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# **Application of Tribology in Foil Bearing Technology**

## **Problem Description**

The compliant foil bearing is a relatively new innovation in the bearing technology world, especially in the high temperature/high load application of aircraft or turbine rotor systems. The foil bearing operates in an oil-free environment and relies on a gas lubricated hydrodynamic film and compliant bumper layer for effective bearing support during operation. “Although there is no sliding contact in the steady state operation of the foil bearing, contact between the foil and journal surfaces will occur at startup and shutdown and occasionally during overload situation, which, under high-temperature conditions, limits the life of the low-friction coating, and thus the bearing.” [1]

In order to expand bearing lives and applications at higher temperatures the effects of contact between the journal and compliant bumper layer needs to be understood. This research project will examine the contact mechanics and wear characteristics of compliant foil bearings, and the benefits of low-friction coatings to prolong bearing life.

## **Introduction**

Bearings are used in rotor industrial applications such as turbines, aircraft engines, automotive applications, etc. They provide support and rotational points on a rotating shaft that transfers power or creates work. Typical bearing technology includes metal to metal contact bearings such as ball or roller applications that use a lubricating fluid, such as oil, to act as a wear reducer and to also control heat generation of the bearing. “While oil-lubricated fluid film bearings provide adequate stiffness and damping characteristics, these support systems are limited by speed and temperature, and require considerable ancillary pumping, sealing, and plumbing. The use of process gas film foil bearings allows for less complex, lighter weight systems with lower emissions and improved efficiencies. Gas bearings for high-performance turbo-machinery should be simple and reliable, load tolerant, and allow for operation at high rotor speeds with good dynamic force properties.” [2]

Foil bearings are a technology that uses an air/gas film between the rotating shaft and top foil for lubrication and bearing stability. Foil bearings do not rely on metal to metal contact in order to operate. Therefore, they do not require the need for a lubricant, such as oil. For additional damping and stability control, foil bearings are use a “bumper layer” either with layers of sheet metal, or intertwined metal wire between the outer journal and top foil which provides damping support in all three degrees of freedom. Figure 1 shows a cross-section of a typical foil bearing.

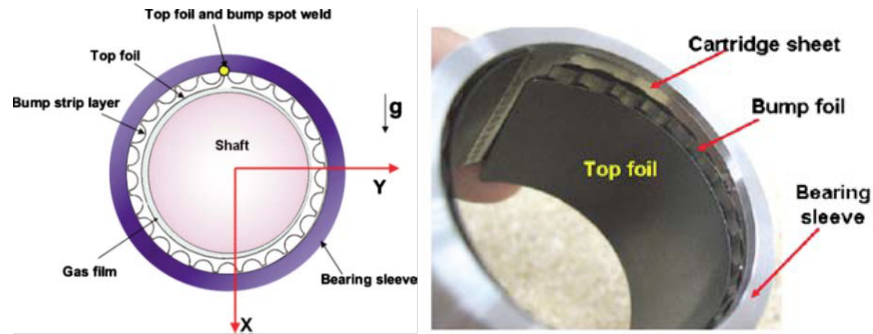


Figure 1: Cross-section schematic and photo of a bumper foil bearing [3]

Effective foil bearing operation relies on the bearing running on a thin gas film layer between the shaft and top foil, and therefore minimal contact between the shaft and the foil. Many things can impact this, including, shaft or foil surface roughness, damping capabilities of the bump strip, shaft speed and temperature. Foil air bearings encounter contact at very low speeds during start-up and shut-down prior to the development of the hydrodynamic gas film and also during momentary bearing overloads such as high speed rubs, maneuvers (aircraft applications) and/or frequency response.

Research shows that during shaft start-up the foil bearing needs to develop the gas film layer to effectively support the shaft. There is generally a critical speed that is dependent on variables including bearing size, gas film clearance, etc. in order to generate the gas film layer. Before the gas film can develop the shaft is in contact with the foil surface. Therefore, any time the shaft is below the critical speed, there is contact with the shaft at both start-up and shut-down time points. Also, as mentioned above, contact can develop during high speed rubs, maneuvers and/or dynamic response. The design work for foil bearings goes into avoiding the dwell time during start-up and shut-down, and the number of high speed and high maneuver time points. Figure 2 shows test data for shaft orbital deflection amplitude vs. shaft speed. The point at which the curve levels off shows when the gas film is developed for a specific bearing and when shaft lift off occurs during bearing operation.

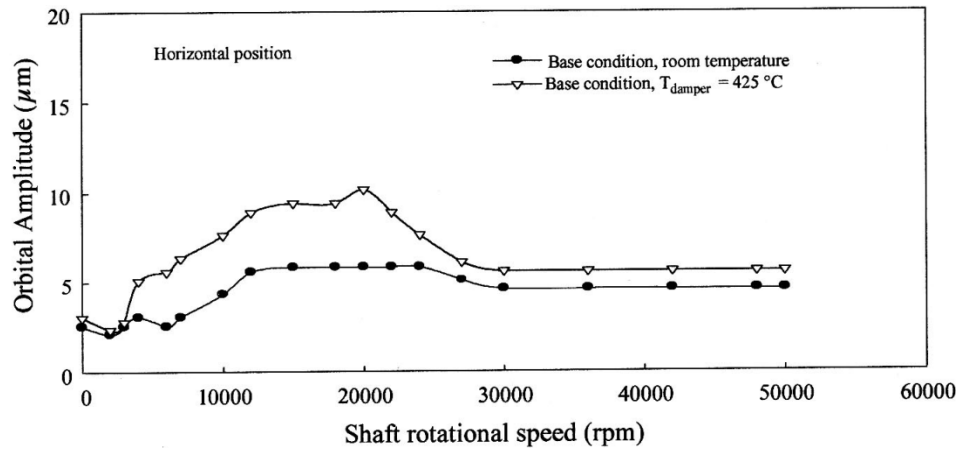


Figure 2: Test Data of Shaft Orbital Amplitude vs. Shaft Speed [2]

### Friction and Wear

Frictional force determination is one of the most challenging aspects of Tribology. The coefficient of friction is an important parameter for stiffness and damping characteristics. Many factors including environment, surface condition, and operating conditions affect frictional parameters. Although the friction coefficient is typically approximated as a constant value, in reality, it is variable even for a simple set of materials due to the many complex variables involved. In most systems, frictional losses cause an increase in temperature at the interface between two sliding surfaces (frictional heating). In addition to frictional heating, the kinetic energy of the frictional pair is converted into energy of other forms, including deformation energy. The combination of frictional heating and deformation energy can lead to wear on the sliding surfaces. Wear is the leading cause of failure for foil bearings.

One method of calculating the frictional coefficient of the foil bearing system is to use an energy approach following Coulomb friction laws. Using a hysteresis approach with a mass-spring model and equations of motion for a harmonic forced vibration, the dissipated energy in the system can be calculated with the following equations, where  $c$  represents damping,  $X_0$  is the original  $x$  position,  $\omega$  (angular velocity),  $\mu$  (friction coefficient) and  $F_n$  (normal force). One can determine the viscous damping in a system with dry friction by combining the two equations. This results in a damping coefficient of  $C_{eq}$ .

$$\Delta E = \pi c \omega X_0^2$$

$$\Delta E = 4\mu F_n X_0$$

$$C_{eq} = 4\mu F_n / \pi \omega X_0 \quad [2]$$

If the damping coefficient of the system is known, the friction coefficient can easily be calculated. The damping coefficient can also be found if the friction coefficient of the system is known. A more detailed explanation of this method can be found in [2].

## Lubrication

As stated earlier in the Background section, the foil bearing relies on a gas (air) film to be generated at the proper “lift off” speed between the rotating shaft and the journal. Air is the working fluid that the foil bearing relies on to provide proper lubrication. The rotating shaft and journal are completely separated by the thin gas layer. The occurrence of the “liftoff speed” is often observed by a seeing a significant torque reduction. The “lift off” speed is the speed at which the pressurized air film is developed. Figure 3 below shows the speed, at which lift off is developed by a reduction in torque at given external static loads. It also shows how the coefficient of friction is reduced due to the development of the air film.

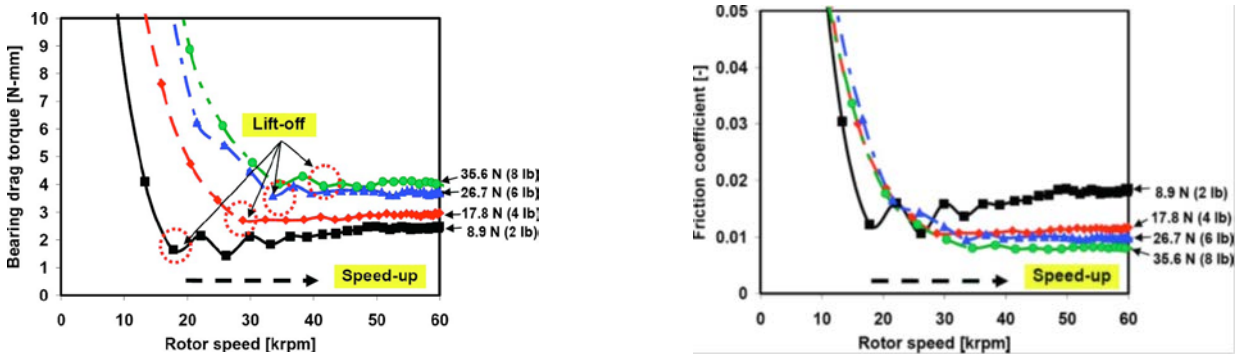


Figure 3: Bearing Drag Torque and Friction Coefficient vs. Rotor Speed [4]

When the air film is developed an adequate air pressure is generated which supports the applied load. The bump foil provides support and compliance under the action of hydrodynamic pressure. The governing equation for the pressure distribution with the ideal gas flow in a foil bearing is given by the Reynolds equation. Assuming an isothermal condition, the dimensionless compressible Reynolds equation is shown below.

$$\frac{\partial}{\partial \theta} \left( \bar{p} \bar{h}^3 \frac{\partial \bar{p}}{\partial \theta} \right) + \left( \frac{D}{L} \right)^2 \frac{\partial}{\partial y} \left( \bar{p} \bar{h}^3 \frac{\partial \bar{p}}{\partial y} \right) = \Lambda \frac{\partial}{\partial \theta} (\bar{p} \bar{h}) \quad \bar{y} = \frac{y}{L/2}, \quad \bar{p} = \frac{p}{p_a}, \quad \bar{h} = \frac{h}{C},$$

$$\Lambda = \frac{6 \mu_0 \omega}{p_a} \left( \frac{R}{C} \right)^2 \quad [5]$$

Solving for  $p/p_a$  results in the curve seen in Figure 4. This assumes that the foil bearing is open to ambient pressure conditions at the 12 o'clock (0 degree) position of the bearing. The highest pressure is then 180 degrees from the opening to ambient air. The figure also shows the comparison between a bumper foil bearing and a rigid bearing. "Note that in a foil bearing the pressure is spread over a greater area. This leads to a greater load-carrying capacity than its rigid bearing counterpart."

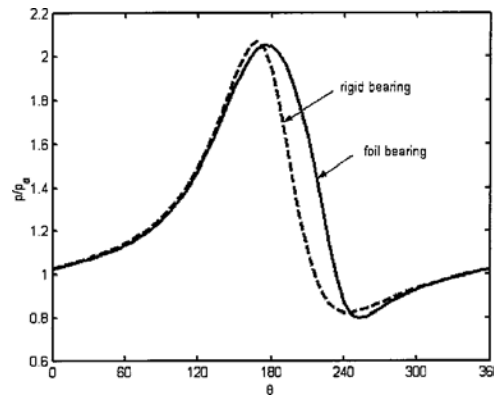


Figure 4: Film Pressure Ratio vs. Theta location on bearing [5]

Load carrying capacity of a foil bearing is directly correlated to the pressure distribution and minimum film thickness. A larger pressure spread, compliant bumper and a thicker film will result in a foil bearing that can handle more load, since more energy is absorbed. Another observation that helps foil bearings absorb load is that film thickness increases as shaft speed increases. This gives the bearing more load carrying capability at higher shaft speeds.

### Stiffness and Contact Force

The bumper layer in a foil bearing acts as a damper to absorb any contact from the shaft so as not to create excessive contact reaction forces. Many methods have been used to calculate or predict the stiffness and reaction of foils under loading. This section will review some of these methodologies and how they apply to foil bearings.

Mechanical properties and stiffness characteristics of a foil bearing are important in maintaining proper load capability and damping of foil bearings. The stiffness of the foil layer has an important role in maintaining proper gas film pressure to lubricate and support the rotating shaft. Theoretical models have been used to calculate stiffness and reactions in a sequence of foils. Two of the most recent

models used curved beam theory and linked springs. Figure 5 shows a schematic of both methodologies.

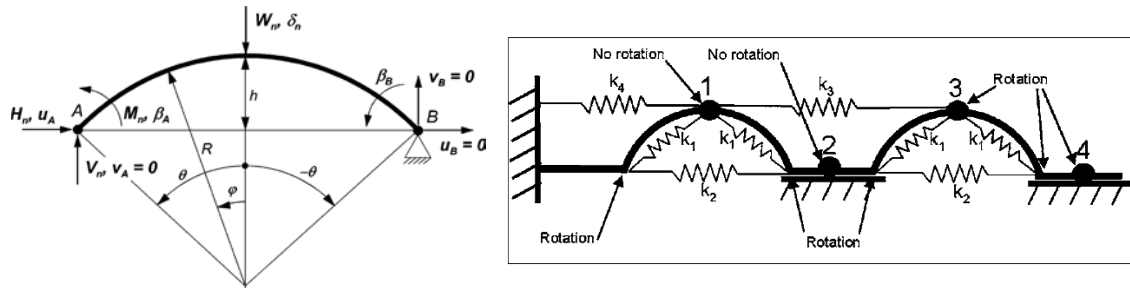


Figure 5: Curved Beam and Linked Spring Schematics [6,7]

The curved beam model is simple in theory, but has certain limitations to understanding the foil bearing as a system. The limitation of this model is simply due to the following assumption that it employs; stiffness of an individual bump  $n$  is not affected by the bumps located towards the fixed end. The linked spring model is much more involved, and more difficult to calculate. The ligaments of the bumper are broken into springs with an associated stiffness in order to model the response of the system. The stiffness of the springs are calculated and then combined to determine the overall stiffness of the bumper type foil bearing. Both theoretical models have been correlated using FEA and test models and have been shown to be reasonably accurate. A majority of the most recent research focused around foil bearings has been on developing tools and calculation methodologies to better predict the behavior of foil bearing structures.

Experimental procedures have also been used to model foil deflection and stiffness. Static load tests are the typical test setup used to evaluate the stiffness. These tests can be modified to be conducted at various temperatures and static load frequencies. Test results show that foil bearings are compliant under small loads. As load increases, bearing deflection levels out due to the stiffening of the foil structure. Figure 6 shows a typical static load test setup and the resulting deflection and stiffness curves that result. Most research surrounding structural capability of foil bearings is around determining how to apply them to high load conditions. Much work has gone into developing bumper shapes and structures to help absorb these larger loads.

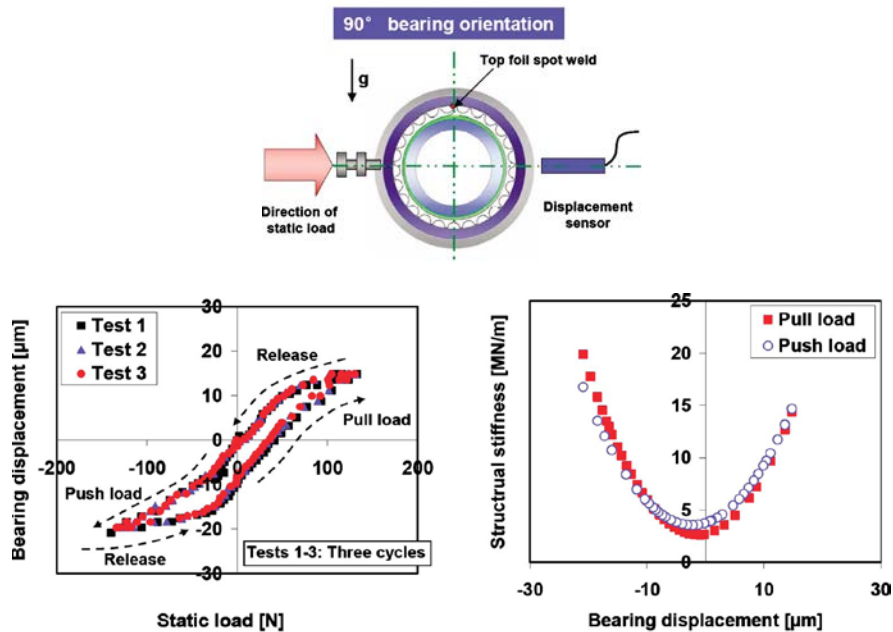


Figure 6: Static Load Test Set up and Displacement and Stiffness Curves [3]

### Low Friction, Wear Resistant Coatings for Foil Bearings

Foil bearings require the use of a solid lubrication to prevent wear and reduce friction during instances of contact. This solid lubrication often comes in the form of a coating or polymer film applied to the top foil of the bearing. Common lubricants, such as, graphite and moly-disulfide ( $\text{MoS}_2$ ) have been used in foil bearing applications, but are limited to 300F. Much research has gone into wear coating development. One of the latest practices is coating the rotating shaft with a high temperature composite coating in order to more effectively apply the coating. It also prevents localized coating failure since the entire shaft surface is exposed to the foil rather than local spots on the foil being exposed to the shaft. The most common high temperature coating used in foil bearing technology is the PS304 coating.

PS304 is a plasma sprayed coating made from a powder comprised mainly of Nickel Chromium, Chrome Oxide and Silver. “Each constituent in PS034 performs a unique function. The NiCr acts as a ductile matrix or binder, the chrome oxide as a wear resistant hardener and the silver and eutectic serve as low and high temperature solid lubricants, respectively.” During multiple start/stops the shaft deposits a soft surface layer on both the shaft and the foil. At elevated temperatures a glassy lubricious film is created which is what creates the solid lubrication that foil bearings need for prolonged lives. In fact,



PS304 has been tested to survive in excess of 100,000 start/stop cycles. The effectiveness of this coating comes in the fact that as temperature increases, the lubricious quality of the coating also increases.

In addition to coating the rotating shaft, many foil bearing applications, employ the practice of coating the top foil with a plasma sprayed aluminum based material, such as, aluminum bronze (Al-Cu) and sputtered alumina ( $\text{Al}_2\text{O}_3$ ). These coatings help to prevent galling wear on the top foil due to shaft to foil contact. Sacrificial coatings are also commonly used as an overlay on the aluminide coating. The sacrificial coatings are typically comprised of a polymide similar to Molybdenum Disulphide ( $\text{MoS}_2$ ). This coating is used to increase contact lubrication during shaft startup and “break-in” and development of the shaft coating on the top foil. Solid film lubrication is extremely important for high temperature, high load foil bearing applications. They prolong bearing cyclic life by preventing wear and galling during numerous start up and shut down cycles.

### **Future of Foil Bearings and Coating Technologies**

Common applications of foil bearings include micro-turbines, cryogenic systems, and aircraft/industrial air systems. All of these applications operate in a relatively low speed and low temperature environment. The future of foil bearing technology and research is focused on high temperature, high rotor speed applications, such as, rotor mechanical bearings for power generation, aircraft engines, and industrial pump applications. High temperature and high load applications are at the cutting edge of research for foil bearing applications. Air lubrication pressure and foil stiffness have been the source for many journals regarding the future of foil bearing research, and how better analysis tools can be developed.

Solid Lubricant coatings are extremely important and necessary in extending foil bearing applications and lives. Coating technology research, as it relates to foil bearings, is continually trying to push the boundaries of temperature limits and effective lubricity. One such area of research is in Diamond-like Carbon (DLC) coatings. “DLC coatings, particularly in the hydrogenated form, provide extremely low coefficients of friction in concentrated contacts.” DLC coatings are deposited using low-temperature chemical vapor deposition. Other alternate methods include, ion-beam deposition, sputtering, cathodic arc-plasma, and laser ablation. DLC can be applied to most metals including high temperature Ni-based super-alloys.

## **Conclusions**

The foil air bearing is a unique bearing technology that operates in an oil-free environment and relies on a hydrodynamic gas film to support and lubricate the rotating shaft. Foil bearings rely on solid lubricants to reduce friction and minimize wear during wall contact at low speed conditions at start-up and shutdown. These low speeds prevent the formation of a hydrodynamic air film. Solid lubrication is typically placed on the shaft and top foil layer with thin, soft polymeric film and sacrificial coatings. Solid lubrication helps to prolong bearing cyclic life. The future of turbine rotor technologies is focusing on the foil bearing as a viable option to help eliminate the need for oil, simplify drive systems, and reduce system weight and its impact on the engine.

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