

High Speed Bearing Technologies For Wastewater Treatment Applications

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INTRODUCTION

High speed bearing technology is applicable for aeration blowers operating at much higher speeds than the typical 60Hz, 3600RPM for cast multistage units. High Speed Turbo (HST) units are usually single stage (though some utilize multiple cores) and rotate from 15,000 to 50,000RPM. At such high speeds, standard roller bearings cannot offer the industry standard L10 bearing life. Two types of bearing technologies have come to dominate the wastewater treatment market for these types of machines: airfoil and magnetically levitated. Often the two technologies are compared as equals, however, in many significant ways they are not. This paper explores history, basic operation, and construction of the airfoil and magnetic bearings. Furthermore, a discussion is offered on advantages and disadvantages of each technology for the wastewater aeration industry.

BRIEF HISTORY OF TECHNOLOGIES

1. Airfoil Bearings

Airfoil bearings originally substituted rolling element and journal bearings in high speed Air Cycle Machines which are at the heart of Environmental Control Systems on gas turbine powered aircraft. Other common applications include bleed air turbo compressors and turbo expanders. These applications typically have light loads and constant speeds. The image below shows the evolution of the airfoil bearings since the Multipad Foil Journal Bearing (Fig. 1a) was introduced in 1960's by Garrett AiResearch (now Allied Signal). Numerous companies such as Honeywell, Hamilton Standard, Mechanical Technology Inc (MTI), ABG-Semca, Sunstrand, British Aerospace, Tupolev and others, made improvements to the basic design. Current research efforts are focused on increased damping and load capacity, advanced anti-friction foil coatings, simplified manufacturing techniques, and improved stability under shock loads.

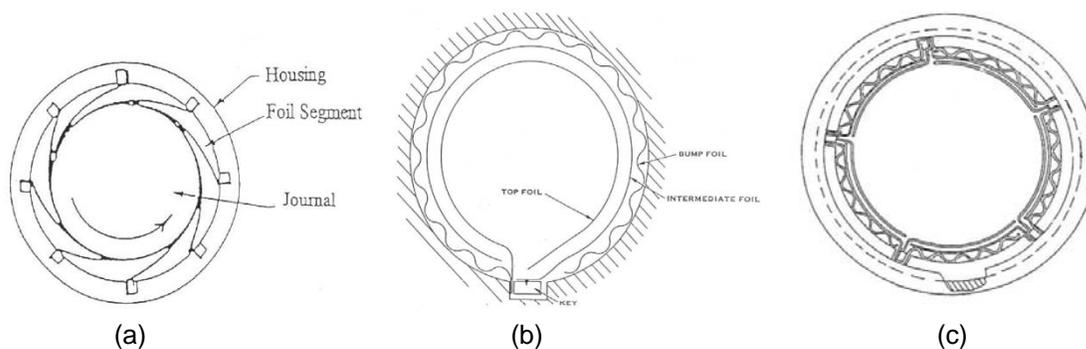


Fig 1 - Evolution of the airfoil bearing technology.
(a) Multipad Foil Bearing concept developed by Garrett AiResearch; (b) Reversed Multilayer Foil Journal Bearing concept developed by Hamilton Standard; (c) Reversed Multipad Foil Journal Bearing concept developed by R&D Dynamics

2. *Magnetic Bearings*

Passive magnetic levitation including patented systems dates back over a century. However, passive systems are inherently unstable. Today, active systems employing electromagnets, sophisticated controllers and algorithms are used almost exclusively. First investigations of active magnetic bearings began in the 1930s for use in ultracentrifuges, which assist in research in molecular biology, biochemistry, polymer science, etc. Today, magnetic bearings are a time-tested technology in the oil and gas industry, sub-sea applications, chillers, high-precision instrumentation, vacuum energy storage, etc. The image below shows a typical magnetic bearing stator. Early research was done at the University of Virginia, with the introduction of the magnetic bearing to the turbo machinery industry in 1988. Further development was done by Magnetic Bearing Inc. and improved upon by NOVA Gas Transmission Ltd. NOVA later created a separate magnetic bearing company - Revolve Technologies Inc. (now part of SKF of Sweden). Current research efforts are focused on improving simulation techniques, increasing stability, and even reducing reliance on feedback systems (such as the Halbach magnetic bearing).

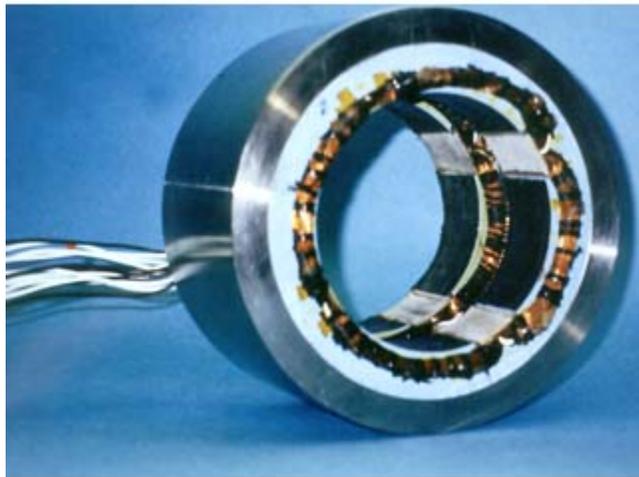


Fig 2 - Stator of a typical magnetic bearing

PRINCIPLES OF OPERATION

1. *Airfoil Bearings*

Airfoil bearings operate similarly to an oil bushing or a journal bearing, but with air as the working medium. Before start-up, a small amount of preload exists between the shaft and the bearing. Additionally, in machines with horizontal shaft orientation, the shaft rests against the bearing due to gravity. Consequently, some of the foils are in direct contact with the shaft while it is stationary. This contact results in friction as the shaft begins rotation relative to the foils before lift off.

The rotating assembly lifts off the bearing due to hydrodynamic pressure that is generated between the shaft and the bearing. In any fluid system (air, water, oil) the velocity of the fluid directly at the surface of a solid boundary will always be zero, even if the fluid stream is moving on a larger scale. Therefore the velocity of the fluid stream increases at some rate with distance from a solid boundary. This velocity difference means that some shear is applied to the fluid. The airfoil bearing takes advantage of this small scale shear to produce hydrodynamic pressure and levitate the shaft. After levitation the shaft becomes non-contacting at around 2,000 to 5,000 RPM. The image below shows an oil lubricated journal bearing operating on the same principle as the airfoil bearing.

To mitigate negative effects of the sliding friction during slow rotation at start up (such as heat generation and wear) solid lubrication is applied to the surfaces. Common types of coatings used as lubricants of the bearing surfaces are Teflon-S and Korolon (chromium oxide). Some military

applications use a polyimide coating developed by NASA. Other coatings include aluminum oxide, titanium nitride, titanium carbide and various boron nitride mixtures. Though studies show excellent wear resistance of the coatings, wear of the foil coating is not well tolerated by the bearing. Once solid lubricant is worn to the substrate, increased friction can cause galling and seizure of the machine. Any contaminants in the air stream of the bearing such as dust or sand will cause accelerated wear.

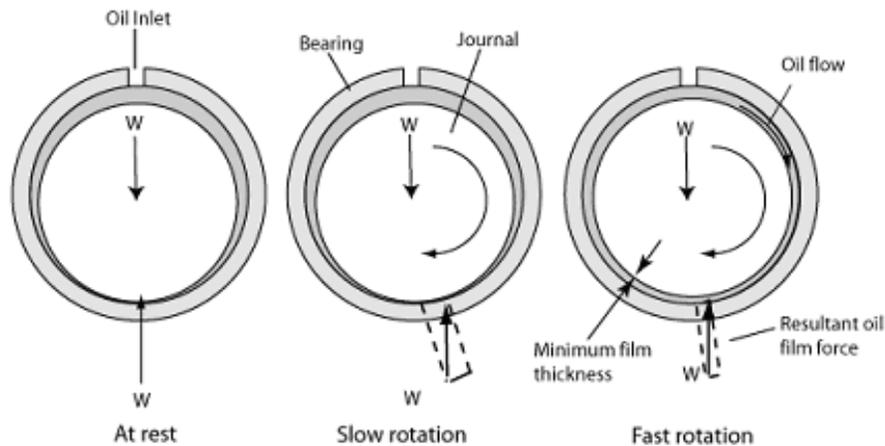


Fig 3 - Oil journal bearing operates on the same principles as the airfoil bearing.

2. Magnetic Bearings

Active magnetic bearing systems rely on dynamically actuated electromagnets for levitation. If compared directly to an oil journal or an airfoil bearing, the working medium of a magnetic bearing is electrical current as opposed to oil or air, and the shaft is supported by an active magnetic field as opposed to an oil film or air pressure. As the bearing is turned on, the electromagnets push the rotating assembly toward the center of the bearing. The system is called active because sensors that are part of the bearing detect the actual location of the center of the rotating assembly and pass the information to a Magnetic Bearing Controller (MBC). The controller decides if the power going to any of the magnets must be adjusted to achieve a more centered position and does so accordingly. A system schematic is shown in Fig 4.

Once the shaft is levitated, rotation can begin with essentially no friction. During normal operation the position of the shaft is monitored thousands of times per second and electromagnets are adjusted accordingly. The active adjustment allows for automatic corrections of small irregularities of the rotating assembly such as imbalances. While operating, a variety of performance characteristics can be monitored and recorded by sensors that are a natural part of the bearing assembly. This gives insight into the temperature, vibration, thrust loads, proximity to surge and system stability of the equipment. The data can be further statistically analyzed showing condition and health of the machine, operating trends, and any early warning signs for the system.

In the event of a power outage, it is standard industry practice to include fail-safe mechanisms as part of the design of the bearing. One such mechanism is a simple UPS that continues to supply power to the magnetic bearing system until shaft rotation has stopped. In wastewater treatment applications, shaft rotation will slow very rapidly due to the discharge backpressure, and will come to a stop within a few minutes at the most. Another method of bearing protection does not require a UPS. At the time of the power outage, the motor is turned into a generator and the harvested power is then used to levitate the rotating assembly.

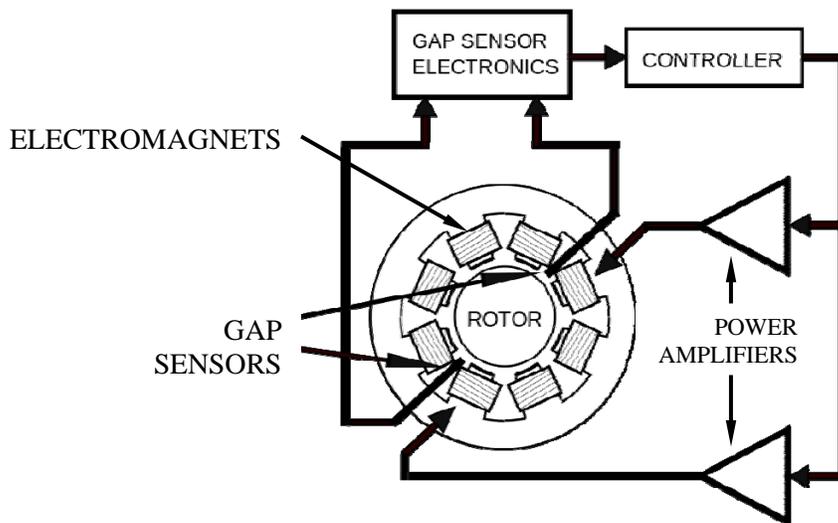


Fig 4 - Magnetic bearing schematic. Gap sensors detect position of the rotor and send the information to the controller. Controller adjusts the power to the electromagnets to re-center the rotor.

Both protection methods are supplemented by one other protection system – the “back-up” bearing. In case of a UPS failure or other problem, the rotating assembly will land on an inner race of a roller bearing installed within the system. Under typical conditions, the rotating assembly does not make contact with the roller bearing because the roller bearing ID is slightly larger than the OD of the rotating shaft. Axial back-up bearings are also a standard component of the magnetic bearing and operate on the same principle.

DISCUSSION

Airfoil and magnetic bearings both offer a viable method of supporting high speed rotating assemblies for centrifugal compressors in wastewater treatment applications. However, given the great differences in features and price points, the choice is not always obvious. The simplest comparison is shown in Table 1. Key differences become obvious for airfoil and magnetic bearings respectively:

- bearing control – passive vs. active;
- bearing health monitoring – passive vs. active;
- contacting – at start up and low speed vs. never;
- failure modes – fewer paths, but catastrophic vs. complex self-protecting system;
- cost – low vs. high.

Bearing control

Bearing control is completely passive for the airfoil bearings. Because there is no actuation or control loops, the stability of the bearing will depend solely on the design of the mechanical components and operating environment. Variability in viscosity, density, thermal conductivity and heat capacity of the bearing operating gas will contribute to bearing stability and must be considered during machine design.

Magnetic bearing control is performed with the control loop of the controller. Position of the rotating assembly with respect to the center of the bearing is determined on the order of 10,000 times per second using the position sensors integral to the bearing. Position information is

then passed to the MBC, which performs calculations and adjusts power sent to the electromagnets of the bearing. Stability of such closed loop systems is easily controlled. The ability to dynamically adjust bearing characteristics allows for a wide stability range, self-protective algorithms, and collection of data for health trending purposes.

For wastewater treatment applications, the advantages offered by the active control of magnetic bearings are significant. Aeration blowers must be designed to handle ambient conditions varying with seasonal changes, day-to-day variation and intraday diurnal cycle. Continuous self-monitoring by the magnetic bearings provides an assurance against catastrophic failure, and gives insight into overall health of this essential equipment.

	•Oil Journal Bearings	•Air bearing	•Magnetic bearing
Working medium	–Oil	–Air	–Electric current
Shaft supported by	–Oil film	–Air pressure	–Magnetic field
Medium delivered by	–Oil pipes or sump	–Ambient air source	–Wires and cables
Bearing stability and characteristics defined by	–Oil film stiffness	–Air gap stability, foil stiffness and configuration	–MBC algorithms
Bearing stability control	–Passive	–Passive	–Active
Key support component	–Oil pump	–Shaft speed	–Controller amplifier
Support component back up	–None	–None	–Backup rolling element bearings and UPS battery back up
Bearing health monitoring	–Passive temperature sensor	–Passive temperature sensor	–Active position sensors, multiple temperature sensors, remote monitoring
Contacting	–At start up and low speed	–At start up and low speed	–Never
Inherent monitoring	–None	–None	–Temperature, vibration, proximity to surge, system stability
Cost	–Not applicable to wastewater industry	–Low	–High

Table 1- Simple comparison of oil journal, airfoil and magnetic bearings.

Bearing health monitoring

Only passive temperature monitoring is easily possible with airfoil bearings. Thermocouples can be installed as a specified extra in some cases onto the exterior of the stationary components in the bearing to monitor local temperature. In theory, in the case of localized heating problem on the bearing, if the problem is identified quickly enough, the machine may be turned off to protect itself. However, temperature monitors for the airfoil bearing are not common practice in the field as the response time of such devices must be fast enough to capture the near instantaneous temperature rise. No other health monitoring is available for the airfoil bearing. Unfortunately, this leaves the machine vulnerable to catastrophic failure, as the condition of the shaft coating, imbalances, and center of rotation are not monitored.

Magnetic bearings have active control of the rotating assembly. The bearings continuously offer a detailed picture of the bearing condition. Shaft position can be related to vibration, dynamic imbalances, and internal diagnostics of the bearing. Temperature sensors detect overall condition of the bearing and the control circuitry. Additionally, the above data can

be used to analyze system resonances, gyroscopic effects, and overall system stability. If a problem is detected, the machine will automatically shut down to protect itself from costly damage. Finally, the collected data can be retrieved via an internet connection anywhere in the world and analyzed further to see large scale trends, comparison to other machines, etc.

Aeration equipment is a significant investment for any wastewater treatment facility. The ability of the blower to detect any impending damage and to protect itself has the potential to save downtime, repair and replacement costs. Even if a blower fails during a warranty period, a lengthy shutdown can be a serious disruption for the plant operation. Having the capability to shut down the machine automatically before any damage occurs is a significant long term cost advantage for the plant owner and operator. Additional understanding can be gained from the data being collected by the machine. Maintenance staff for the plant can begin to analyze a machine fault without being on site.

Contacting

Soft polymer coatings such as Teflon on the foils of an airfoil bearing will tend to wear at the contacting point with the journal at start, stop and low speed operation (typical liftoff speeds of 2000 to 5000 RPM). A better performer is a hard solid lubricant applied on to the surface of the rotating journal. This eliminates localized wear and distributes it randomly over the circumference of the journal. Endurance tests on PS304 (Korolon) coating have shown the number of start/stop cycles at 5.0 PSI load and 352F to be in excess of 100,000. However, under room temperature conditions, the number of start/stop cycles is reduced by over 50%. Additional consideration must be given to the typical loads seen by the bearings in the wastewater industry. Of the radial and thrust airfoil bearings, thrust bearings are typically more vulnerable to high loads. To minimize loads and extend airfoil bearing life, blower designers will often use thrust balancing lines or employ a "double-ended" motor design in which mirrored blowers are assembled onto both ends of the motor. It should be noted that balancing lines will reduce the overall efficiency of the machine as it reroutes some of the process air to the bearing. Double-ended designs have a larger wetted surface area, and consequently have higher surface drag, compared with typical single stage machines.

Magnetic bearings do not experience contacting under normal operation and therefore do not have physical wear. Contacting is only possible if no power is provided to the bearing. This may happen during a power outage or internal component failure. Back-up systems are typically built-in to commercial magnetic bearings to prevent damage in either scenario. In case of a power loss, the rotating assembly will slow down within seconds and come to a full stop in less than 2 minutes due to the load provided by the back-pressure of an aeration system. For that duration the rotating assembly can be supported in two ways. One commonly used option is a UPS unit which provides power to levitate the bearings until full stop. In case of a UPS failure, the rotating assembly will land on a set of back-up roller bearings. Back-up roller bearings are specially designed to have an internal diameter slightly larger than the diameter of the rotating shaft. During normal operation there is no contact between the rotating assembly and the roller bearings. Additionally, the roller bearings are designed and tested for multiple shaft landings at full load and RPM. Another method of protection against power failure is using the inertia of the rotating assembly after a power loss as a power source for the bearing levitation. With this option, the back-up roller bearings are also employed.

Machines utilizing airfoil bearings are capable of many starts and stops; however, shaft coating will degrade with repeated cycles, ingestion of dust and other contaminants. Coating condition is not easily inspected. Further study may end speculation on the longevity of the airfoil bearing coatings in wastewater treatment applications. Until then, magnetic bearings offer a reliable, long-term solution for aeration blowers.

Failure modes

It has been demonstrated by the scientific community that many airfoil bearing failures occur as a result of a thermal run-away effect. Because the air bearings rely on viscous shearing of the operating fluid, some heat is generated as part of normal operation. If left unchecked, heat build-up can cause localized hot spots and uneven mechanical heating and may lead to bearing

seizure. Failures of this type tend to occur rapidly with little to no warning. Amount of preload between the inner foils of the bearing and the shaft as well as bump foil designs will contribute to this condition. Careful consideration and simulation of these factors is required during machine design as they will affect overall machine longevity. Other failure causes include ambient environment. Ambient dust and salt water moisture can cause significant damage to the coatings on the shaft or foils and can even initiate a catastrophic failure. Typical designs try to limit particulate ingestion with reverse pitot cooling air intakes for the bearings. The working fluid in the radial bearings will not typically circulate and the positive pressure inside the bearing will naturally limit particulate ingestion. However, the thrust bearing tends to accelerate the working fluid radially and will naturally have some flow between the foil and the thrust flange. To eliminate the possibility of damage and extend life of the machine, the air supplied to the bearing must be properly filtered.

Magnetic bearings are much more complex compared to the airfoil bearings and, consequently, have more failure modes. However, the self-protection mechanisms virtually eliminate the possibility for a catastrophic failure. For most problems, the machine will shut down before a failure occurs. Dusty and moist environments do not affect the magnetic bearings as the clearances between the rotating and stationary components are generally large enough to accommodate some particulates. Furthermore, the performance of the bearing is not affected by the particulates in the air as the working medium is electric current.

Protection is offered against costly catastrophic failure by magnetic bearings; however, a simpler system such as the airfoil bearings offers fewer methods to fail. The choice of the bearing technology lies with the plant designer, owner and operator. It is important to consider effects of failure, time to repair or replace the equipment, cost of the event, and the reputation of the equipment provider before making this key decision.

Cost

Cost is often the deciding factor in technology selection. The initial cost of blowers with airfoil bearings is typically significantly less than magnetic bearings. This is due to the complex system the magnetic bearings need for proper operation. However, direct comparison of the technologies shows that the two are **not equal**. The added cost of blowers equipped with magnetic bearings offers significant long term advantages over the life of the machine. Selecting airfoil bearings for blowers for your plant will offer a lower upfront cost, and fewer failure modes. However, should something go wrong during the typical expected 20 year life span, the possibility of a catastrophic failure and high repair and replacement costs can be expected to be much higher with the airfoil designs. Selecting the bearing technology for your application should take into account capital equipment cost, long term management and maintenance, and considerations for failure modes.

CONCLUSIONS

Finally, we can easily point to the significant differences between magnetic and airfoil bearing technologies. Though both bearing types are acceptable for the wastewater treatment industry, they are not equal and should not be compared as such. The simplicity and low cost of the airfoil bearings mean that comprehensive monitoring, active control, and self-protection of the blower is limited at best and in some cases not possible. However, the advantages of remote access to check status and health of the machine, data trending, multiple fail-safe mechanisms, and many other features come with a higher up-front cost with magnetic bearings.

In some cases airfoil bearings will be the preferred choice for a particular plant design. These may be designs with very low horsepower requirements, continuous operation (few start/stop cycles), and a clean air supply. However, it is possible that in most cases magnetic bearings will be the preferred technology due to long term advantages of the technology.

FURTHER READING

"An Overview of Magnetic Bearing Technology for Gas Turbine Engines", D. Clark et al.
NASA/TM-2001-213177

"Magnetic Bearings at Draper Laboratory", A.Kondoleon et al. NASA-CP-3336-Pt-1

"Performance and Durability of High Temperature Foil Air Bearings for Oil-Free
Turbomachinery", C. DellaCorte, NASA/TM-2000-209187

"Remaining Technical Challenges and Future Plans for Oil-Free Turbomachinery" C. DellaCorte
NASA/TM-2010216762

"Foil Bearing Starting Considerations and Requirements for Rotorcraft Engine Applications", K.
Radil et al. ARL-TR-4873

Figure Credits

Fig 1 a,b,c - "Foil Air/Gas Bearing Technology - An Overview" by Giri L. Agrawal, published by
The American Society of Mechanical Engineers, Publication 97-GT-347

Fig 2 – <http://spinoff.nasa.gov/spinoff1996/images/114.jpg>

Fig 3 – www.wikipedia.com

Fig 4 – www.wikipedia.com