GET YOUR BEARINGS STRAIGHT

BEYOND MAGNETIC BEARINGS, PLENTY OF INNOVATION IS TAKING PLACE IN AIR BEARINGS AS WELL AS TRADITIONAL PRODUCTS

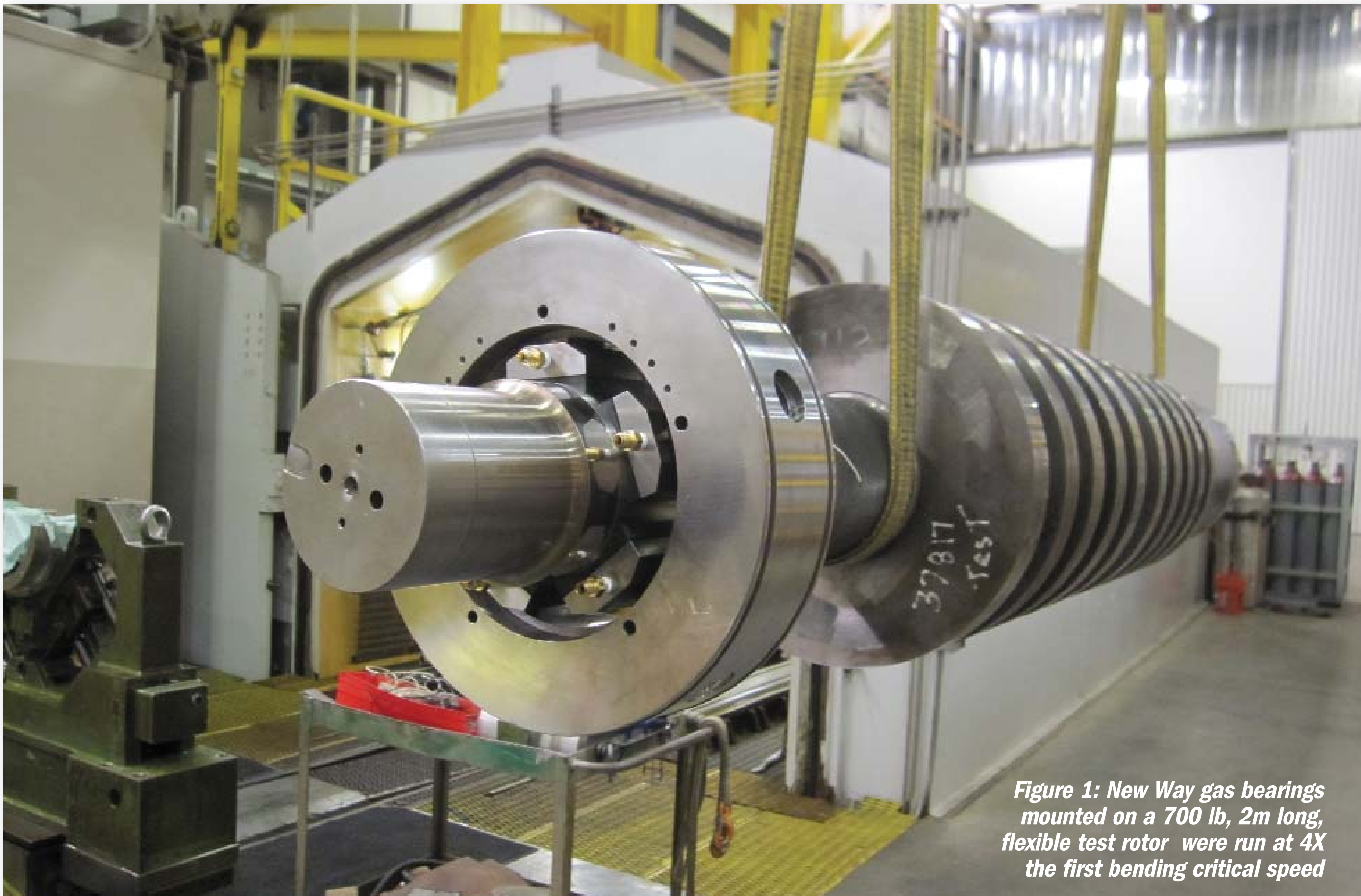

Figure 1: New Way gas bearings mounted on a 700 lb, 2m long, flexible test rotor were run at 4X the first bending critical speed

DREW ROBB

Ask most people about innovation in bearings and they will mention magnetic bearings. Certainly, they deserve the spotlight. It seems that every turbine OEM and major bearing supplier has been eager to augment its arsenal with mag bearings.

Examples include Dresser-Rand acquiring Synchrony, MAN Diesel & Turbo buying Mecos Traxler, SKF picking up S2M and Waukesha Bearings taking over Glacier Rotating Plant Bearings. The large number of mergers tells a tale of fast-paced development and rapidly maturing technology.

"Mag bearings are crossing the chasm between highly specialized applications into more of a mainstream adoption by other machine builders," said Lars Kahlman, Senior Application Specialist, SKF Fluid Machinery.

Yet magnetic bearing breakthroughs may not even be regarded as being on the forefront of bearing technology. Indeed, recent work on air bearings and the incorporation of advanced materials, such as ceramics can possibly stake a claim as being on the cutting edge (Figure 1).

Wherever you look, vendors, such as SKF, Dresser-Rand Synchrony (p. 30), Lufkin, Kingsbury, Waukesha Bearings, Mecos, GMN Bearing, Calnetix, LA Turbine, Capstone Turbine and New Way Air Bearings, are incorporating a host of new features into their wares, many of them squarely targeted at the turbomachinery market.

The traditional bearing field, if it can still be called that, is a hotbed of innovation. Vendor after vendor has responded to the challenges posed by turbomachinery applications that drive the limits in terms of high temperatures, high pressures, harsh environments and faster machinery.

"The big push is to find bearings that can handle faster speeds and heavier loads," said Joseph Hart, RMT Bearings Sales Manager for Lufkin (part of GE Oil and Gas). Lufkin-RMT has introduced Spray-Bar Blocker and By-Pass Cooling advancements to its tilting pad journal bearings and thrust bearings. The goal is to reduce operating temperatures while handling increased load capacities and surface velocities. This same technology is offered in its Ultra Pressure Dam Sleeve Bearings and Ultra Thrust Bearings.

Waukesha Bearings (WB) offers tilting pad thrust, journal, combination and fixed profile bearings, used in pumps, motors, compressors, turbines, generators and gearboxes. Examples include: Maxalign bearings that reduce power loss and handle misalignment in large shaft turbomachinery; Flexure Pivot bearings that eliminate pivot wear, pad flutter, and tolerance stack up; and MLSF bearings that improve stability and lifespan when compared to conventional floating ring bearings.

In addition, WB supplies housed horizontal and vertical bearing assemblies. They include options such as cooling, electrical insulation, hydrostatic jacking, self-contained ring or disc lubrication, and instrumentation, for use in pumps, motors and generators in applications, such as nuclear power stations and air-cooled units for LNG pumps.

The company also employs advanced material bearings, such as Hiperax and Hidrax, to withstand high temperatures, high loads and abrasive materials, as well as axial and radial magnetic bearings, RDS auxiliary bearings, position sensors and control systems that increase reliability and availability and reduce the need for on-site maintenance.

"We are seeing more partnerships between OEMs, end users and bearing suppliers, which allow each expert to share their knowledge for improved technical collaboration and testing validation," said Barry Blair, Chief Engineer for Fluid Film Bearings at WB. "There is higher market demand for directed lubrication, the use of synthetic oils and other lubricant options. We are also noticing lower power losses, lower oil flow rates and smaller oil tanks."

For small diameter shafts operating at high speeds and high loads, Flexure Pivot bearings address problems such as pivot wear and vibration increase. They have an integral pad-pivot-retainer design, manufactured as one piece (Figure 2). WB's ISFD technology for radial bearings ups the damping capability to combat sub-synchronous vibrations.

Additionally, WB is a presence in magnetic bearings. Its compact Zephyr controller can fit a redundant controller configuration in the same space envelope as older non-redundant controllers. The controllers for these magnetic bearing can measure and process all data required to commission the bearing system, eliminating the need for ancillary equipment such as signal analyzers. These controllers can now be placed 500 meters away from the machine, said Richard Shultz, Chief Engineer at WB.

Kingsbury specializes in tilting pad thrust and journal bearings, with applications in turbines, compressors, generators, motors, pumps, gearboxes and auxiliary equipment. This includes tilting-pad thrust bearings, which incorporate leveling plates to equalize the load among the individual pads and accommodate misalignment between the collar and housing. The equalizing feature provides higher load capacity (Figure 3).

Non-equalizing tilting-pad thrust bearings, as the name implies, have no equalization system, which reduces the overall axial height of the bearing. These Kingsbury bearings are best for applications with axial space limitations. The design requires tighter bearing and casing manufacturing tolerances. A means for adjustment is sometimes required to align the bearings and rotor during assembly.

Figure 3: Kingsbury specializes in tilting pad thrust and journal bearings

Figure 2: The flexure pivot tilting pad bearing introduced by Waukesha Bearings is a monolithic part, being turned and bored as a solid. The pivot pads are mostly separated from the structure by precision machining

In addition, Kingsbury supplies tilting-pad journal bearings that have several design variables that are used to attain reliable and stable machine performance. Tilt-pad pivot designs accommodate shaft misalignment.

Both equalizing and non-equalizing tilting-pad thrust bearings and tilting-pad journal bearings are available in two styles:

- Flooded lubrication bearings that circulate oil around the pads are used for low-to-moderate bearing surface speeds
- Direct lubrication bearings that introduce cool, fresh oil at the leading edge of the bearing pad, and reduce oil flow requirements and power loss in high-speed applications.

"Bearing power loss and oil flow requirements increase exponentially with speed and significantly influence machine efficiency and oil lube system size," said Scan DeCamillo, Kingsbury's Manager of R&D. "Direct lubrication is a technology designed to lower bearing oil flow requirements and power loss as turbomachinery continues to increase in size and speed."

Recent research, said DeCamillo, has been focused on a direct-lube design for journal bearings designated between-pad-groove (BPG), which introduces direct lube technology in a more robust bearing design of simpler construction. SSV (sub-synchronous vibration) grooves for use in direct lube journal bearings eliminate a low-amplitude, broadband, radial, sub-synchronous vibration (Figure 4).

Two further features — high-speed tapers and axial dampers — address high temperatures and axial SSV encountered in thrust bearing applications at high-speed and low-load conditions. "SSV grooves, high-speed tapers, and axial dampers are being incorporated in many high-speed turbomachinery applications," said DeCamillo.

New materials

Work is also being done to replace the traditional babbitt material in bearings. The temperature limitations of babbitt are being approached as turbomachinery technology continues to push bearing surface speed and load capacity requirements. Alternate materials are already used in niche applications such has PEEK (polyetheretherketone), other polymers and ceramics.

"One of the challenges in applying alternate technologies to industries, such as oil, gas, and chemical processing, is that the change will affect other systems and standards," said DeCamillo. "Monitoring and alarm systems that are presently set up for babbitted bearings would need to be addressed. Higher operating temperatures will also require a change to higher temper-

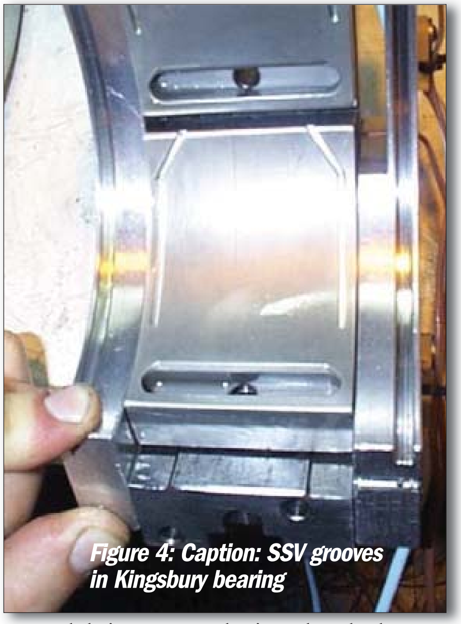

Figure 4: Caption: SSV grooves in Kingsbury bearing

ature lubricants; synthetics already have a good history."

SKF is very much on the forefront when it comes to the use of ceramics. Kahlman of SKF said that the use of new materials and combinations of materials to create application-specific solutions for industry challenges has led to mixing and matching of ceramic rolling element bearings, with stainless steel used for the rings. These are available from SKF in single-row, deep-groove ball bearings, angular contact ball bearings, 4-point contact ball bearings and cylindrical roller bearings.

"They have been applied in various screw compressors for sour and other process gas applications and in high-performance pump applications for both cryogenic and subsea applications," said Kahlman.

Another recent development is the use of plasma coating on the outside diameter of a bearing used in electric motors, which insulates them from the passage of electric current through the bearing. These find application in some motor-driven drive trains in turbomachinery. In the more experimental stage, rolling element bearings have been developed that are lubricated with pure refrigerant for centrifugal compressors and chillers, thereby eliminating the need for external lubrication.

Sensorized bearing technology, too, has been developed for the oil & gas industry. This SKF unit acts as a non-drive end bearing to support the rotor shaft, and as an encoder to monitor and control a motor. It bolts to the rotor shaft and motor housing shield.

The SKF sensor bearing unit consists of an aluminum end cover, hybrid bearing, impulse ring and sensor adjusted, lubricated and sealed at the factory. It contains a hybrid, deep-groove ball or cylindrical roller bearing, a magnetic impulse ring and a sensor embedded in the end cover and connecting cables.

The impulse ring, fixed to the rotating inner ring of the bearing, is magnetized with a sequence of north and south magnetic poles. A number of digital impulses, equal to the number of pole pairs on the impulse ring, are generated on each revolution.

The output signal provides information about speed and direction of rotation. For critical applications, units are available with a second sensor for mechanical redundancy. And some sensorized bearings are embedded with condition monitoring capabilities that can communicate with the outside world.

In addition, SKF has upgraded its ball, cylindrical and tapered bearings to gain extended life in more conventional turbomachinery applications. Known as the Explorer series, their longer life is attributed to material improvements and subtle internal geometry changes.

The SKF Explorer performance class, for example, includes cylindrical roller bearings designed for heavy industrial applications. They go up to 420 mm outside diameter and are said to run cooler, provide a 15% higher load-carrying capacity, and longer life compared to standard cylindrical roller bearings.

In applications with frequent starts and stops, conventional bearings can suffer due to slow formation of a lubricant film. SKF's approach is to create a surface finish that promotes the formation of the lubricant film via a reengineered PEEK cage and a 40° contact angle.

Magnetic bearings

The first successful application of active magnetic bearings for industrial turbomachinery dates back to 1976. French company S2M (now part of SKF) pioneered the technology and developed contactless magnetic bearings for turbo-molecular pumps (TMPs).

Today more than 130,000 TMP units equipped with SKF S2M technology are in operation, said Askar Gubaidullin, Business Development Manager, SKF Magnetic Mechatronics, S2M. "This year the 1,000th SKF S2M magnetic bearing system was put into operation in oil and gas. The portfolio covers applications for turboexpanders, centrifugal compressors, heavy duty electric motors, gas turbines and generators."

He added that the power range of magnetic bearings in rotating machinery varies from several hundred horsepower in the case of a small-frame turboexpander and up to 43,000 HP (32+ MW) for a natural gas pipeline compressor (Figure 5).

"There is a little bit of magic when a 10-ton rotor supported by mag bearings continues with a smooth rotation showing just 20 microns of vibration, as is the case with a 9 MW oil-free gas turbine coupled to a

Figure 5: This radial magnetic bearing of 310 mm bore diameter is employed in centrifugal compressors in the power range of 16 to 32 MW. Courtesy of SKF

power generator in operation in a dozen Russian combined heat and power plants," said Gubaidullin.

SKF S2M mag bearings are also used in GE's ICL integrated motor-compressor line. The compressor and motor combined in a hermetically sealed casing are running on magnetic bearings immersed in pressurized clean gas. These units do not require a lubrication oil system, gear box, dry gas seals or external cooling system.

"Magnetic bearings widen the operating range of the machine and allow rotation at higher-speeds," said Gubaidullin. "The integrated system is compact, and brings operational and environmental benefits, as well as higher reliability and reduced maintenance."

One of the more challenging ongoing projects is subsea compression. SKF S2M's magnetic bearings are being used to equip the compressors and high-speed motors for the Åsgard Subsea Gas Compression System off the Norwegian coast (Turbomachinery International Sep/Oct 2014), scheduled for installation in 2015.

The core of subsea compression technology is an oil-free integrated motor compressor designed to boost the falling gas flow rate. The first motor-driven compressor of this kind was developed in the early 1990s. These integrated compressors with SKF S2M magnetic bearings have since accumulated millions of hours of service time.

This subsea work has given rise to a new range of electromechanical and electronic parts to support magnetic bearings used in turbomachinery. SKF is now commercializing its E300V2 electronic control cabinet.

Features include remote monitoring and automatic diagnostics with a view to providing plant operators with a higher degree of autonomy. A high-resolution, data-acquisition system monitors operating parameters, such as rotation speed, vibrations and temperatures in real time. The user can visualize

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rotation orbits, 3D waterfalls and graphs with spectral analyses, time snapshots and other bearing-related parameters.

Lower prices

As magnetic bearing applications have grown in popularity, their lower pricing has made them more accessible. Calnetix Powerflux Magnetic Bearings, for example, have been incorporated into several turbomachinery applications.

They have been used to meet the shock-and-vibration requirements of U.S. Navy chiller applications for their next generation high-efficiency chiller systems. They also form the backbone of a family of high-speed integral, oil-free air compressors.

"Calnetix bearings were chosen as the key enabling technology for a low-loss and low-profile, power-dense hermetically sealed compressor," said Venky Krishnan, Director of Programs, Calnetix Technologies. "In addition, we are using Powerflux magnetic bearings in our Carefree Integrated Power Module (IPM), the heart of our Organic Rankine Cycle (ORC) systems."

This consists of an integrated, high-speed turbine expander and high-efficiency generator. The magnetic bearings allow for non-contact operation and have lower power consumption compared to ball or fluid-film bearings. They also monitor rotor imbalance, and need no lubrication system or seals. These systems are being used in various small-scale, heat-recovery applications throughout the world.

On the development front, Larry Hawkins, Director of Technology, Magnetic Bearings at Calnetix, called attention to a constant flux edge sensor. It is used to measure axial displacement from a radial surface in the presence of external fields. Additionally, the company has begun production of a new combination bearing topology (radial and axial support in one structure).

"This side-by-side combo bearing has thrust bandwidth equivalent to a standalone thrust bearing with lower windage losses and an axially shorter overall package," said Hawkins. "There is also ongoing development by many vendors related to improving control response during process upset or overload conditions. These schemes improve recovery of shaft levitation after a process upset and limit time and loads on the auxiliary (backup) bearings."

Mecos, meanwhile, is providing magnetic bearing systems for the turbomachinery industry, particularly in oil & gas. Bernhard Mandel, Director of Sales & Marketing, mentioned recent breakthroughs in software tools related to magnetic bearings for better rotor and stator alignment, and to compensate for manufacturing imperfections. "We have also developed new coatings for sour gas applications which improve durability, and tools for better touchdown (backup) bearing control."

Magnetic bearings need the support of touchdown bearings. They come into play during any mag bearing interruption, such as when the unit is still spinning but creates so much torque that the mag bearings cannot hold the shaft in position. As a result, touchdown bearings are needed for a fraction of a second.

"The most obvious use of touchdown bearings would be an electrical loss where the rotor would drop onto the backup bearings and coast down," said Andy Robbins, Vice President of Engineering, GMN Bearing USA.

His company supports the turbomachinery market with touchdown bearings for magnetic bearings and traditional duty-cycle bearings. Its touchdown bearings are being used in such applications as high-speed motors, turboexpanders and high-speed pumps.

Robbins said the touchdown bearing market has entered an expansion phase as magnetic bearings grow in demand. The main increase is in the amount of testing, but there are small TMPs that already have magnetic bearings and back up bearings in full production.

Gas and air bearings

Magnetic bearings are not the only approach to oil-free bearings. There is growing interest and deployment of air bearings (a.k.a. foil gas or gas bearings) as an alternative way to eliminate the need for oil.

Christopher DellaCorte, NASA's Senior Technologist for Tribology & Rotating Machinery at the Glenn Research Center in Cleveland, led the Oil-Free Turbomachinery team that conducted research in high-temperature foil gas bearings for eventual use in gas turbines. "In the long term, we expect this technology to impact power generation, automotive turbocharging and microturbine propulsion, Unmanned Aerial Vehicle (UAV) turbines, air compression and blowing, and space power generation," he said.

Having answered many of the fundamental questions about foil gas bearings and their potential, the NASA team is now developing corrosion resistant, shockproof ball bearings and gears made from NiTi-based superelastic materials.

Foil gas bearings rely upon a self-generated gas film for lubrication. The film viscosity (and hence the pressure) is low as the viscosity of air is much lower than oil. Pressures are directly proportional to surface velocity (rpm times shaft diameter) and are typically tens of psi, said DellaCorte, whereas oil-lubricated bearings have film pressures of hundreds of psi. Therefore, foil gas bearings thrive on light loads and high speeds.

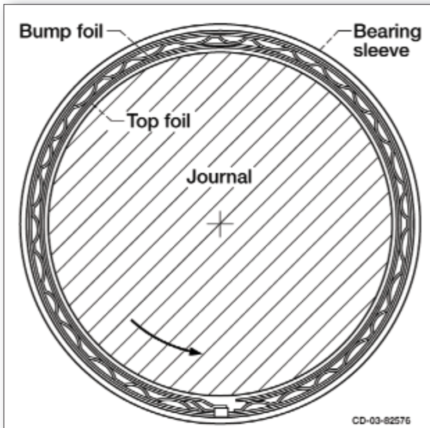

Figure 6: Example of foil gas bearing

"Bearings for microturbines in the 5 kW to 300 kW class that operate on foil journal bearings range from 1" to 3" diameter," said DellaCorte. "Rotor masses range from less than a pound to a few hundred pounds. We now see electrically driven air compressors on the market that are pushing 500 HP on foil bearings."

As for going larger than that, he believes that some type of hybridization might be required, perhaps using mag bearings for rotor lift at zero rpm and for damping. Bottom line: engineering load capacity is always going to be limited to 10-to-50 psi, which limits machine size.

NASA has developed PS300 and PS400 tribocoatings for high-temperature bearings and durability. They enable foil bearings to endure tens of thousands of start-stop rubs without undue foil wear. This opens up the field for oil-free turbochargers for cars and trucks, fuel cell compressors and microturbines for hybrid cars.

DellaCorte thinks that once turbochargers with foil gas bearings become broadly available in the automotive market as a further way to lower emissions, improve fuel economy and reduce turbo failures, it will open the door to this bearing technology becoming more readily available and far more economical to deploy.

Bump foil bearings (BFB) are the most common type of foil bearing with a long history in air cycle machines onboard military and commercial aircraft. They are now also commonly employed in microturbines.

They consist of a flat piece of metal that is stamped to have ridges that constitute the bumps, then rolled and inserted into a precision bore. A thin top sleeve, often with a low friction coating is inserted inside the bumps. Generally 25-to-50 μ of radial clearance is

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designed between the top foil face and the outside diameter of the rotor (Figure 6).

"Since clearances can be a challenge when working with stampings and foils, the bumps must be compliant, and as the load goes up, more bumps come into play, distributing the load across a broad area," said Drew Devitt, Chief Technology Officer of New Way Gas Bearings. "The rotor could still whirl or whip inside of the design clearance, so it is not unusual to see BFBs shimmed between the precision bore and the bump strip to reduce the clearance in three or four spots."

Mesh foil bearings are also attracting interest, added Devitt. The idea is that at least some of the load transmitted through the pad is supported by a metal wire mesh. The mesh may be of stainless steel, aluminum or copper. The friction losses between the wires in the mesh as they spring results in a damping mechanism that is insensitive even to the high heat levels in gas turbines.

New Way has been studying the issue of damping in turbomachinery and specifically flexible rotors supported on externally pressurized gas bearings using multiple gases. On nitrogen, temperature probes just below the bearing face showed a 1°C temperature rise after 20 min at 9,000 rpm, while with CO_2, the bearings cooled 2°C. Devitt believes this is an industry first for gas bearings (Figure 1).

New Way has a line of externally pressurized radial gas bearings. These bearings, said Devitt, compare favorably with other types of bearings (Table A). They are appropriate for highly loaded applications: applying a 600 psi supply pressure will result in 300-to-400 psi of average pressure in the gap. They fit in the same space as tilting pad oil bearings, but can operate on process gases, and up to 600°C in oxygen and higher if oxidation is not an issue.

Other companies, such as Barber Nichols and Capstone Turbine, are involved in gas bearing development. Barber Nichols deploys foil gas bearings operating on supercritical CO2 (SCO2) (Turbomachinery International Sept/Oct 2012). The power density of supercritical CO2 is such that a 1 MW impeller is only 1.5" diameter.

"An air bearing consists of a cartridge, underspring and hydrodynamic foil," said Robert Gleason, Capstone Turbine's Senior Vice President of Product Development. "The rotation of the rotor group with respect to the foil generates a pressure wedge that supports the rotor group on a dynamic boundary layer of air."

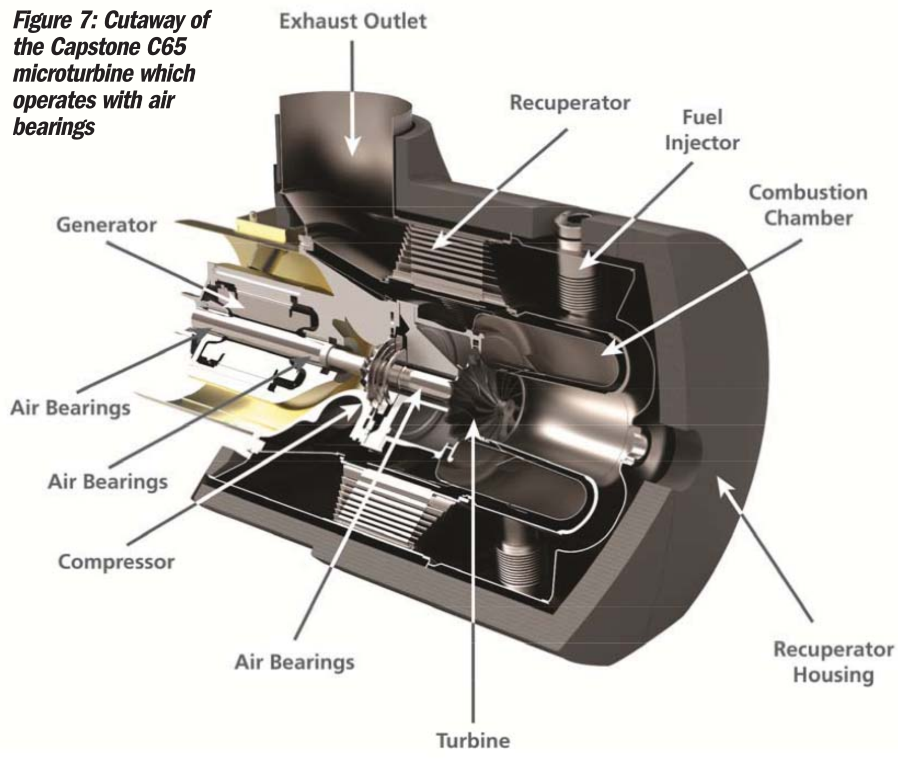
Air bearing dampening is accomplished by the underspring, and forces from the boundary layer of air, he explained. Air bearings can support the rotation of the rotor group up to speeds of 96,000 rpm, and the maintenance interval is greater than 40,000 hours.

Capstone Turbine uses air bearings because of their excellent performance when operating in hot environments, compared with oil and magnetic bearings. "Oil lubricated bearings coke when exposed to excessive heat and can require added cooling," said Robert Gleason, Capstone Turbine's Senior Vice President of Product Development. They also require schedule changes to maintain health of oil, present environmental hazards and are not conducive to tight rotational clearances. Magnetic bearings can require added cooling and additional controls, are sensitive to heat and demagnetization, and require backup bearings in the event of an overload or bearing failure.

Capstone is working with the U.S. Department of Energy on a new generation of air bearings to provide high dynamic load capacity at high temperatures. These are intended for use in next generation Capstone products including the dual spool C370 microturbine system (Figure).

Said Gleason: "With the advancement in recent coating technologies, wear coatings within the bearing system are now impervious to all types of humid environments thus allowing coastal, off-shore oil platform, and marine product applications where other technologies would be prone to failure or environmental toxic monitoring." TI

Figure 7: Cutaway of the Capstone C65 microturbine which operates with air bearings



Rating of Bearing Types vs. Performance Characteristics

Ranking Key: 3=Superior Rating 2=Average Rating 1=Low Rating

	Oil Bearing	Magnetic Bearing	Foil Bearing	Flexure/Pivot Hybrid-Type Bearing	Externally-Pressurized Gas Bearing
Zero Friction at Start	1	3	1	2	3
Service Cost	1	1	3	3	3
Heat Generation	1	1	3	3	3
Process Compatibility	1	2	3	3	3
Shear/Speed	2	3	3	3	3
Load	3	2	1	2	3
Damping	3	3	1	1	3
Total Score	**12**	**15**	**15**	**17**	**21**