temperature solid lubricant (refs. 6 and 7). Lower friction coefficients may be obtained for low temperature applications by using highly polished shaft surfaces with thin dense chrome plating and organic polymer coated topfoils.

Foil Bearing Applications

Although originally discovered in the early 1950s gas foil bearing technology first developed for use in turbomachinery in the 1960s to support high speed rotating shaft systems that could not operate using conventional oil-lubricated bearings or rigid geometry gas bearings due to contamination, speed and thermal stability requirements (refs. 8 to 10). Foil bearings have evolved to the point where they are in commercial use in specialized applications such as air cycle machines, turboexpanders and compressors, and small micro-turbine systems (refs. 11 and 12). Foil bearings have also been demonstrated as “proof of concepts” in diesel engine turbochargers, auxiliary power units, expendable turbojet engines, and selected hot section bearings in gas turbine engines (refs. 13 to 15).

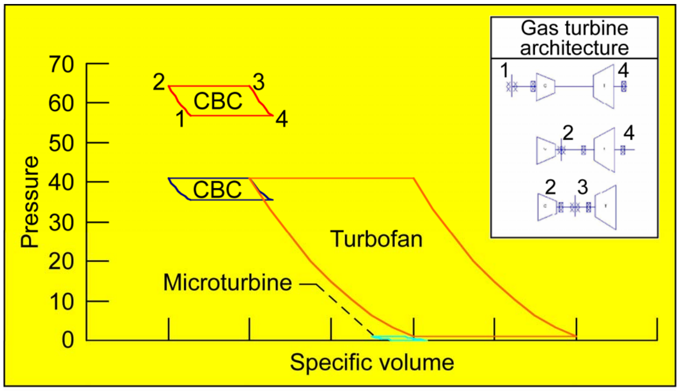

Figure 2.—Representative Brayton cycles and turbomachinery architectures.

The implementation of foil bearings to new applications requires an understanding of foil bearing operation at a variety of operating conditions. Figure 2 shows several candidate Brayton cycle applications along with various single-spool architectures that could be used with these cycles. In addition to high pressure and temperature conditions found in the central region of a Brayton cycle machine, potential high altitude aeronautical applications require low pressure operating characteristics to be understood. Examination of the cycles and architectures in figure 2 indicates that in order to make strategic decisions in the conceptual design phase, the machine designer requires knowledge of foil bearing sizing and operation over an extremely large range of pressures and temperatures. The current test program has investigated the behavior of foil bearings in the highly loaded region (near load capacity) as a function of temperature from ambient conditions to 500 °C and pressure from 0.1 atmospheres to 2.5 atmospheres in air. Additionally, limited data of lightly loaded foil bearings in pressures up to 48 atmospheres has been analyzed in this study. The current study is intended to provide design guidance at the system level to bound the sizing and performance of foil bearings at various operating conditions. An experimental approach is taken in this study because foil bearings are somewhat poorly understood analytically and there are currently no non-empirical, predictive design tools that can be used to accurately determine foil bearing performance over such a wide range of loads, pressures, temperatures, and speeds.

Test Rigs and Procedures

The primary test rig used in generating the current database is the ambient pressure rig. The rig is shown in figure 3. The rig consists of a motor driven spindle and journal capable of speeds up to 30,000 rpm. A furnace can enclose the test bearing and journal. Testing can be conducted at temperatures up to 500 °C. A pneumatic loader is used to apply variable loads in excess of failure loads for a generation III foil bearing. A precision load cell mounted outside of the furnace measures bearing reaction torque. The entire test rig is enclosed in an aluminum chamber. This chamber can be evacuated to 0.1 atmospheres and pressurized to 2.5 atmospheres. A variety of inert gases can be used in this test

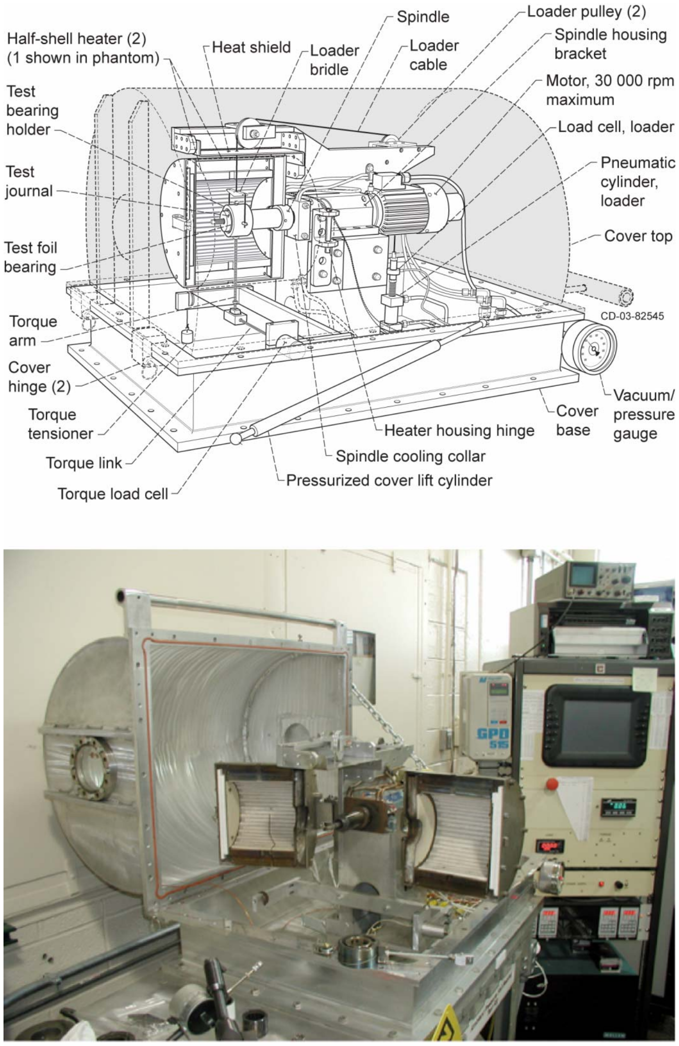

Figure 3.—The ambient pressure rig.

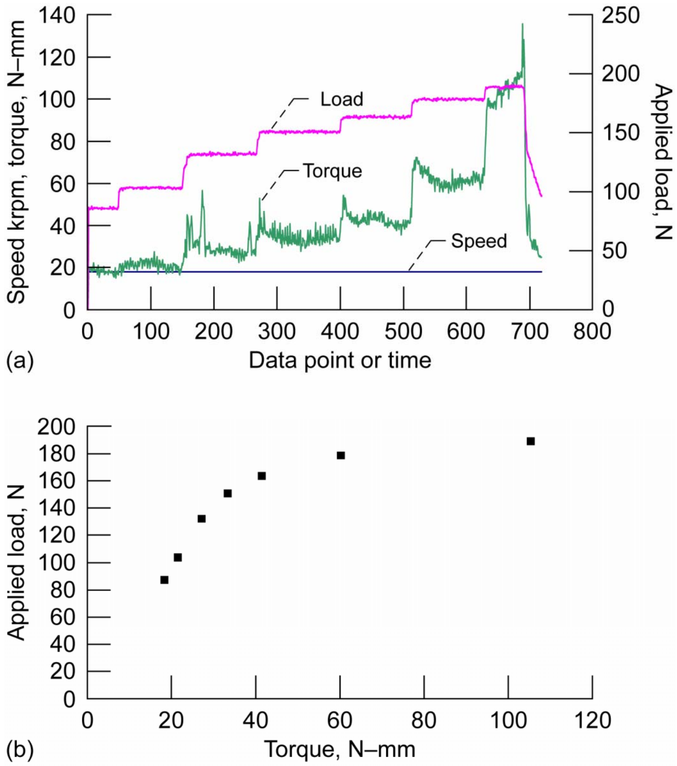

Figure 4.—(a) Typical time trace from the ambient pressure. (b) The resultant load–torque characteristic.

rig to investigate gas property effects on foil bearing performance. For the current test program only air has been used as a foil bearing lubricant. Generation III foil journal bearings with uncoated Inconel top foils running against conditioned PS304 high temperature solid lubricant coated shafts were used in this study. The test procedure used on this rig includes a preliminary conditioning of the PS304 coated shaft which includes running 500 start-stop cycles under load at high temperature to develop a highly polished, smooth, and lubricious hydrodynamic surface on the shaft. This conditioning procedure also transfers solid lubricants from the shaft coating to the top foil. Once the foil bearing and shaft have been properly characterized and conditioned, performance testing was conducted. The performance tests are conducted at constant speed, temperature, and pressure. Once these conditions are set and stable, the radial load was applied to the bearing. The load was increased in steps while the reaction torque is monitored on the data acquisition system. Figure 4 shows a typical time trace of such a performance test as well as the resultant load – torque characteristic of the bearing at the test conditions. The load, and hence reaction torque, continue to increase until the gas film is no longer able to support the load. This condition is indicated when the reaction torque rises sharply with a modest increase in radial load. The resultant data can then be analyzed to determine the load capacity and load – torque characteristic of the foil bearing at a given operating condition. The load capacity is typically determined by averaging the incipient film rupture and post load capacity points (the two points in the upper right in figure 4(b)).

A second rig used in this study is the high pressure rig. The rig is shown in figure 5. The rig is a simplification of the ambient pressure rig. The simplifications were made in order to certify the rig to extremely high pressure, up to 48 atmospheres. The rig consists of a motor driven spindle and journal capable of speeds up to 42,000 rpm. Testing is limited to 38 °C [100 °F]. Radial loading is accomplished by placing balanced annular weights over the journal, as such the maximum load that can be tested in this rig is approximately 55 N [12 lbf]. There is no ability to vary applied radial load on this rig, which limits the steady state test data to lightly loaded conditions. A precision load cell is mounted close to the bearing center due to space limitations. This close coupling of the load cell also limits the range of reaction torque and power loss that can be measured on this rig. The entire test rig is enclosed in a pressure vessel. This pressure vessel can be evacuated to 0.1 atmospheres and pressurized to 48

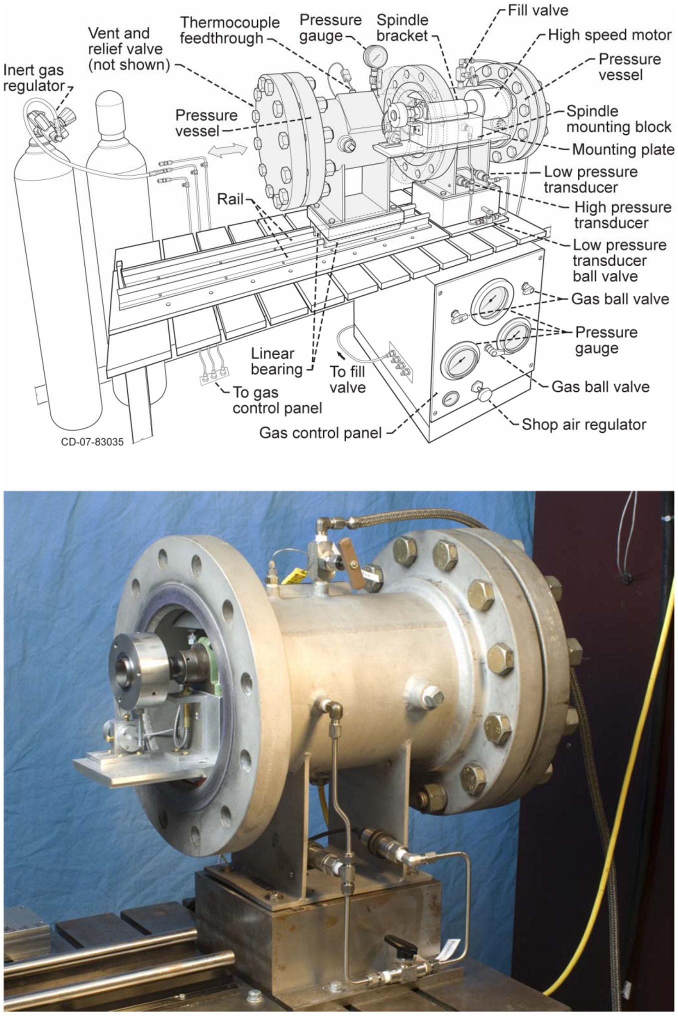

Figure 5.—The high pressure rig.

atmospheres. A variety of inert gases can be used in this test rig to investigate gas property effects on foil bearing performance. For the current test program only nitrogen has been used as a foil bearing lubricant. Generation III foil journal bearings with uncoated Inconel top foils running against conditioned PS304 high temperature solid lubricant coated shafts were used in this study. The test procedure used on this rig includes a preliminary conditioning of the PS304 coated shaft, which includes running a series of start-stop cycles under radial load. High temperature start-stop cycles cannot be run on this rig, which therefore limits the load capacity coefficient to approximately 0.19 mN/(mm^{3}krpm) [0.7 lbf/(in.^{3}krpm)]. The test procedure for this rig includes using one fixed, "deadweight" load, setting the chamber test gas and pressure, and accelerating to maximum speed as quickly as possible. Steady state data is then collected by reducing speed in set increments and recording reaction torque until the minimum power loss level is found. Figure 6 contains reduced data showing the similarity of steady state and startup data for the high pressure rig.

Figure 6.—Typical transient and steady state data from the high pressure rig.

Experimental Results

Experimental results obtained from the ambient pressure rig are shown in figures 7, 8, and 9. Figure 7 presents specific power loss as a function of applied load for a series of rotational speeds. The conditions in the test chamber, bearing cavity, are ambient temperature, 25 °C, and pressures ranging from 0.1 to 2.5 atmospheres. The performance of the bearing at 0.1 atmosphere pressure is characterized by (l) low load capacity, (2) small operating range, and (3) non-linear load versus power loss trend. Beginning with the 0.7 atmosphere bearing performance and continuing through the 2.5 atmosphere performance the operating range and load capacity of the bearing continues to increase with increasing pressure. In addition, the load versus power loss trend begins to show two phases. The first phase is a gradual, nearly linear, trend followed by a sharp, non-linear, trend in this characteristic as the load capacity point is approached. The foil bearing performance trends as a function of ambient pressure can be summarized such that for increasing pressure the load capacity and linear operating range increases.

Figure 8 presents power loss as a function of applied load for two different temperatures, 200 and 400 °C, at 1.0 atmosphere of pressure. The trend shown in this figure indicates that foil bearing load capacity decreases with increasing temperature. Since, for a gas, absolute viscosity increases with temperature, this result is often considered somewhat contradictory when compared to traditional hydrodynamic theory. Typically, hydrodynamic pressure and load capacity increase proportionally with viscosity. These results, which are consistent with previously published data on compliant foil bearings, point primarily toward a softening of the compliant foundation due to thermal effects on the Inconel X-750 modulus. An additional impact is the reduced lubricant density at higher temperatures that reduces the massflow through the bearing. With reduced massflow but similar rates of shear in the gas film, heating is increased and a thermal run-

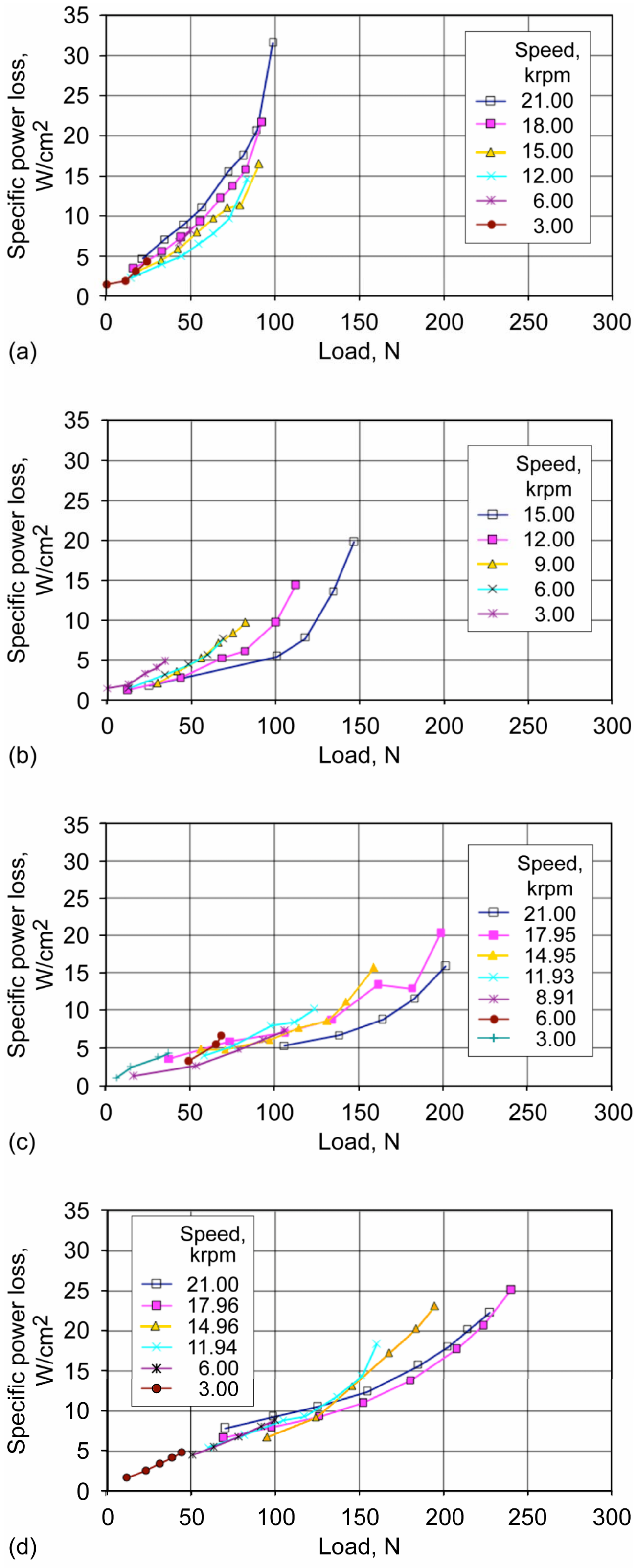

Figure 7.—Foil bearing performance in air at ambient temperature and various pressures. (a) 0.1 atm. (b) 0.7 atm. (c) 1.5 atm. (d) 2.5 atm.

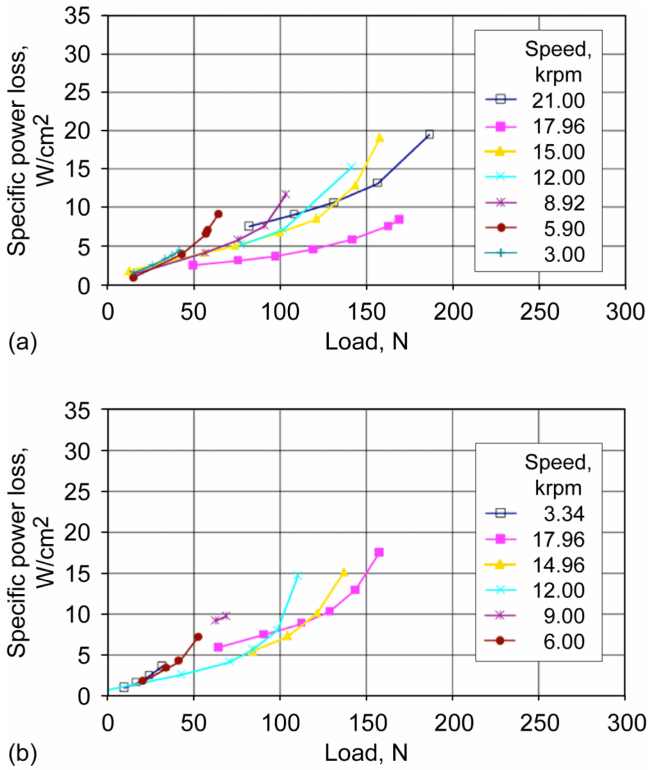

Figure 8.—1.0 atmosphere ambient pressure foil bearing performance in air at two temperatures. (a) 200 °C. (b) 400 °C.

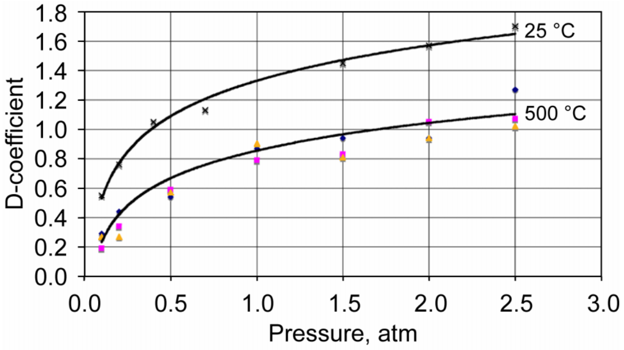

Figure 9.—Load capacity coefficient versus pressure for 25 °C and 500 °C.

away load capacity failure is more likely to occur at lower loads for a high temperature gas. Figure 9 presents a compilation of foil bearing load capacity coefficient spanning the range of test data from 0.1 to 2.5 atmospheres and 25 to 500 °C. The trend shows an increase in load capacity with increasing bearing cavity pressure. Below approximately 0.5 atmospheres of pressure the load capacity drops off dramatically, which is indicative of a starved bearing condition. Under these conditions there simply are not enough molecules of lubricant to support the load. At higher pressures load capacity increases with increasing pressure.

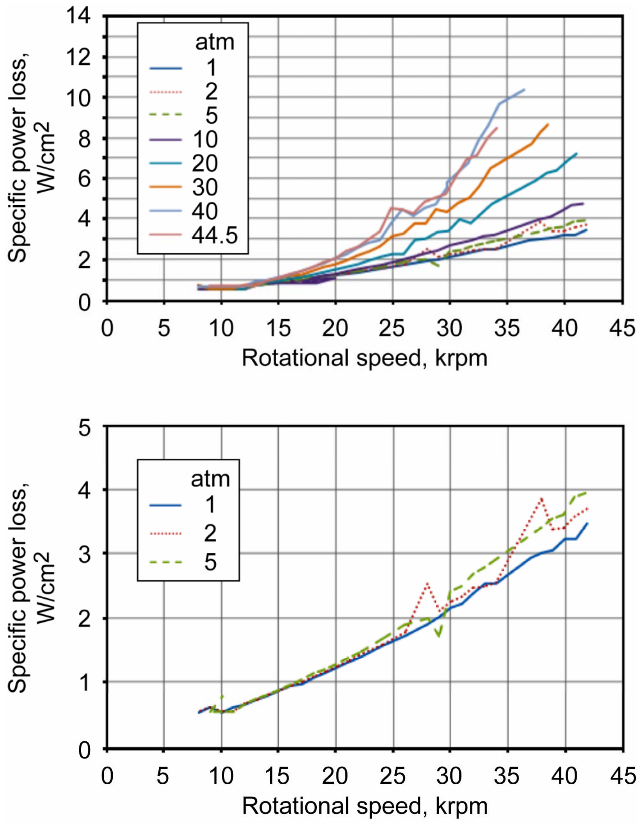

Figure 10.—The lightly loaded region of the foil bearing performance map from 1 to 44.5 atmosphere ambient pressure. Applied load = 14 N.

Lightly loaded bearing performance data is presented in figure 10. The data show specific power loss versus rotational speed for ambient pressures up to 48 atmospheres, 25 °C, nitrogen gas, and constant load of 14 N (3.1 lbf). The trends converge at the minimum power loss point, but diverge with increasing speed. The overall trend shows an increase in bearing power loss with increasing pressure. This appears to be an opposite trend to that discussed previously with regard to the temperature effects. In this instance, the increased lubricant density appears to be detrimental to the performance and power loss of the bearing. While no bearing failures occurred due to the high pressures, and in fact the absolute power loss remained low compared to the power loss at load capacity, these contrary trends require further investigation. Although, the two test rigs utilized in this study have a capability range with some overlap, it is critical to the complete understanding of these trends that the entire foil bearing performance map from load capacity to the very lightly loaded regime be tested in a consistent manner.

Conclusions

The experimental results presented herein demonstrate the performance variability of foil journal bearings with respect to load, speed, ambient temperature, and ambient pressure. While these results encompass only a small range of potential foil bearing applications they do provide initial design guidance to designers of future microturbines. Foil journal bearings exhibit an increase in load capacity with increasing pressure and a decrease in load capacity with increasing temperature. These results are consistent with the fact that the compliant foundation is softened at elevated temperatures and that foil bearings typically fail or reach load capacity due to a thermal overload. The reduced massflow through the bearing at low pressures and high temperature therefore leads to reduced load capacities. Foil bearings show robust operation down to 0.5 atmospheres of ambient pressure. Below this pressure level it appears as though foil bearing operation would be more challenging.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

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