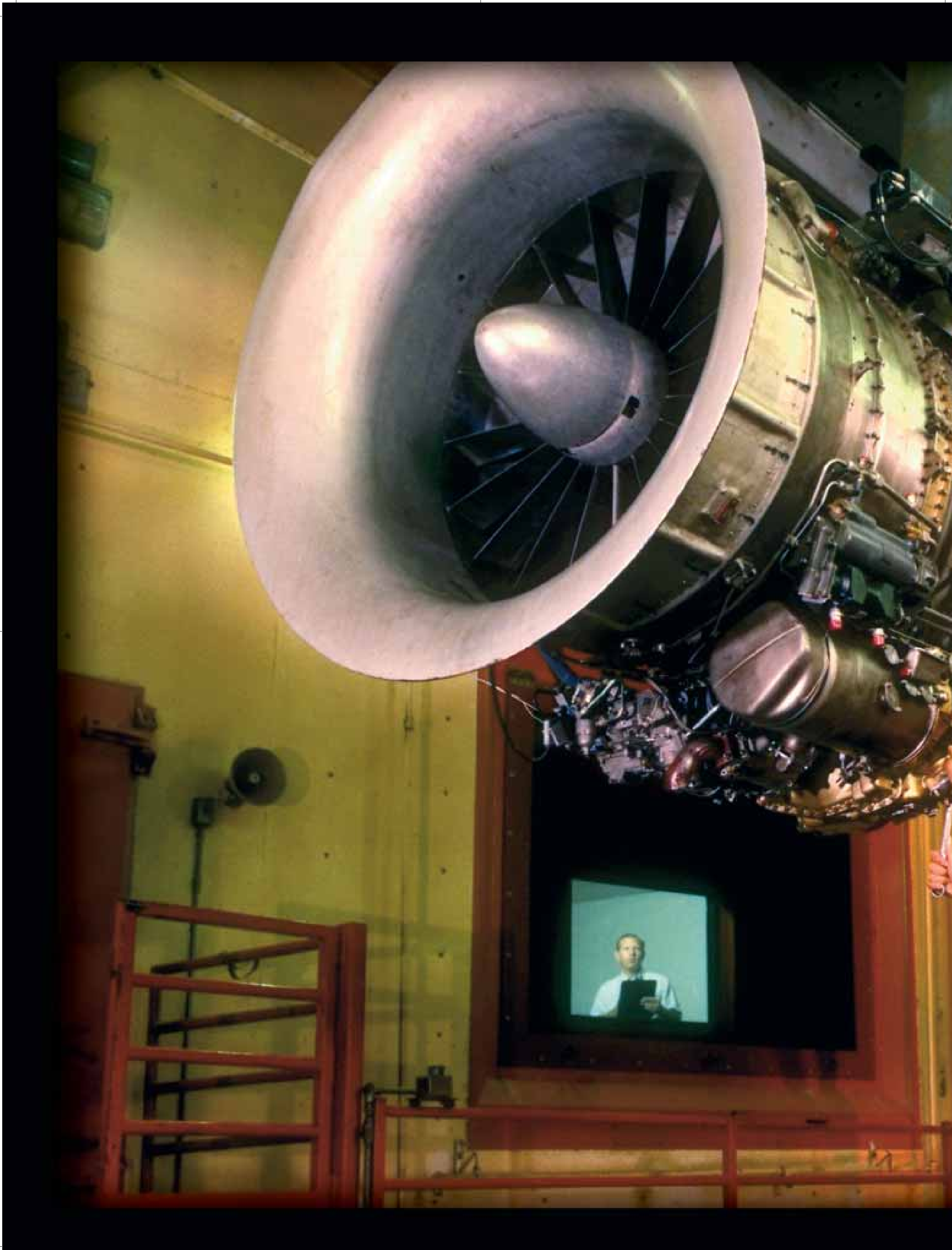

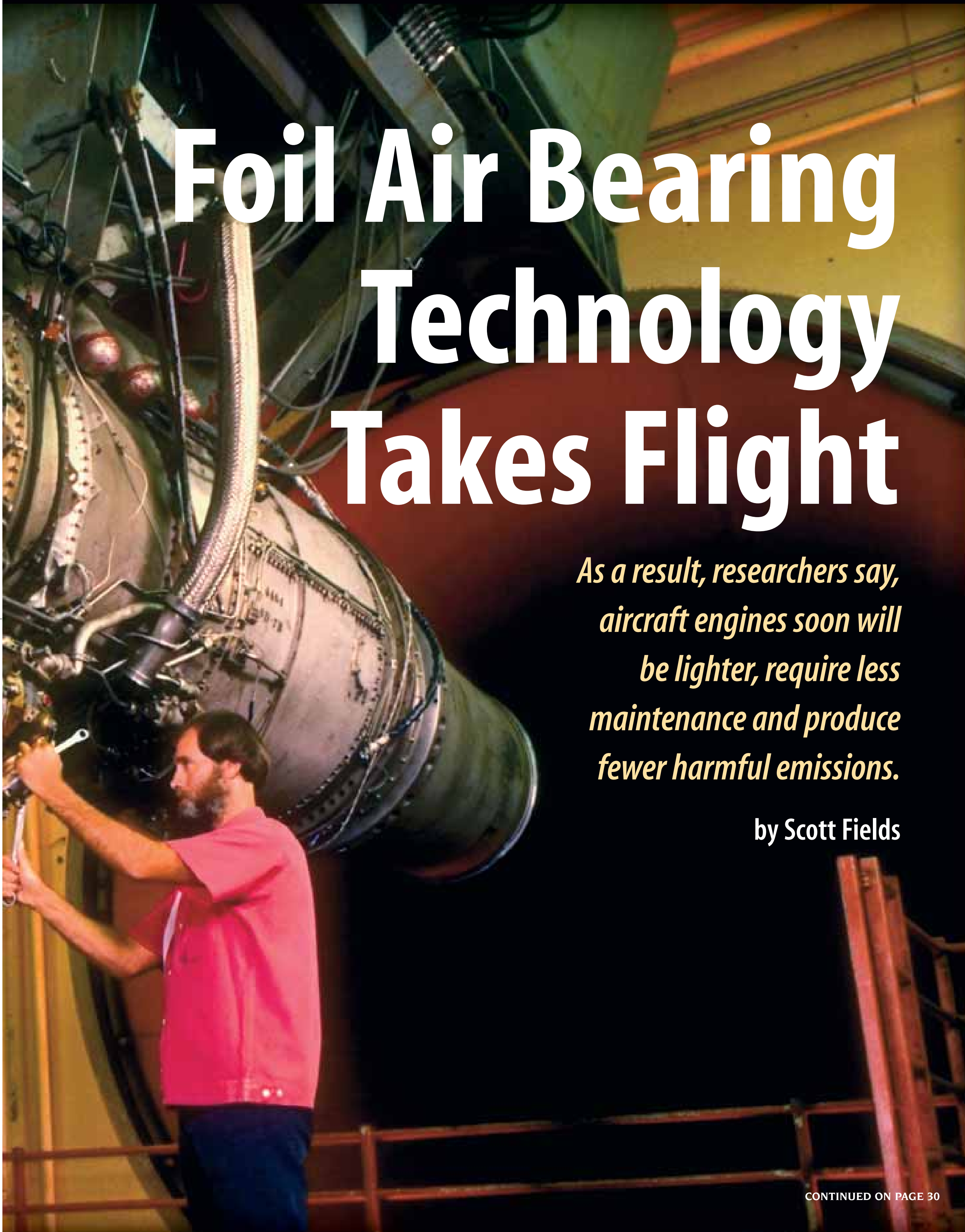

Foil Air Bearing Technology Takes Flight

As a result, researchers say, aircraft engines soon will be lighter, require less maintenance and produce fewer harmful emissions.

by Scott Fields

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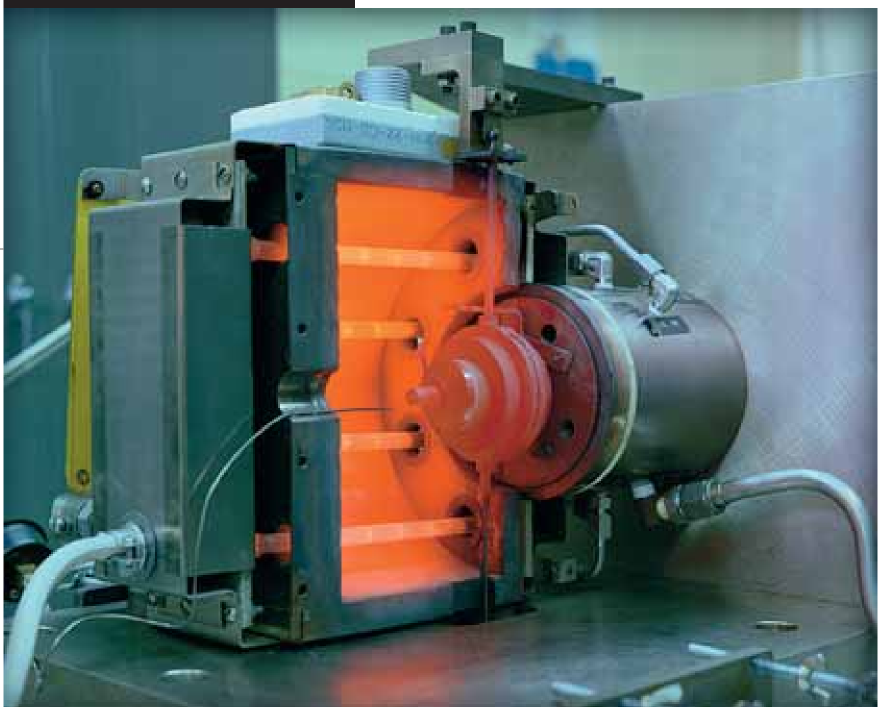
Recent work on foil air bearings may lead to more efficient and less polluting aircraft as well as other innovative applications. Air bearings—which rather than lubricating with oil float a shaft on air, helium or almost any gas—date back at least 50 years.

But plain-vanilla air bearings have what can, in some applications, be a fatal flaw, says Dartmouth engineering professor Francis Kennedy. "Once the shaft stops you don't have any air to separate the surfaces, and they rub on each other," he says. "You have to have something that is going to protect the surfaces from damage."



Source: NASA Glenn Research Center

Low speed foil bearing test rig operating at 760 C (1,400 F)

For low-temperature applications, coatings such as nickel can protect the surfaces sufficiently. But high-temperature applications, such as in a turbojet, can destroy bearing surfaces if they are allowed to touch.

That's where the foil air bearing comes into play. Like any air bearing, it uses air as the lubricant between the shaft, which is usually called a journal, and the bearing sleeve. Air, however, serves as a lubricant only when the shaft is spinning at high speeds. As the shaft rotates it draws air into the bearing, which produces a pressurized lubricant film. Until this film is established—when the journal is at rest or ramping up to speed—the foil maintains the spacing between the shaft and bearing housing. (The exact speed depends on the shaft's diameter; for a 1 3/8-inch shaft the foil's lift-off speed is about 2,000 rpm.)

Foil air bearings first came into widespread use in the 1960s, when they began to appear in such applications as the air-cycle machines that cool and pressurize commercial and military airplanes and, more recently, natural-gas compressors. But these bearings couldn't operate at high temperatures. Now, however, breakthroughs in coatings and foil design may result in radically lighter jet turbine engines, tiny, unmanned aircraft and turbocompressors for fuel-cell-powered automobiles.

According to Dr. Hooshang Heshmat, president of Mohawk Innovative Technology, Inc., in Albany, N.Y., foil air bearings have several advantages over oil bearings. They can be stored indefinitely, unlike oiled bearings, which must be cleaned and run periodically. They require less maintenance. They last longer. They are more efficient because, since the bearing wall doesn't contact the journal, the only friction is shear force in the film of air. This friction is almost unmeasurable: A 20,000-pound balanced rotor can be rotated by applying less than a gram of force to a 10-inch arm. And they are environmentally benign.

"Anytime you have oil, whether it's your car engine or your aircraft engine, it's going to leak through the shafting system straight into the engine area or compressor area and load the environment with the heavy, high-chain molecules," says Heshmat.

Other types of oil-free bearings share some of these advantages, Kennedy says, but they also have drawbacks that may make them unsuitable for aviation applications. Magnetic bearings, for example, have some of the advantages of foil air bearings, including very low friction, low maintenance and oil-free operation. But magnetic bearings stop working if they lose electrical power, a critical failing in applications such as aviation. They are also not as efficient as air bearings, Kennedy says. “Magnetic bearings require quite a bit of energy, electricity in particular, and that has to come from somewhere.”

Fixed air bearings, which depend entirely on air pressure to keep the elements apart, work without a source of electrical power. But they have other disadvantages. Not only do the elements touch when there is no hydrodynamic film present, they offer very little damping, an attribute at which oil bearings excel.

Adding foil between the elements helps, NASA engineer Dr. Samuel Howard says. “Air-lubricated bearings are notoriously bad at damping,” he explains. “So if you put this flexible structure in there you get more damping because as it moves around it’s sliding. That sliding translates into frictional heat, which translates into more damping.”

Air bearings—whether fixed or foil—also usually work better at temperature extremes than oil bearings. Most oils break down at very high temperatures and become overly viscous at low temperatures. Eliminating oil eliminates these problems.

And because oil bearings or fixed air bearings must have a smaller gap between the bearing wall and journal than foil bearings, they are more susceptible to seizing, a problem exacerbated at high speeds. At high rpms, heat and centrifugal force can cause a two-inch-diameter shaft to grow as much as 0.0020, which can intrude significantly into a narrow gap. This larger gap also helps air foil bearings better tolerate dusty and sandy conditions than oil-dependant bearings. Not only is there no oil to which particles can adhere, the motion of cooling air through the bearing’s gap also flushes out small particles.

An engine that incorporates foil air bearings will be lighter than its oil-dependent counterpart. Foil bearings are somewhat lighter than the ball bearings they replace. But the biggest weight saving comes in the elimination of the lubrication system—pumps, filters, plumbing and so on—that oil-lubricated bearings require. And because these components would no longer be needed, systems that use foil bearings instead of oil lubrication will require considerably less maintenance, says Heshmat.

Source: NASA Glenn Research Center

Thrust Foil Bearing

Foil air bearings first came into widespread use in the 1960s, when they began to appear in such applications as the air-cycle machines that cool and pressurize commercial and military airplanes. But these bearings couldn’t operate at high temperatures.

“Twenty-five percent to 35% of all engine maintenance is directly related to the lubrication oil,” says Heshmat. “You have to change the oil. You have to change a bearing.”

In fact, NASA engineer Kevin Radil says, “The main benefit is the maintenance savings. You can cut by half the maintenance of an engine. You do get weight reduction. You achieve some increase in power density and even some reduction in direct operating costs. But the thing that we like most about the bearings is that they’re maintenance-free. You put them in and then you don’t

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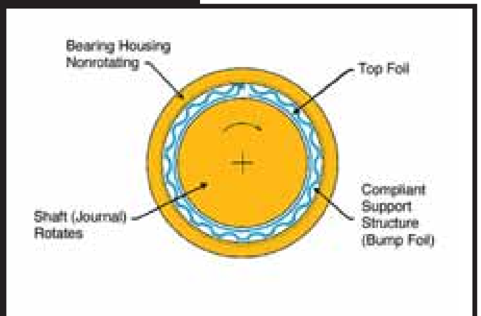
have to mess with them anymore."

But before the bearings can be used in applications as critical as aviation engines, researchers must establish their durability and stability at high temperatures, Radil says. Currently scientists at NASA's Glenn Research Center in Cleveland, working with bearing manufacturer Mohawk Innovative Technology, Inc., are testing a foil air bearing for what could be the first oil-free gas turbine aircraft engine.



Source: NASA Glenn Research Center

Foil bearing cross section schematic (bump foil style bearing)

This less-than-100-pound engine—produced by Williams International—delivers 780 pounds of thrust and is intended for four- and six-passenger commercial airplanes. Williams produces turbine engines for such light business jets as the Cessna CitationJets and the Raytheon Premier. NASA and industry researchers are currently laying the groundwork for future tests of this engine. Mohawk has been testing its foil air bearings in a WJ24-8 turbojet engine, which is the main propulsion engine for the Navy's BQM-74 series of target drones. Mohawk has also developed a tiny, nine-gram, foil air bearing that, Heshmat predicts, will be used in mesoscopic turbojets.

[Foil air bearings] can be stored indefinitely, unlike oiled bearings, which must be cleaned and run periodically. They require less maintenance. They last longer. They are more efficient.

NASA's focus, however, is on the passenger-jet engine. "We have done 100,000 start-stops at high temperature without wearing out the bearings, which translates—if you're doing five flights a day, 300 days a year—to about 60 years of life, which is a lot longer than the engine will be around," says Radil. "There's a finite life, but it is going to outlive the application."

The more than 100,000 start-stops is more than three times the 30,000 expected start-stop cycles of the turbojets in which they would be installed, according to Mohawk documents. These tests were conducted at between 75 F and 1,200 F at sustained speeds of 120,000 rpm. According to Heshmat, by the end of the decade foil air bearings will appear in commercial turbojet engines. Before that can happen, however, load capacity will have to increase from the current less than 1,000 pounds to about 1,500 pounds.

Researchers also are using computer modeling to better understand the rotodynamic stability of turbomachinery that incorporates foil air bearings.

"The challenge of foil bearings is that you must address both the flow of the fluid inside the bearing and the deflection of the foil themselves," says Pennsylvania State University engineering professor Marc Carpino. "So you have to solve this coupled fluid structure problem at the same time. And that makes predictions substantially more complicated." Early results indicate that stiffness increases with load and decreases with speed. But the data indicate that "stiffness is not expected to change by orders of magnitude over the normal operating range of most turbomachinery." That, researchers say, is "a promising sign for [foil air bearings'] eventual integration into oil-free turbomachines."

Complicating the modeling is the complexity of the current bearing foil design. In any foil air bearing the foil must prevent the journal from contacting the housing at start up and shut down and also must lift off at high speeds so the journal can spin freely, supported just by hydrodynamic pressure. Early foil air bearings incorporated layers of flat foils that were arranged like the iris shutter in a camera. As these bearings ramp up toward operating speed, the layers flatten and spread away from the journal.

Most modern foil bearing designs use several layers of foils in which the innermost or "top foil" rests upon an elastic support structure. This support structure varies depending upon design and often includes cantilevered springs, web-shaped foil protrusions and corrugated bump foils.

Among the recent designs is the "bump foil" design. In this design the flat top foil sits closet to the journal. The hydrodynamic film forms between the journal and this top foil. Attached to the top foil is a bump foil, which acts as a spring to provide compliance. One of the most common types of bump foil looks like—from the side—a cross-section of corrugated cardboard. The bumps act as springs, providing additional support to the journal. At operating speed, the foil— which typically is about 0.004 inches thick—deforms, flattening the bumps.

The latest bump foil bearings being developed are of the so-called "generation III" variety. What distinguishes one generation from another is the complexity of the spring resistance in the bump foil. The bumps in generation I are uniformly stiff. Generation II bump foils vary but only on one axis. In generation III bearings, however, the stiffness of the bumps is varied to optimize air film pressure.

"Say, for example, that there is more fluid leaking out than you want in a certain area, then you can make the stiffness near the ends greater," says Howard. "So that as you go from the center out the gap between the top foil, which is the bearing surface and the shaft, gets smaller so it pinches the flow off." This complex variation of bump stiffness increases the load capacity of generation III bearings to more than twice that of best previous generation designs.

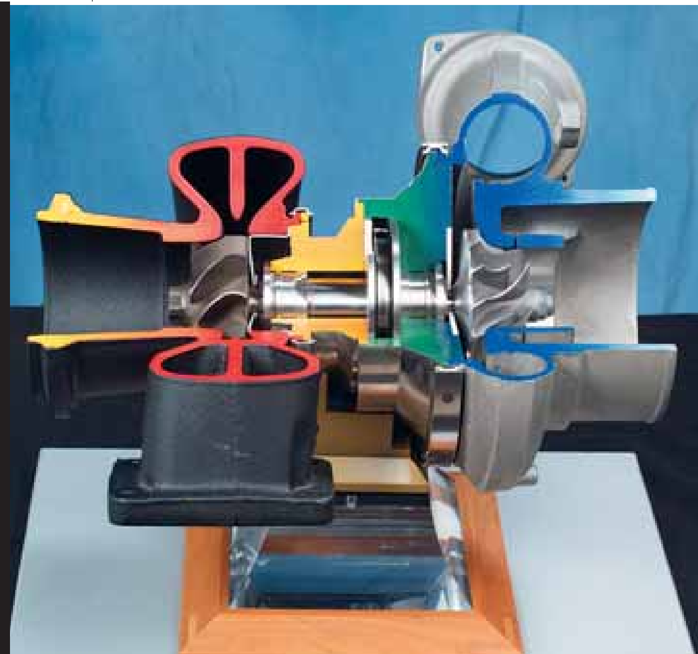
As the rotational speed increases, the hydrodynamic action allows the bearing to support even more load. On a turbocharger simulator Mohawk has been able to spin a turbojet at 121,500 rpm. This speed represents that maximum capacity of the testing apparatus rather than of the bearing.

"The foil bearing has literally and theoretically no speed limitations," says Heshmat. "The only speed limitations that come into the picture are the ultimate yoke strength of the shaft we are spinning. And there are materials now that can reach very high yoke strengths, close to almost 300,000 psi."

"One of the key enabling technologies that allowed us to go after high-speed, high-temperature applications was the coatings," says Radil. "That was a major obstacle that was around for many years."

In most foil air bearings some sort of coating is applied to the foil and the journal to lubricate the surfaces at low speeds when they contact each other. Most often that coating is Teflon®.

But Teflon breaks down at temperatures above 500 F, well below a turbojet's operating temperature. As a result, much of the foil-air bearing work at NASA's Glenn Research Center has focused on developing a journal coating that can survive a turbojet's high operating temperatures and stay intact for many thousands of starts and stops. Currently they are using a solid-lubricant coating called PS304.



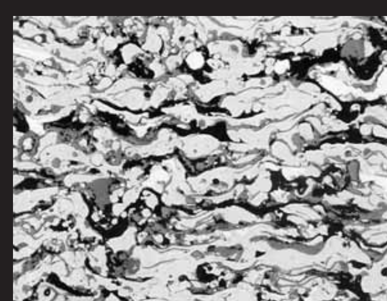
Source: NASA Glenn Research Center

Oil-free turbocharger with foil bearings from Mohawk Innovative Technology, Inc. The turbocharger is a modified Borg-Warner turbocharger.

'The foil bearing has literally and theoretically no speed limitations.'

"The coating is a very resistant coating, a wear-resistant coating," says Radil. "It's not a low-friction coating; it's a wear-resistant coating." The coating is applied to the shaft using a plasma spray (that's what the "PS" in PS304 stands for). The coating incorporates a chrome-oxide hardener (CR_2O_3), a nickel-chrome binder (NiCR), silver (a low-temperature lubricant) and fluorides (which are high-temperature lubricants).

"Adding this all together gives you a nice coating system—a tribological system—that allows you to do start-stops without wearing out the bearing, " says Radil <<



Source: NASA Glenn Research Center

PS304 solid lubricant coating photomicrograph.

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