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"Foil Air Bearings Cleared To Land," by Giri L. Agrawal,
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Foil air bearings cleared to land

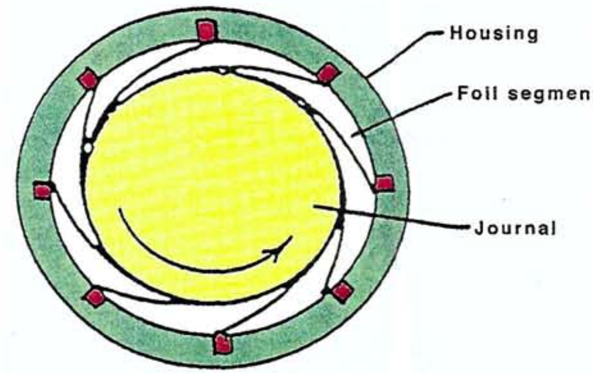
Although their primary use has been in the air cycle machines of aircraft, foil air bearings show potential in land-based turbomachinery as well. **By Giri L. Agrawal**

OVER THE LAST 25 years, foil air bearings have made significant progress. The reliability of many high-speed turbomachines with foil bearings has increased more than tenfold, compared to those with rolling element bearings. A high-speed rotating machine called the air cycle machine (ACM) is at the heart of the environmental control systems (ECSs) used on aircraft to manage cooling, heating, and pressurization. Today, the ACMs for almost every new ECS on military and commercial aircraft, and on many ground vehicles as well, use foil air bearings. Old ECSs with rolling element bearings are being converted to foil air bearings.

A machine with foil air bearings is more reliable than one with rolling element bearings because it requires fewer parts to support the rotative assembly and needs no lubrication. In operation, the air/gas film between the bearing and the shaft protects the bearing foils from wear. The bearing surface is in contact with the shaft only when the machine starts and stops, and a coating on the foils limits wear at those times.

The low clearances and tolerances inherent in foil air bearing design and assembly permit what is called a soft failure: if a bearing fails, its foils restrain the shaft assembly from excessive movement. As a result, the damage is most often confined to bearings and shaft surfaces. Damage to the other hardware, if any, is minimal and repairable during overhaul.

Foil air bearings can handle severe environmental conditions such as the ingestion of sand and dust. A reversed pitot design at the cooling flow inlet prevents large particles from entering the bearing's flow path, and smaller particles are continually flushed out of the bearing by the cooling flow. This ability to withstand contamination eliminates the need for filters in the airflow.



The foil journal bearing's multiple pads form an iris that expands at start-up.

Compressor and turbine rotors have better aerodynamic efficiency at higher speeds. Foil bearings allow these machines to operate at higher speeds without the limitations imposed by ball bearings. In fact, due to the hydrodynamic action, foil air bearings have a higher load capacity as the speed increases.

Many oil lubricants cannot operate at very high temperatures without breaking down. At low temperature, oil lubricants can become too viscous to operate effectively. Foil air bearings, however, operate efficiently at very high temperatures as well as at cryogenic temperatures.

Foil air bearings have been operated in process fluids other than air, such as helium, xenon, air-conditioner refrigerants, liquid oxygen, and liquid nitrogen. For applications in vapor cycles, the refrigerant can be used to cool and support the foil bearings without the need for oil lubricants that can contaminate the system and reduce efficiency.

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JOURNAL BEARINGS

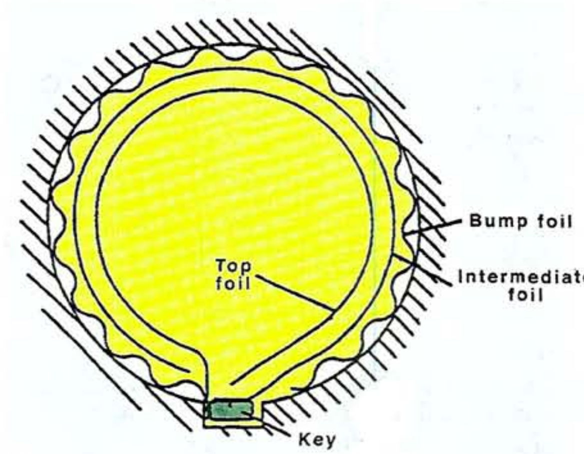
The principle of an air bearing, whether of the journal or thrust type, is simple. When two surfaces form a wedge and one surface moves relative to the other, pressure is generated between the surfaces due to the hydrodynamic action of the fluid carrying the load. In a journal bearing the shaft deflects and a wedge is formed due to the eccentricity between the shaft center and the bearing center.

Even though the principle of an air bearing is simple, application is complex. For instance, in a journal bearing the running radial clearance between the shaft and bearing is usually less than 0.0005 inch for a 2-inch-diameter shaft at 36,000 rpm. But the shaft growth caused by temperature and centrifugal force could be 0.0020 inch. In addition, damping is required to suppress any whirl instability, and there can be misalignment between various rotating parts and stationary parts.

These problems are solved by foil bearings. While the shaft is stationary, there is a small amount of preload between the shaft and the bearing. As the shaft turns, hydrodynamic pressure is generated, pushing the foils away from the shaft and making the shaft completely airborne. This phenomenon occurs instantly during start-up at a very low speed. When the shaft is airborne, the friction loss due to shaft rotation is quite small. As the shaft grows, the foils get pushed farther away, keeping the film clearance relatively constant. In addition, the foils provide coulomb damping due to their relative sliding. This damping is essential for the stability of the machine.

Various concepts of foil journal bearings have been tested. Garrett AiResearch (now Allied Signal) in Los Angeles did the pioneering work on foil air bearings. The multipad concept shown in the illustration on the opposite page has been pursued by AiResearch since they produced the first ACM to use foil air bearings, for the DC-10's ECS in 1969. Multiple pads form an iris and provide a preload when the shaft is not turning. During starting, the iris expands and a cushion of air is formed between the bearing and the shaft. The same machine is also used for the Airbus A-300. The rotating assembly has three rotors: a turbine, a compressor, and a fan. The machine runs at 48,000 rpm. To date, over 80 million hours have been accumulated on this machine. Later versions such as those for the Boeing 767/757 feature a supportive spring behind each pad. This increases the load capacity significantly. The top foil is coated with Teflon-S or a polyamide coating to provide lubricity during starts and stops.

A reversed multilayer journal bearing concept shown in the illustration above has been pursued by Hamilton Standard, in Hartford, Conn., in the B-1B, B-2, SAAB-2000, 747, 777, and other aircraft. The single corrugated (bump) foil, which has a bilinear spring characteristic, is restrained in an axial keyway in the outer shell along one edge. The intermediate and top foils are attached to a key along one edge and are wound in opposite directions. The top foil has a thin coating that provides lubricity during startup and shutdown. A wedge is formed due to the radial displacements of the shaft as it rotates. Hydrodynamic action draws the working gas into the wedge where it is locally compressed. The corrugated foil acts as a spring to accommodate expansion, excursions, and any misalignment. It also provides a flow path for the cooling air to remove parasitic heat from the bearing. In the reversed multilayer foil bearing, the adjacent foils move in opposite directions. The net result is that relative movement is additive, which in turn produces high coulomb damping.



A corrugated "bump" foil acts as a spring and air vent in this journal bearing.

The Hydresil foil journal bearing was developed by Mechanical Technology Inc. in Latham, N.Y. Both the bump foil and the top foil are spot-welded to the sleeve. Various versions have been patented. The load capacity of the Hydresil is comparable to that of the multipad or reversed multilayer foil bearing, but the Hydresil has lower damping. The reversed multilayer concept is the most stable and least affected by shock loads.

Even though the reversed multilayer concept has high damping, its foils have a tendency to protrude like a telescope during assembly. In addition, manufacturing is costly because all bends near the keyway have tight tolerances. A new concept called the reversed multipad, shown in the diagram on the following page, has been patented by R&D Dynamics Corporation in Bloomfield, Conn. It has the benefits of both the multipad and reversed multilayer designs. It has high damping and yet requires low preload. Low preload makes the machine start at a low torque. Due to its multipad design, the tolerances are not tight.

THRUST BEARINGS

Thrust bearings withstand axial loads in rotating machinery and work on the same hydrodynamic principle as journal bearings. In a journal bearing the wedging action comes from eccentricity between the center of the rotating shaft and the center of the bearing itself. In a thrust bearing the wedge is designed into the geometry, taking into account any deflection due to the axial load.

A radial-spring foil thrust bearing invented by AiResearch was first used for the DC-10 in 1970. Its multiple radial springs transfer the load to the housing, and foils between the springs deflect under pressure, forming the wedge required for the hydrodynamic action. In some later designs a spring is formed out of the bearing plate by chemical etching instead of being spot-welded to the plate. This change reduces manufacturing cost but compromises performance in some instances.

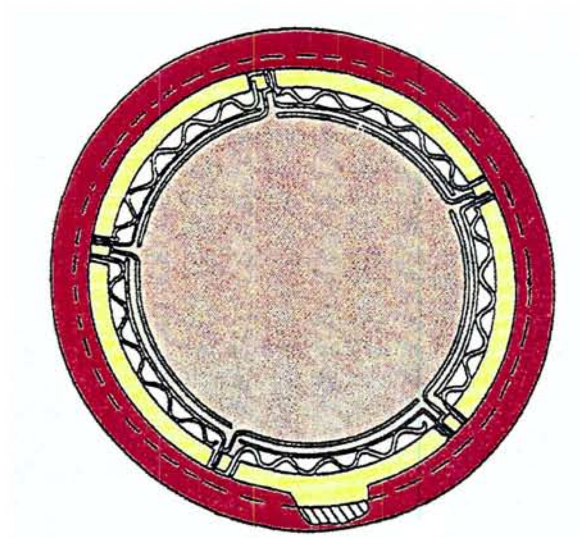
A dual-spring thrust bearing invented by Hamilton Standard consists of two washer-shaped plates similar to radial-spring thrust bearings. The coated pads, welded to the top plate, are supported on stiff bump foil springs to optimize the wedge shape required for load capacity and lift-off. The bottom plate has several softer bump foil springs welded to it. These are required to optimize the overall spring rate and damping of the bearing. The dual-spring-rate thrust bearings have approximately 15 percent higher load capacity than the radial-spring bearings, but they are more expensive to manufacture.

Both journal and thrust bearings apply a small amount of preload on the shaft when the machine is not running. The foil face touching the shaft is coated for lubricity during startup and shutdown. The shaft in a typical DC-10 ACM, which runs at 48,000 rpm, is fully airborne at about 2,000 rpm. Several coatings are used on the foils. Most commercial aircraft ACMs use DuPont's Teflon-S, which is effective up to 475°F. Most military aircraft ACMs use a polyamide coating, which was first researched by NASA Lewis. Both AiResearch and Hamilton have modified the polyamide's basic formula and application process to suit their needs. Their coatings are effective up to 700°F. Extensive research on high-temperature coatings has been conducted by NASA Lewis, the Air Force's Wright Laboratory, AiResearch (Phoenix Division) and Mechanical Technology Inc.

Analysis and Testing

The analysis of foil air bearings requires simultaneous solutions or iteration methods to solve foil elasticity equations and fluid hydrodynamic equations. Foil elasticity equations are nonlinear and involve large-deformation theory. A foil can deform as much as five times its own thickness. Hence most finite-element or finite-difference methods do not provide satisfactory results. Hydrodynamic equations are nonlinear Reynolds equations with continuously changing boundary conditions. Semiempirical methods seem to provide reasonable results. Sufficient test data are collected by varying the geometrical parameters and test parameters of the bearing. Results are correlated using a multiple regression method. Then a model is prepared using coefficients of the multiple regression analysis. Hydrodynamic equations are solved using the preferred final geometry. An inverse method is used to design the foil geometry in the unloaded position.

This approach has been used by AiResearch and Hamilton Standard to design and successfully develop many foil air bearing machines in use today. Others have taken more conventional approaches and have not succeeded. Design of the machine parameters such as static and dynamic loads, critical speed, thrust loads, rotor clearance, seals, and cooling flow must be correlated with the design of the foil air bearings.



The reversed multipad foil journal bearing offers benefits of other designs.

New Applications

Many applications of foil air/gas bearings other than air cycle machines have been built and successfully tested, but nothing appears to be currently in production. AiResearch successfully tested a vapor-cycle machine on Navy P-3 aircraft with Freon as the working fluid. A similar machine will be built for F-22 aircraft. R&D Dynamics is designing a commercial air conditioning compressor that uses R-134a refrigerant. A cryogenic foil-bearing turbopump working in liquid oxygen was built by AiResearch and successfully tested by NASA. Both AiResearch and Hamilton Standard have built foil-bearing high-speed fans for the Space Station. Several cryogenic foil bearing turboexpanders for air separation plants have been built for the Navy. AiResearch built a high-temperature foil bearing auxiliary power unit for B-2 aircraft in 1985. The unit ran successfully but failed the endurance test. The conclusion was that coating wear at high temperature was the cause. Since then much research has been done in the areas of foil coating and bearing design. Recently R&D Dynamics jointly with Allison Engine Co., built a missile engine with a hot-end foil bearing capable of withstanding temperatures up to 1,000°F.

Foil bearings have strong potential in a number of applications. Among these are a small general aviation gas turbine engine; oil-free cryogenic turboexpanders for gas separation plants; auxiliary power units for various aerospace and ground vehicles; and, taking advantage of automated manufacturing methods, automotive gas turbine engines, vapor-cycle centrifugal compressors, and commercial air/gas compressors. ■

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