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A New Foil Air Bearing Test Rig for Use to 700 °C and 70,000 rpm

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A NEW FOIL AIR BEARING TEST RIG FOR USE TO 700 °C AND 70 000 rpm

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SUMMARY

A new test rig has been developed for evaluating foil air bearings at high temperatures and speeds. These bearings are self acting hydrodynamic air bearings which have been successfully applied to a variety of turbomachinery operating up to 650 °C. This unique test rig is capable of measuring bearing torque during start-up, shut-down and high speed operation. Load capacity and general performance characteristics, such as durability, can be measured at temperatures to 700 °C and speeds to 70 000 rpm. This paper describes the new test rig and demonstrates its capabilities through the preliminary characterization of several bearings. The bearing performance data from this facility can be used to develop advanced turbomachinery incorporating high temperature oil-free air bearing technology.

INTRODUCTION

Foil air bearings are compliant, self-acting hydrodynamic fluid film bearings which use air as their working fluid or lubricant. Recent advances in foil air bearing design, finite element based rotordynamic analyses and high temperature solid lubrication provide the opportunity for new applications such as advanced oil-free turbomachinery. Potential applications include oil-free turbocompressors and gas generators and, eventually, gas turbine engines operating on foil air bearings at both low and high temperatures.

One impediment to the continued use and development of foil air bearings is the scarcity of appropriate bearing performance test facilities. Existing facilities for foil bearing development have lacked either the ability to make torque measurements or run at speeds above 60 000 rpm (refs. 5 and 6). This paper describes a new facility for testing the performance of foil air bearings and their complimentary start/stop lubricants over a wide range of speeds and temperatures.

The bearing load, speed and temperature are the test variables which can be controlled. Bearing friction (torque) can be measured during start-up and shut-down as well as while airborne. Table I lists the test capabilities of the new facility. The rig design layout and other aspects are discussed in detail in the following sections. The performance of several foil bearings is reported in the final section to illustrate the data output and capabilities of the test rig.

General Layout/Design

An illustration of the test rig is shown in figure 1 with call-out labels highlighting important features. The rig consists of an impulse air turbine driven spindle, over-hung removable test journal and bearing, furnace scatter shield, and data/health monitoring support system.

Spindle Description

An aluminum impulse air turbine drives the spindle to its maximum safe speed of 70 000 rpm. The turbine is supplied with filtered, compressed air from 0 to 120 psi and is controlled by a regulator and two pneumatically operated shut-off valves. One of these valves is proportioned for speed control. The other is controlled by on/off timers for evaluating bearing material durability during multiple starts and stops. For emergency shut downs, this on/off valve is closed by the alarm circuitry of the test rig.

The spindle is supported on two preloaded angular contact ball bearings. The ball bearings are of the hybrid type made with silicon nitride balls and steel races with a bronze cage. A common turbine engine oil (MIL-L-23699 C) is used to lubricate and cool the bearings. Lubrication is delivered through oil jets which are independently controlled via manual needle valves to allow adjustments for optimum oil flow rates. The jets are supplied by a gear pump that draws oil from a temperature controlled sump. A scavenge pump assists in the drainage of oil from the spindle back to the sump.

The front bearing has a bore (35 mm) slightly larger than the back bearing (25 mm) to accommodate the large radial loads applied to the test foil bearing by the pneumatically controlled loading system. At the maximum test speed of 70 000 rpm, the bearings are expected to last 600 to 6000 hr depending on the radial load.

Sealing of the oil-lubricated support spindle from the test section is accomplished by using both a slinger seal and a purge gas buffered labyrinth seal. Compressed air is used for the purge gas. A labyrinth seal alone is used at the turbine end to prevent oil from leaking from the spindle. A tie bolt running through the center of the shaft is used to clamp the components (turbine, seal runners, bearing races, etc.) together.

A series of heat shields are used to protect the bearings and spindle from the extreme test temperatures. The shields are comprised of several layers of superalloy sheets stacked over the front of the spindle each separated by an air gap. Behind this stack is a ceramic insulator which further reduces conductive heat transfer from the stack to the spindle housing. The front (test chamber side) section of the drive spindle (shaft) is made from a thin walled superalloy to act as a heat dam to reduce heat conduction from the test journal to the center part of the spindle. The relatively low thermal conductivity of superalloys compared to most metals and steels further reduces the heat flow. Using the described methods of thermal management there is no difficulty in achieving a 600 °C thermal gradient between the test journal and the oil lubricated section of the spindle located just 50 mm away.

Test Specimen Description

The removable test journals are also hollow and are shown in figure 2. The journal is held onto the spindle shaft with a locking nut affixed to the front end of the tie bolt. The test journals are nominally 35 mm in diameter and 35 mm long. The journals have a series of twelve equally spaced, threaded holes in the front face to accommodate weights for in-place high speed dynamic balancing. Journals which are coated on the outside diameter are usually premachined to a smaller diameter (typically 0.5 mm) to compensate for the coating thickness.

The test bearings have an inside diameter of 35 mm and a length of 25 mm and are generally made up of several layers of foils (top and spring bump foils) welded into a rigid test bearing sleeve 46 mm in diameter. Schematics of typical leaf-type and bump-type foil bearings are shown in figure 3. The sleeve fits into a deadweight housing sized to simulate the static contact pressures (loads) for an intended application. Typical static loads experienced by foil bearings during start-up and shut-down are 7 to 21 Kpa (1 to 3 psi).

A torque rod is attached to the top of the dead weight housing and passes up and out of the furnace test chamber where it is connected to a force transducer using a connecting rod. A counter weight is used to maintain a light (100 g) preload on the transducer and to help locate the bearing torque arm (fig. 4).

A cable, attached to the dead weight housing, passes through the bottom of the furnace. The cable is connected in series to a flexure spring pack, load cell and pneumatic cylinder located under the test rig table. By pressuring the pneumatic cylinder, additional load (up to 500 N) can be applied to assess bearing power loss and load capacity.

Furnace/Scatter Shield Description

The furnace is comprised of eight (500 W) Quartz tubes equally spaced circumferentially inside a double walled superalloy furnace enclosure. The furnace is split into two sections along the torque arm centerline facilitating access to the test specimens. Ceramic fibrous insulation is incorporated between the double walls to reduce heat loss. With this furnace, the specimens can be heated from 25 to 700 °C in less than 15 min. Proximity thermocouples located inside the furnace are used for temperature measurement and control.

The furnace is surrounded by a scatter shield designed to contain any shrapnel which might result from a high speed bearing/shaft failure. The scatter shield is fabricated from 1.25 cm thick stainless steel and, like the furnace, is made in two sections. Each furnace/shield side is bolted together and is light enough to be manually lifted by one person. A third section of the scatter shield is formed from a plate which covers the front of the furnace for added safety. Access holes for the torque arms, load cable and a front viewing port are provided in both the furnace and shield.

Instrumentation/Health Monitoring

The measurements system for the test rig can be separated into two subsystems: instrumentation for bearing performance data collection and instrumentation for test rig health monitoring. For data collection, the instrumentation is used to measure bearing torque, applied load, ambient temperature and shaft speed. The bearing torque is measured using a Linear Voltage Differential Transducer (LVDT) force transducer connected to a torque arm as shown in figure 4. This transducer has a working range of ± 250 g force with 0.1 g resolution which corresponds to a bearing torque of 520 N-mm (± 73.2 in.-oz) with a resolution of 0.2 N-mm. Bearing torque measured during foil bearing start-up/shut-down prior to lift off is typically 140 N-mm (20 in.-oz). Once airborne, the torque is substantially reduced to about 7 N-mm (1-2 in.-oz) depending on the bearing load.

The foil bearing is loaded in two ways. The first is by the weight of the bearing housing which is sized to provide static loads of 7 to 21 KPa (1 to 3 psi). Additional load, up to 500 N, is applied through the pneumatically operated cable system described previously. By applying varying loads on the bearing during full speed as well as start/stop cycling, bearing friction, power loss, and load capacity can be established.

The ambient bearing temperature, that is, the temperature of the air surrounding the bearing housing, is measured using three independent chromel-alumel thermocouples. The signals from these thermocouples are also used for control of the furnace temperature by a proportional, integral, derivative (PID) type controller.

Test shaft speed is a critical bearing performance parameter. It is precisely measured using a noncontacting optical sensor system. This system uses a fiber optics probe which shines an LED light source onto the face of the drive turbine. The face is coated with flat black paint except in one small angular segment which is polished aluminum. Each time this polished segment passes the fiber optics probe, the incident light is reflected back into the probe and detected by a light sensor built into the probes signal conditioner. The signal conditioner converts the reflected light pulse into a corresponding electrical pulse which is counted by a frequency to analog converter to display shaft speed. In addition, the pulse signals are fed into a digital vector filter used to measure shaft vibration and phase angles in order to provide data used for dynamic spin balancing of the shaft.

Although not affecting the data, the health monitoring system of the rig is critical to its operation. This system is comprised of flow meter sensors which monitor oil flow to and from the bearing spindle, oil and bearing temperature sensors, supply air pressure sensors, two accelerometers 90° apart at each support bearing location. In addition, a controlled temperature cooling water loop runs through the spindle and oil sump.

All of these sensors are monitored by electronic readout gages with alarm trip points which, depending upon the alarm condition, have the ability to partially or fully shut down the test rig. For example, if the furnace temperature exceeds the alarm set point the power to the quartz tubes is shut off while leaving the oil pumps operating. This prevents heat soak back from coking the oil in the bearings. On the other hand, if the oil supply flow meter senses low oil flow, the air turbine, oil pumps and furnace are all turned off.

The alarm that initially trips also engages a readout on an annunciator panel so the operator can know what caused the rig to shut down. By utilizing this comprehensive health monitoring system the test rig can be safely operated unattended. Unattended operation is especially important for durability tests which may run for over 100 hr.

Test Facility Operation

The facility operates in two modes, continuous manual operation for bearing performance measurements and automatic start/stop operation for durability assessments. Under continuous manual operation, a test bearing is mounted onto the test shaft and all of the appropriate connections are made (i.e. torque arm, load cable, thermocouple placement etc.). Then the bearing is started by opening the air supply valve. The bearing is accelerated to beyond its lift-off speed, which is typically 3000 to 6000 rpm, to a nominal speed of 20 000 rpm. Then the furnace is heated to the desired test temperature and allowed to soak for 15 min. At this point, measurements of bearing torque, or power loss, as a function of speed and load can be made by varying these parameters while monitoring the torque. Figure 5 is an example of bearing torque as a function of speed under a constant 18N (4 lb) load. As can be seen from the figure, the torque is highest at very low speeds corresponding to a very thin gas film and hence high shear rates. At increased speeds, the torque is reduced through a minimum and then increases monotonically. This general behavior is typical of fluid film bearings and resembles the Stribeck effect. Figure 6 shows bearing friction (torque) as a function of load at 40 000 rpm and 25 °C. This figure shows that bearing friction increases with load, an expected result.

This data can be used to give turbomachinery designers valuable information on bearing performance. For example, at 40 000 rpm and a 120 N (24 lb) load the power loss is measured as 130 W (0.174 HP) or a calculated friction coefficient of 0.017. Using this value, the power loss can then be added to a thermal system analysis to determine cooling requirements.

To determine bearing load capacity, the rig is run to a high speed and a load, lower than the expected load capacity, is applied. The turbine speed is then gradually lowered until a sharp rise in bearing torque, which signals sliding contact, is observed. The speed at which this occurs is considered the load capacity. After recording this speed the bearing is accelerated and the procedure is repeated several times to determine the minimum speed required to support the selected load for a particular bearing at a given temperature.

Figure 7 shows the load capacity plotted as a function of shaft speed for a single test bearing at temperatures from 25 to 650 °C. Although there is some overlap, the load capacity decreases with temperature. This is probably because the bearing support structure stiffness decreases as the temperature increases. Partially off-setting this effect, the kinematic viscosity of the gas increases with temperature leading to an increased hydrodynamic effect. Clearly this type of performance data could be used to model the complex elastic-hydrodynamic system operating in a compliant foil bearing.

Durability assessments are made by utilizing the rig in its automatic start/stop mode. In this mode, the turbine is turned on and off using a set of timers connected to the air supply system. A typical cycle starts from rest and accelerates the bearing to 40 000 rpm, then lets the system coast down to rest again over a 20 sec period. With this timing sequence, the bearing experiences 3 start/stop cycles a minute or 4 320 in a 24 hr period. Figure 8 shows the bearing torque as a function of speed during a cycle. During initial rotation, the foil experiences dry sliding contact against the journal and the torque is the highest. As the bearing accelerates the gas film pressure builds forcing the compliant bearing surface away from the shaft resulting in lower friction. Lift off occurs around 5000 rpm and is often accompanied by a slight discontinuity in the torque signal as shown in the figure. The reverse occurs during shut down. At elevated temperatures the behavior is similar but less pronounced because bearing preload is reduced due to thermal expansion, as shown in figure 9.

For a typical durability assessment, a bearing is operated in the start/stop mode unattended with 24 hr inspection intervals to measure wear and inspect bearing surfaces. Durability assessments are expected to last from 10 000 to 20 000 start/stop cycles to simulate various turbomachinery applications. These types of durability assessments are critical to determine long term bearing performance and the effects of wear and debris on bearing operation.

CONCLUDING REMARKS

The high temperature, high speed bearing test rig has been fully developed. In its present form, it is capable of measuring foil bearing performance at temperatures to at least 700 °C and speeds to 70 000 rpm. The data from this test facility can provide valuable input for bearing development and application. The results from this facility may enable future more aggressive applications of compliant foil air bearing technologies to oil-free turbomachinery.

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TABLE I

Rig parameter	Range of values	Estimated accuracy
Test speed	0 to 70 000 rpm	±10 rpm
Test temperature	24 to 700 °C	±5 °C
Test load	5 to 500 N	±0.3 N
Torque measurement	0 to 520 N-mm	±0 N- mm ±0.2 N-mm

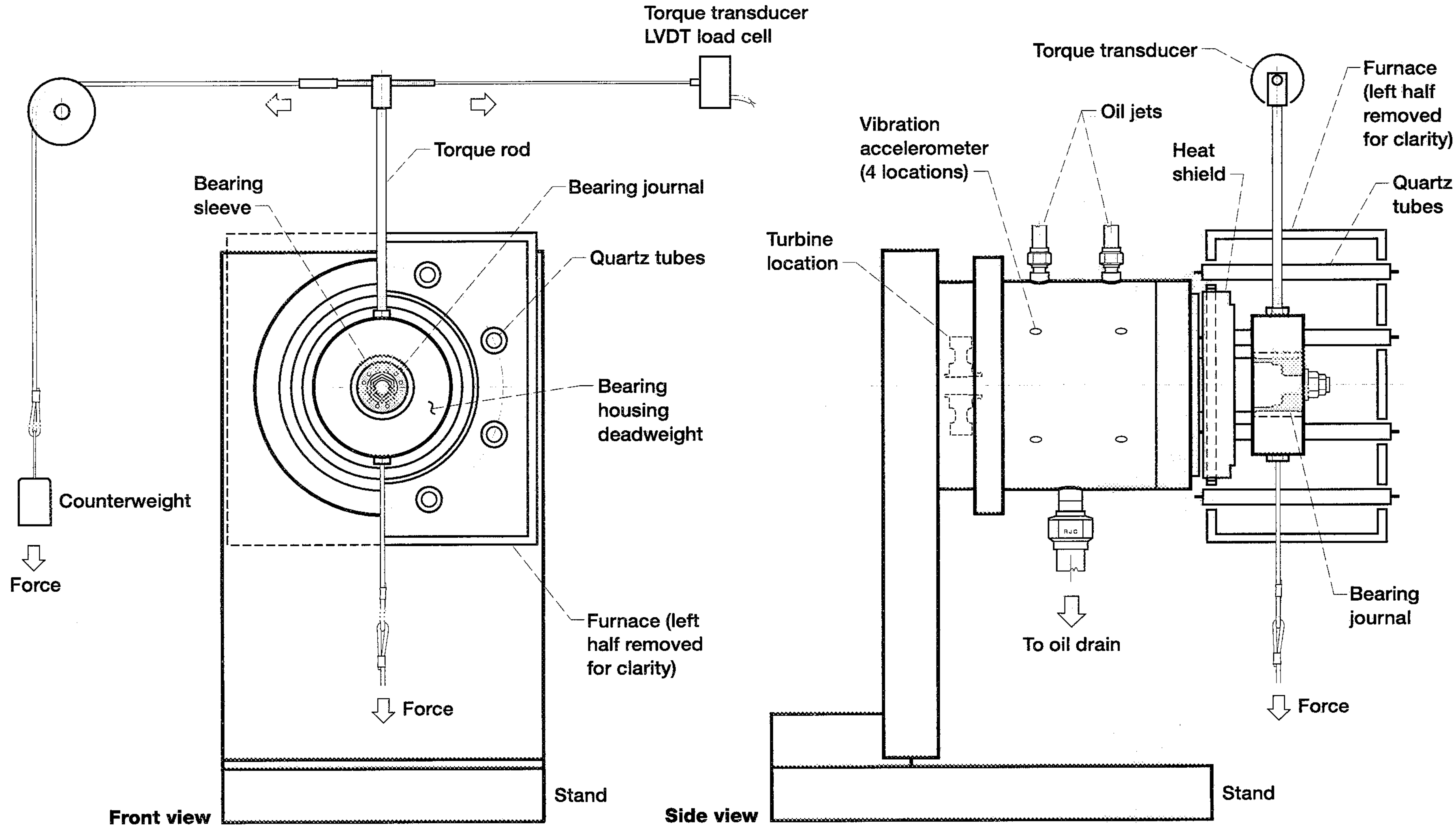

Figure 1. —Schematic view of high-temperature, high-speed foil bearing test rig.

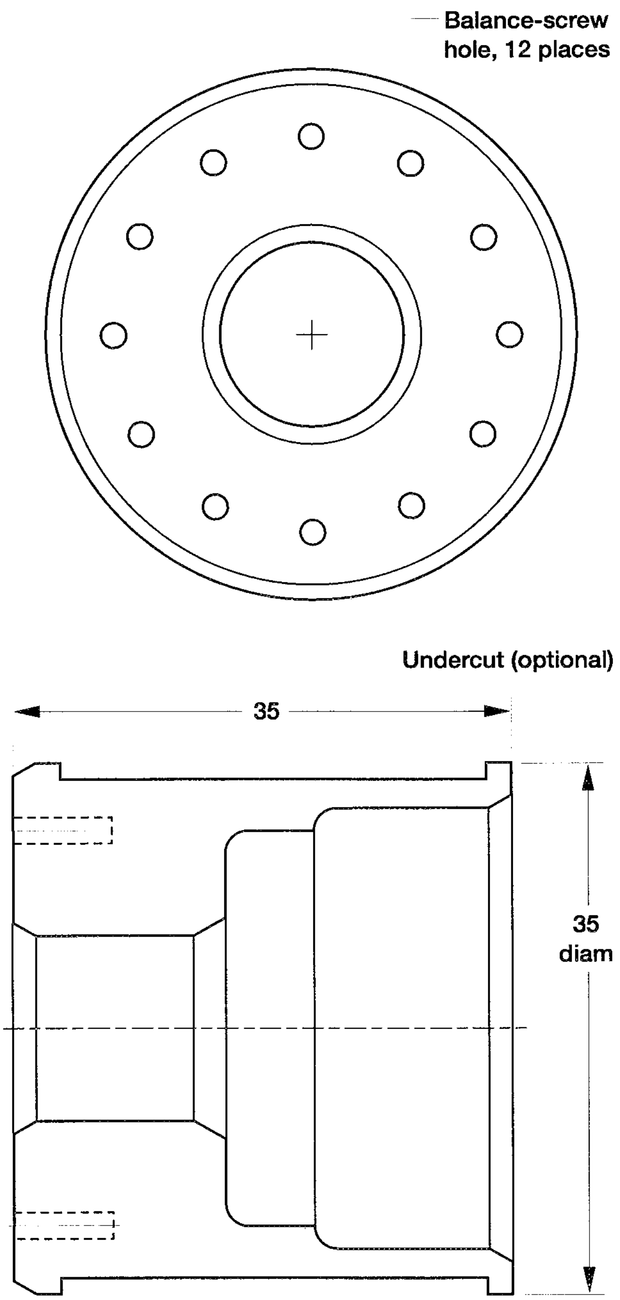

Figure 2.— Test journal. Note undercut on outside diameter of journal may be machined to accomodate a journal coating. Dimensions in mm.

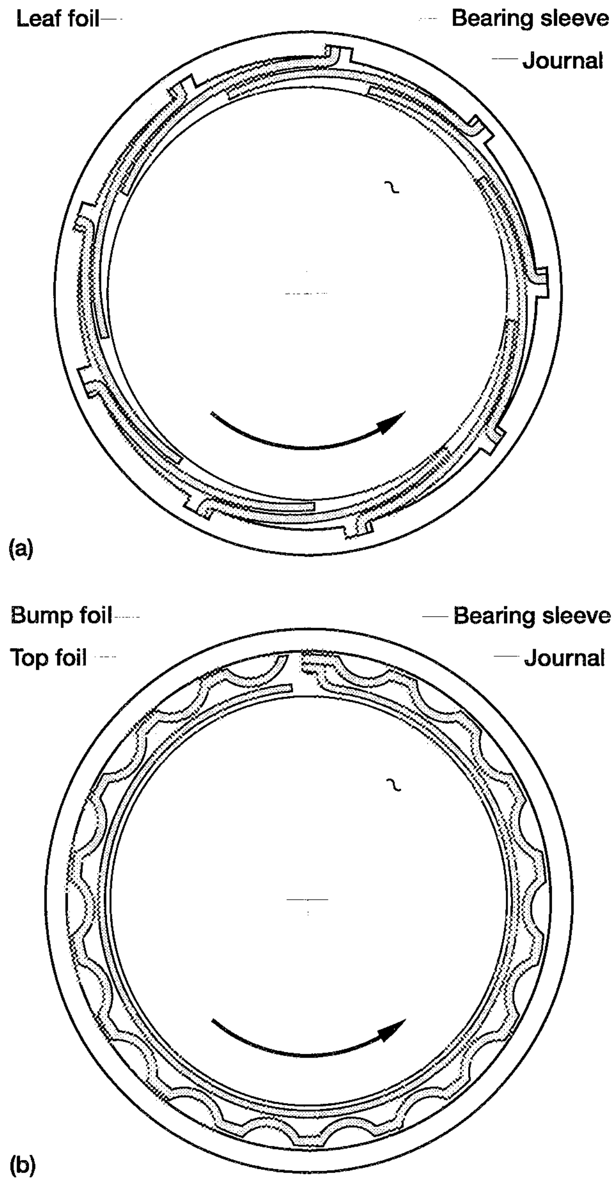

Figure 3.— Typical foil bearing test sleeves. (a) Leaf-type foil bearing. (b) Bump-type foil bearing.

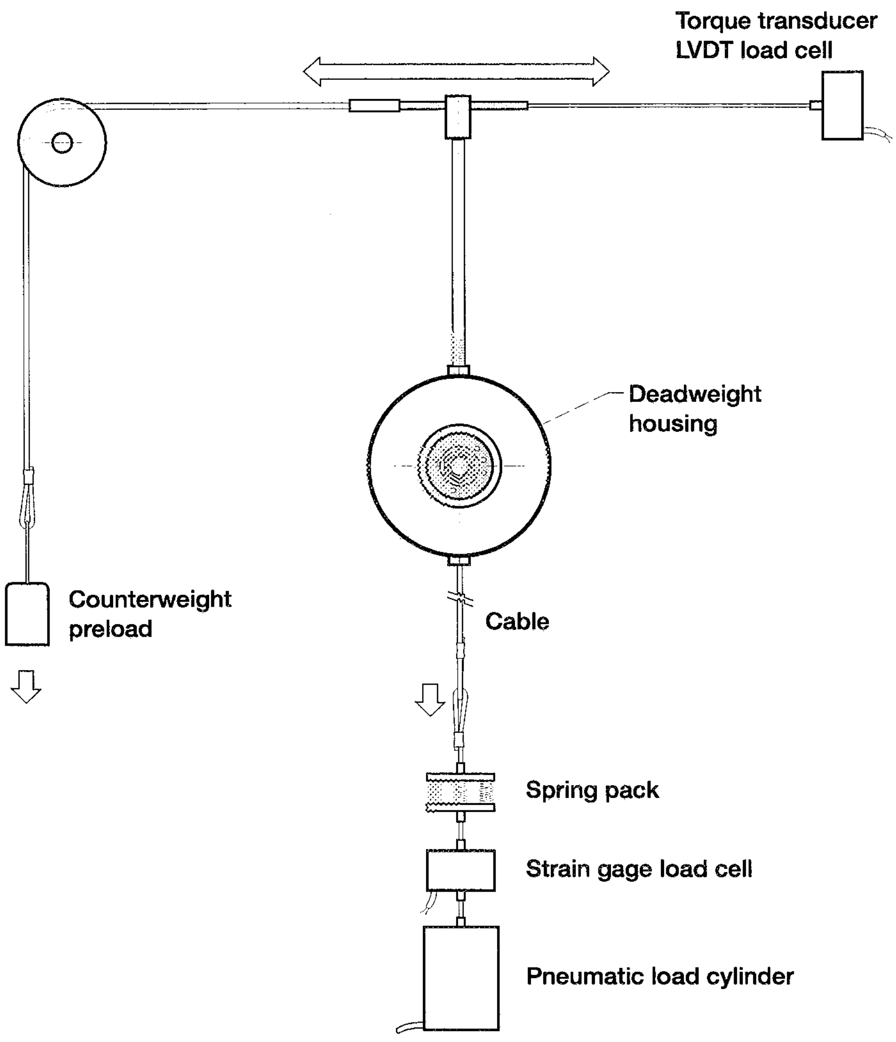

Figure 4. —Test rig partial front view showing torque and load measurement system.

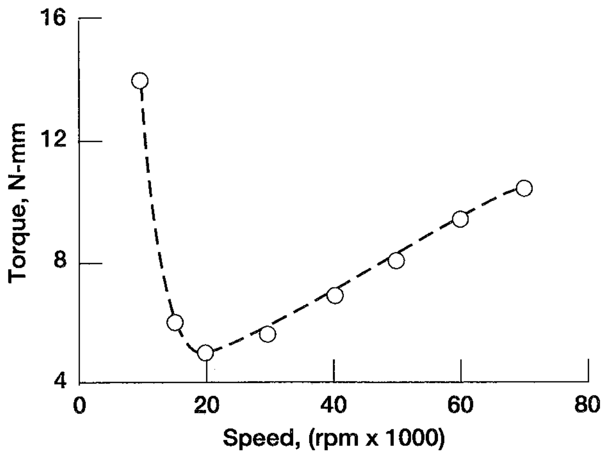

Figure 5.—Bearing torque versus speed under an 18 N load at 25 °C.

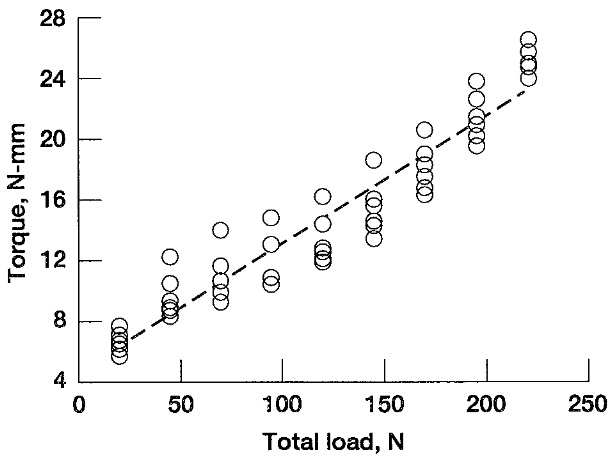

Figure 6.—Bearing torque versus load at 40,000 rpm and 25 °C.

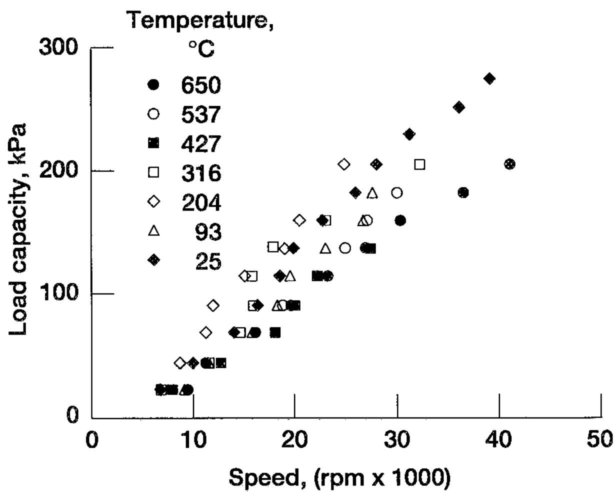

Figure 7.—Bearing load capacity versus speed at various ambient temperatures.

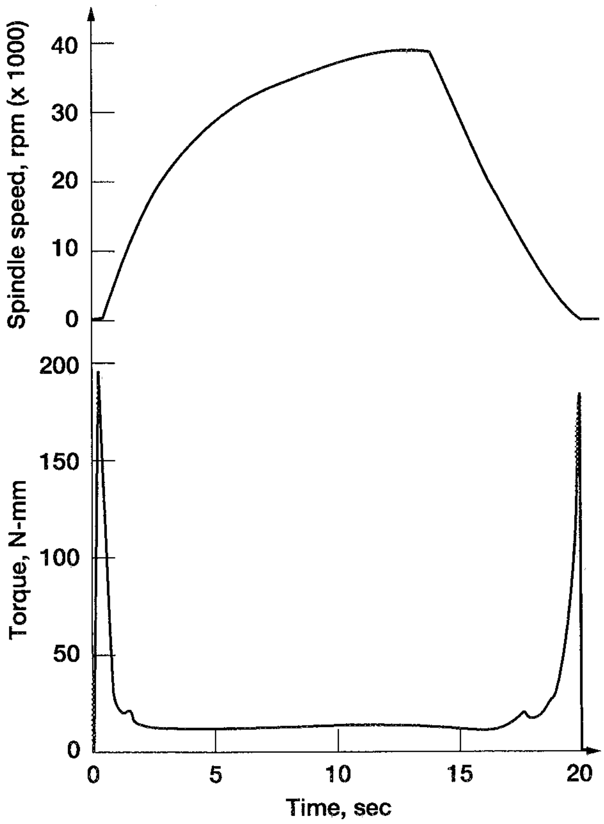

Figure 8.—Bearing torque and shaft speed versus time for one start/stop cycle at 25 °C, 18 N static load.

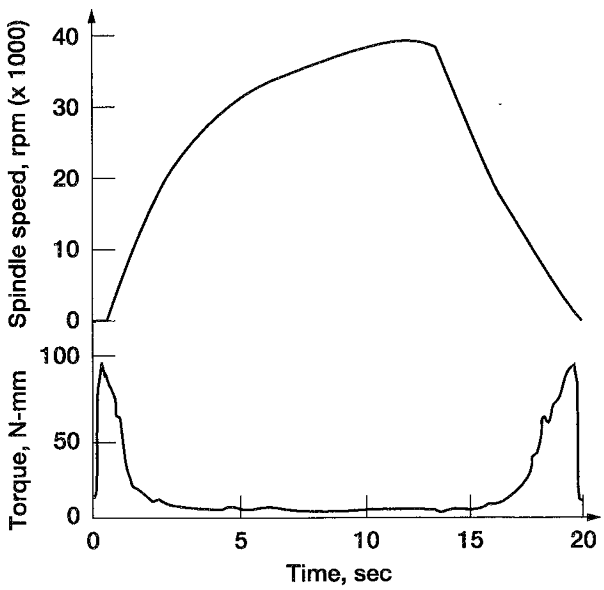

Figure 9.—Bearing torque and shaft speed versus time for one start/stop cycle at 537 °C, 18 N static load.

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