TECHNICAL PAPER

POROUS VS. ORIFICE AIR BEARING TECHNOLOGY

By Andrew J. Devitt
Chairman and Chief Technology Officer
New Way Air Bearings
April 2, 1999

1 INTRODUCTION TO AIR BEARINGS

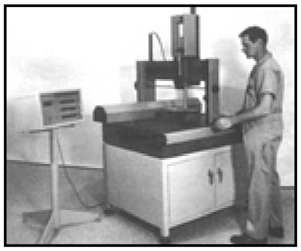
Air bearings have been a niche type technology employed mostly in laboratories and instruments. Today few engineers would consider air bearing technology for a "production machine". But as the drive for precision presses the technical limits of other bearing types the high precision properties of air bearings become more attractive. At the same time air bearings have become easier to use, less expensive, more robust and more readily available.

The object of this article is to first put air bearings into their historical context in the bearing industry, showing where they have been used successfully. The second part will discuss the relative merits of different types of air bearings and some of their potential applications.

Air bearings are not a new technology. In 1828 Rev. Wills published a work in the Cambridge Philosophical Society entitled "On the Pressure Produced on a Flat Surface When Opposed to a Stream of Air Issuing from an Orifice in a Plane Surface". Over the century's air bearings have become more sophisticated but still today, most air bearings operate on this same basic principle.

A. Kingsbury in 1897 experimented with a 6"diameter journal bearing supported on externally pressurized air. His problems, the practical problems of matching bore and shaft geometry and size so as to achieve a consistent .0005" gap all the way around were a manufacturing challenge at the turn-of-the-century. Small gaps are required with air because its viscosity is so low. Kingsbury found that the higher viscosity of water or oil worked better with the relatively large gaps that could be manufactured in the day. Today the company he founded, Kingsbury Corporation, is still a major supplier of fluid film bearings for applications like ship propeller shafts and shafts for hydro electric turbines.

Russ Shelton is known by some as the father of the CMM for his early work using air bearings and granite in the 60's. Mr. Shelton used porous carbon air bearings on CMM's he built 25 years ago. Some of these machines are still in use with no significant problem with the air bearings.



1

In 1904 air bearings were used in turbines. G. Westinghouse received a patent for an air thrust bearing used in a vertical steam turbine. Thrust bearings were easier to make as two flat surfaces are easier to match than ID and OD surfaces. The low viscosity of air with nearly zero friction was an important factor in the high efficiency of the Westinghouse steam turbine.

Due to the close tolerance machining operations necessary to make air bearings and the lack of suitable equations and computing power for optimizing them, air bearings saw very limited applications. While air bearings languished, high quality steel and hardening techniques made the rolling element bearing revolution possible. Rolling element bearings first replaced bushing type journal bearings, then the ball screw supplanted the Acme thread and even now the linear rolling element guide is solidifying its market lead over plain ways in the machine tool market. Rolling element bearings have been so widely accepted that air bearings are used in only relatively obscure ultra-accurate applications.

Although obscure, air bearings were an important enabling technology in meeting the exacting needs of the defense department and the nuclear power industry during the 50's and 60's. US National Labs were leaders in the application of air bearings to ultra- precision machine tools. Machines were constructed that could cut a mirror surface finish on 3 meter diameter metal optics with form accuracies measured in fractions of a wave length of light.

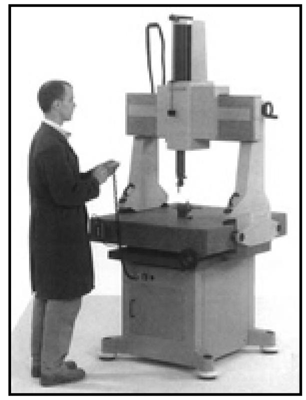
The technology was commercialized when IBM used air bearing spindles to produce large hard disc drives during the 70's. The hard disc drive industry still relies almost exclusively on air bearing spindles for spin stands. This because air bearing spindles have error motions on the order of 2 millionths of an inch which is about 100 times better than conventional spindles, allowing for higher data concentrations.

Wafer steppers, the machines which impart the logic patterns in computer chips are also almost the exclusive domain of air bearings. In these machines repeatability is of ultimate importance. A wafer that has been exposed with a pattern later returns to the same machine which must be able to overlay another pattern with accuracies

1

measured in the 10's of nanometers. Again, because of zero friction, position repeatability is higher. Zero contact bearings are also favored in clean room environments because they do not produce particles from wear or require lubrication. Measuring machines were early applications for air bearings. The check mate was the first CMM to employ air bearings and granite technology in 1965. Most CMM's today still employ air bearings for the zero friction and straighter motion. The smooth silent operation are especially evident in the resolution of scanning or measure on the fly type machines.

Several major manufacturers of CMM's use porous carbon air bearings in the machines they build today. The L.S.Starrett Company uses New Way® porous carbon air bearings in their current machines. The Starrett RMS at right uses the New Way® air bearing as an aesthetic design feature.



Although air bearings dominate the bearing technology of these applications they remain relatively unusual. If air bearings have so many technical advantages why aren't they more widely used? First, they have not been readily available as a standard product in the market of course now you can buy them from New Way. There are and have been companies that sell air bearing systems (usually based on their own internally developed air bearing design) but only recently have air bearings debuted as a modular commodity type product. Second, when available, they have been expensive to purchase or alternatively as some companies found out they are expensive to develop internally. Third, they have not been easy to employ. Selecting the right size bearing with the correct number and size of orifices to optimize the bearing performance and maintain stability can be a daunting task.

2

AIR BEARING STABILITY

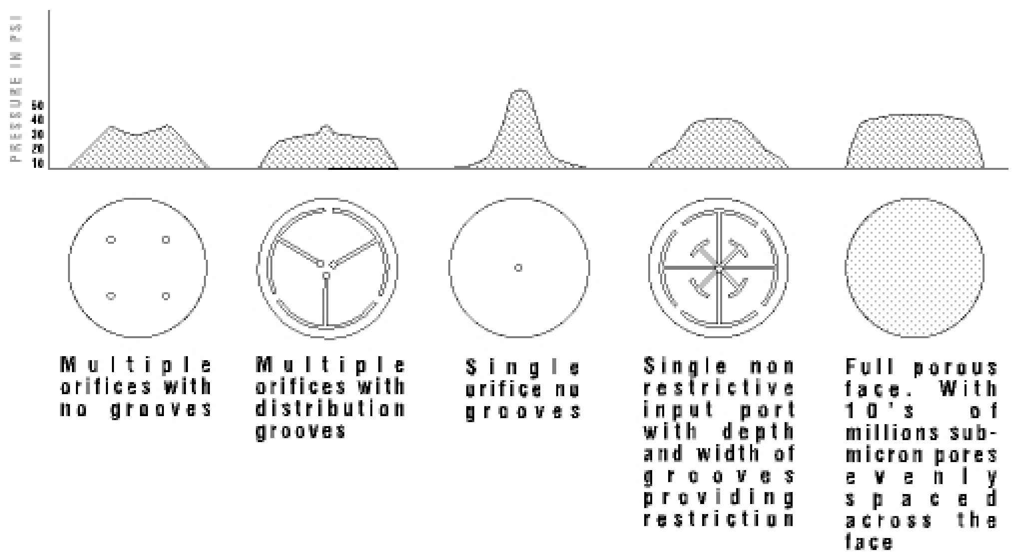
An air bearing is said to be unstable if it is subject to an oscillation that can be observed as a vibration or hum. This instability is known as "pneumatic hammer" and occurs when the air escaping across the face is restricted by a gap slightly smaller than one allowing equilibrium. In this situation, air pressure then increases displacing the bearing upward and resulting in a larger gap. The air pressure then escapes more easily, lowering the pressure, allowing the bearing to drop until the pressure increases again and the cycle is repeated resonating at the natural frequency of the structure.

Today, as in Wills' original work, orifices are used to control the flow of air into the gap. Frequently jeweled orifices (watch makers bearings) sized exactly to let just enough air through to carry a certain load at a certain gap with a certain air pressure are used to limit the upper half of the pneumatic hammer cycle and thus making the bearing stable. This is a sensitive balancing act because the flow through a gap increases as a cubed function of the gap, meaning that a small change in gap makes for a large change in flow. What this means practically is that a small change in gap, from say some extra load, results in significantly less flow defeating the restriction of the orifice and allowing the bearing to become unstable.

The technical issues regarding the design of orifice bearings are documented in several reference documents. Calculations are used to determine the optimal size and location for the orifice, often shallow air grooves (.002 deep by .010 wide) are used to improve the pressure profile under the bearing. A different type of bearing, groove compensated bearings are distinguished from orifice bearings because they do not depend on the orifice for restriction of air flow. Instead precise grooves control the flow of air into the bearing gap. The depth of these grooves are often 5 microns or less and may not be visible on the surface at first glance. Groove compensated bearings are considered to have relatively high stiffness compared to orifice type bearings. Design and tolerancing on the depth and width of the grooves becomes the critical factor in producing bearings with appropriate and consistent performance characteristics.

2

Many engineers who have had a need for the technical advantages of air bearings have consulted these air bearing cookbooks to build their own bearings because air bearings were not commonly available. This course of action required a development effort but the company gained a proprietary “Black Magic” while gaining the advantages of air bearings.



3 POROUS COMPENSATION

There is a more elegant method for controlling the flow through the gap. The ideal air bearing design would supply air pressure equally across the whole face of the bearing and automatically restrict and dampen the air flow to the face at the same time. This can be achieved by diffusing the air through a porous bearing face. The stability of a porous media air bearing is due to the damping effect of the torturous passageways the air must flow through to reach the face. This damping effect makes it difficult for the volume of air in the gap to change quickly, resulting in a naturally stable air bearing. This makes using air bearings easier.

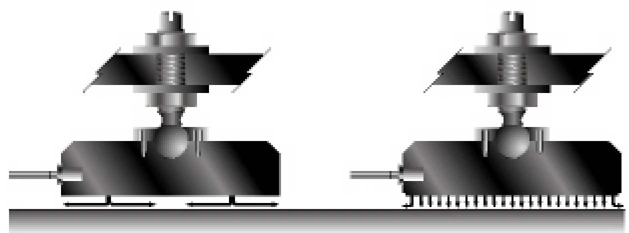
Porous air bearings were developed in the 60's and had their genesis inside the National Labs mentioned earlier. Again, like orifice air bearings, porous air bearings have been a build it yourself technology. Unfortunately little reference information is available on how to make them. The challenges of manufacturing porous bearings with consistent characteristics prevented wide spread use of the technology.

Sheffield Corporation, (now Giddings & Lewis Metrology), a builder of CMM's is one of the few companies that developed their own porous media bearings. They consider the technology an important technical advantage. It was originally employed on the Apollo Machine in 1982, they continue to use porous bearings today.

The L.S. Starrett Co. Built a rolling element bearing CMM until 1987 when they redesigned their machines to employ the advantages of air bearing technology. They elected to purchase New Way® porous media air bearings instead of developing their own air bearings. Today they continue to purchase their bearings. It was not until recently though that standard size bearings were available off the shelf in small quantities at a low cost.

3

Very few engineers designing a new machine have the luxury, time or money to develop their own air bearing technology. This is why it is important news that porous media bearings are commercially available from stock in standard sizes. Methods for mounting air bearings do not have to be re-invented, making them easy to implement. Again the natural stability of porous air bearings make them easy to use.



Orifice Type

As air escapes from the orifice it expands and so its pressure drops as it flows across the face of bearing resulting in variances of pressure in the air gap.

Porous Carbon Type

The air pressure drops as it flows through the porous layer. Even pressure then bleeds from the entire bearing face resulting in a more uniform pressure in the air gap.

4

AIR BEARING STIFFNESS

Once a bearing is stable, stiffness is usually the most important performance characteristic when evaluating air bearings.

Stiffness is the ratio of the change in air film thickness in response to a change in load. The stiffness of an air bearing is highly dependent on the thickness of the air film. The thicker the air gap the more compressible it is, so to optimize stiffness small air gaps are necessary.

Porous bearings have the advantage here because they can fly at lower air gaps without experiencing collapse (see graph). Collapse occurs when the gap becomes so restrictive as to starve regions for flow and pressure. Air bearing collapse can be seen in reverse during initial lift off. By slowly increasing the air pressure from "0" to an orifice air bearing that is grounded by a load it can be seen that a high percentage of the operating pressure is needed before the bearing will pop up as flow is established across the face of the bearing. This is because a flat orifice air bearing grounded on a flat guide way has only the area of the orifice and any air distribution grooves available to establish this initial lift.

With porous bearings initial lift is achieved with a low percentage of the operating pressure and the film thickness gradually increases as the pressure is increased. This is because pressure is bleeding out of the whole face and lift is not so dependent on flow across the face of the bearing.

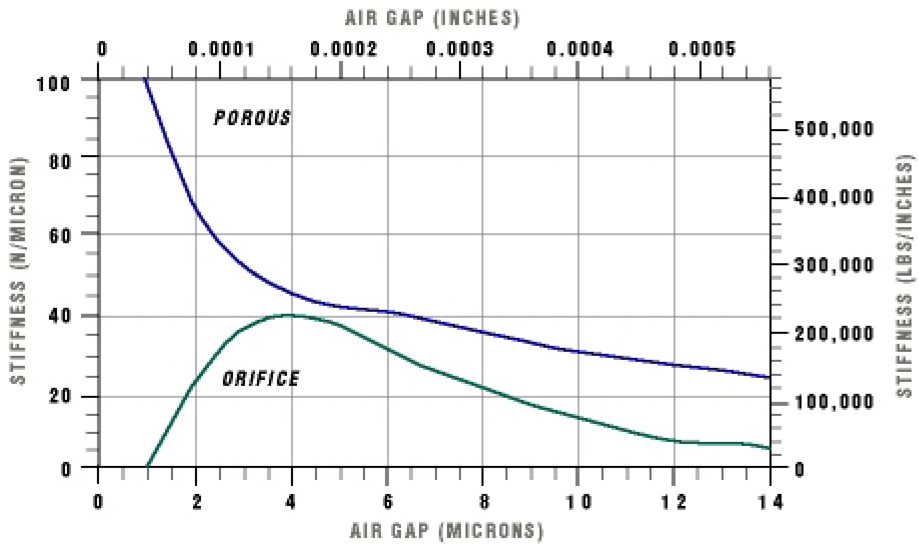
This phenomenon results in much higher stiffness for porous air bearings, especially at lower air film thickness'.

Note that the stiffness curve for the porous bearings sweeps up dramatically at gaps below 4 microns while an orifice bearing loses stiffness quickly below that gap.

Another interesting point is that below 4 microns the air film starts to exhibit a significant squeeze film damping. Conventional air bearings are considered to have a relatively low damping function. Porous media air bearings by virtue of their ability to fly at a thinner air films can deliver increased stiffness and damping at the same time.

4

Usually increased stiffness results in lower damping, it is not often in precision machine design that it is possible to increase both so easily.



5

CRASH RESISTANCE

This increasing stiffness as the gap gets smaller makes the bearing harder to crash, an important safety feature resulting in a more-robust bearing.

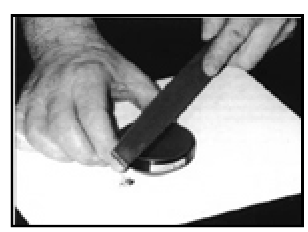
Should a touch down occur while in motion the plain bearing qualities of the air bearing faces becomes important. The hard air bearing faces typical found on orifice type bearings like hard coated aluminum, stainless steel or nickel coated steel can scratch or gualle a guide surface of granite or steel.

Unfortunately the guide way is usually the most difficult and expensive part to repair or replace. Scratches in the guide way if they are more than .002" deep or wide can crash a new orifice or groove compensated bearing and the fly height will certainly be affected as the bearing passes over the scratched area, so even minor scratches can be a significant problem.

Porous bearings typically employ a porous carbon face similar to a technical graphite. the graphite gives good plain bearing properties and because it is relatively soft it will not mar the guide ways. Even if contaminants get between the guide and bearing the bearing will scratch sacrificially saving the guide way.

Most amazingly even a severely scratched porous media air bearing will continue to fly. This is because the scratch eliminates pressure film in only the area it consumes. It will change the pressure profile under the bearing making the bearing fly somewhat lower but instead of collapsing the air film gets stiffer.

An orifice bearing that gets a scratch anywhere near an orifice or groove will crash as all the air the orifice escapes out the path of least resistance, the scratch, instead of producing pressure between the bearing faces.



5

In summary porous media air bearings are more damage tolerant, have a higher air film stiffness and are naturally stable. Now that they are commonly available what industries should be considering the use of air bearings?

Table 1: 2.5" Diameter Porous Carbon Bearing Score Test
(60 PSI Supply Pressure)

Average of 3 Trials Flat			Average of 3 Trials Scored (Score is 1/16" deep + wide)		
Load/ lbs.	Lift/ micro in.	Air Flow/ C.F.H.G	Load/ lbs.	Lift/ micro in.	Air Flow/ C.F.H.G.
120	210	0.40	120	130	0.35
150	165	0.35	150	100	0.30
180	125	0.30	180	070	0.25

$$\frac{60\text{lbs.}}{0.000085} = 705{,}882\ \text{lbs./in.} \qquad \frac{60\text{lbs.}}{0.000060} = 1{,}000{,}000\ \text{lbs./in.}$$

$$\text{Avg. Stiffness} = \frac{\Delta\text{load}}{\Delta\text{lift}}$$

6 POSSIBLE APPLICATIONS

Air bearings could be appropriate in many industrial applications where oil lubrication is a problem. This includes many dusty environments, because oil and dust have an affinity for each other. The messy mixture is like a lapping slurry causing premature ware. In contrast the guide way for an air bearing remains dry and the positive pressure under the bearing makes it difficult for light dry dust to get under the bearing. Dusty environments like textile factories stay much cleaner without oil. Sugar factories or pharmaceutical production lines would be other applications.
In some fiber pulling applications the application of constant force is critical to fiber quality. The zero friction feature of air beaings can eliminate force variations.
Crystal pulling is another interesting application where the low error motions and damping functions of air bearings are important. The fact that air bushings perform radial and linear motions was a plus.

Dry diamond machining , already popular in Europe, is likely to see growth in the United States. The elimination of coolant in the cutting process results in environmentally clean chips which because of high speed spindles are more like a dust. In this dry dusty environment air bearing ways and spindles combined with linear motors could eliminate oil lubrication. This combination would certainly help to make metal cutting a cleaner process.

The LS Starrett Company CMM equipped with New Way® air bearings.

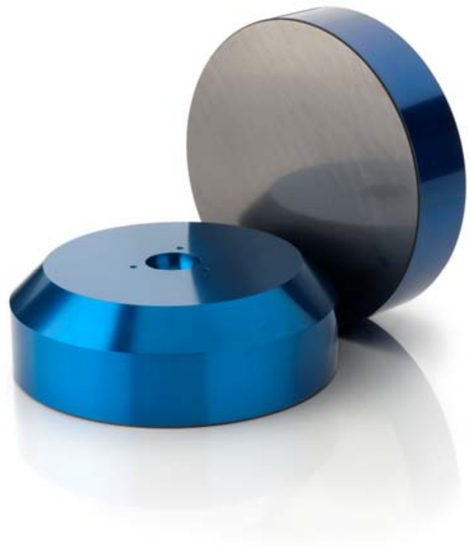
6

It is interesting to note that most machines doing work inside a micron (.00004") and all of them doing nanometer type steps employ air bearings. It would be a natural progression for air bearings to be employed in more production environments requiring high precision.

Testing machines benefit from the zero friction aspect of air bearing material testing machines and fatigue type testing will not be influenced by differences in friction caused by wear because there won't be any. It is interesting to note that the preload force or starting force static coefficient of friction of rolling element bearings are often tested using air bearings.

High speed applications are often appropriate for air bearings. Air bearings have no moving parts to limit accelerations and because there is no contact there will be no wear. A zero wear technology is a perfect answer to the seemingly unlimited cycles of high speed machines.

Automation in the Printing and Image industries is a promising area for air bearings. High quality drum scanners require stages that can carry the rotating optics down the axis of the drum without pitch or yaw errors. That is because these angular errors are multiplied by the abby effect and limit resolution.



Frictionless Motion™

50 McDonald Blvd., Aston, PA 19014 USA
www.newwayairbearings.com

Phone: 610.494.6700 Fax: 610.494.0911
info@newwayairbearings.com