# Comparison of Bearings
# --- For the Bearing Choosing of High-speed Spindle Design

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**ABSTRACT**: Bearing is the most important part of my project – High Speed Spindle; meanwhile, it is difficult to design or to choose. This paper is a detailed review highlighting the differences of most types of bearings which are utilized in industry field or currently developing these days.

## 1. Basic Concepts

The concept behind a bearing is very simple: Things roll better than they slide. Bearings reduce friction by providing smooth metal balls or rollers, and a smooth inner and outer metal surface for the balls to roll against. These balls or rollers "bear" the load, allowing the device to spin smoothly.

There are many types of bearings available, each used for different purposes and different conditions. Two major types of bearings are contact bearings and noncontact bearings. By considering the ball material, I separate the contact bearings to steel bearings and ceramic ball bearings. On the other hand, there are bearings that can run without any contact between the sliding surfaces in the bearing. These noncontact bearings are hydrostatic/hydrodynamic bearings, air bearings, and magnetic bearings.

Numbers of properties for a certain bearing should be considered during the process of design. These include speed limits, applied load, accuracy, stiffness, manufacturability, cost, etc. Most of them will be discussed between the different bearings as follow.

Because my final project is design of high speed spindle, the bearing selection or design should under the high speed condition. Limited by the speed property of steel bearing, steel bearings will not be concerned in this paper.

## 2. Speed Limits

Because the density of ball of the ceramic bearings is only 40% that of steel, substituting steel

balls with ceramic ones greatly facilitates high-speed rotation. In a machine tool spindle under position preload, the centrifugal force on ceramic rolling elements is substantially lower, resulting in superior high-speed performance. [1]

Hydrostatic/hydrodynamic bearings have only viscous friction associated with a fluid film layer being sheared during the motion of the bearing. But they can experience hydrodynamic effects on high speed condition if the lands are too wide, and considerable heat can be generated as a result. [2]

Same as Hydrostatic/hydrodynamic bearings bearings, air bearings have only viscous friction associated with a air film layer being sheared during the motion of the bearing. When using high-speed spindle, the bearing gap should be large enough to ensure that the friction power is less than twice the pumping power.

Magnetic bearings do not limit the speed or acceleration of components they support. System of 100,000 rpm and higher have been built for applications ranging from special pumps to spindles for ultrahigh-speed machining.

| Bearings | Approximately maximum speed (DN*) |
|---|---|
| Steel bearings | 1,000,000 |
| Ceramic bearings | 2,000,000 |
| Hydrostatic/Hydrodynamic bearings | 1,000,000 |
| Air bearings | 4,400,000 |
| Magnetic bearings | 4,500,000 |

Table 1. Speed Comparison

* Top speed alone is not enough to describe a bearing. A better measure is the product of bearing diameter in mm (D) and top speed in rpm (N), which is DN number.

## 3. Applied Load

Ceramic bearings

Hydrostatic/hydrodynamic bearings distribute the load over a large area, huge loads can be supported. For example, machine tools with multitude carriages often used hydrostatic/hydrodynamic bearings, and offshore oil platform desks, which may weight 20,000 tons, are transferred from the fabrication yard to a barge using fire hoses to supply water to hydraulic bearings on the desk's feet.

Because of the different film layer, approximately only one-fifth of load can be support by air bearings than hydraulic bearings.

Virtually any magnetic load can be supported by a suitable magnetic bearing, depending on how much one wishes to pay and how much room on has. Increasing the proportion of the load that is supported by permanent magnets decrease the current that must pass through the coils and the resultant heat generated.

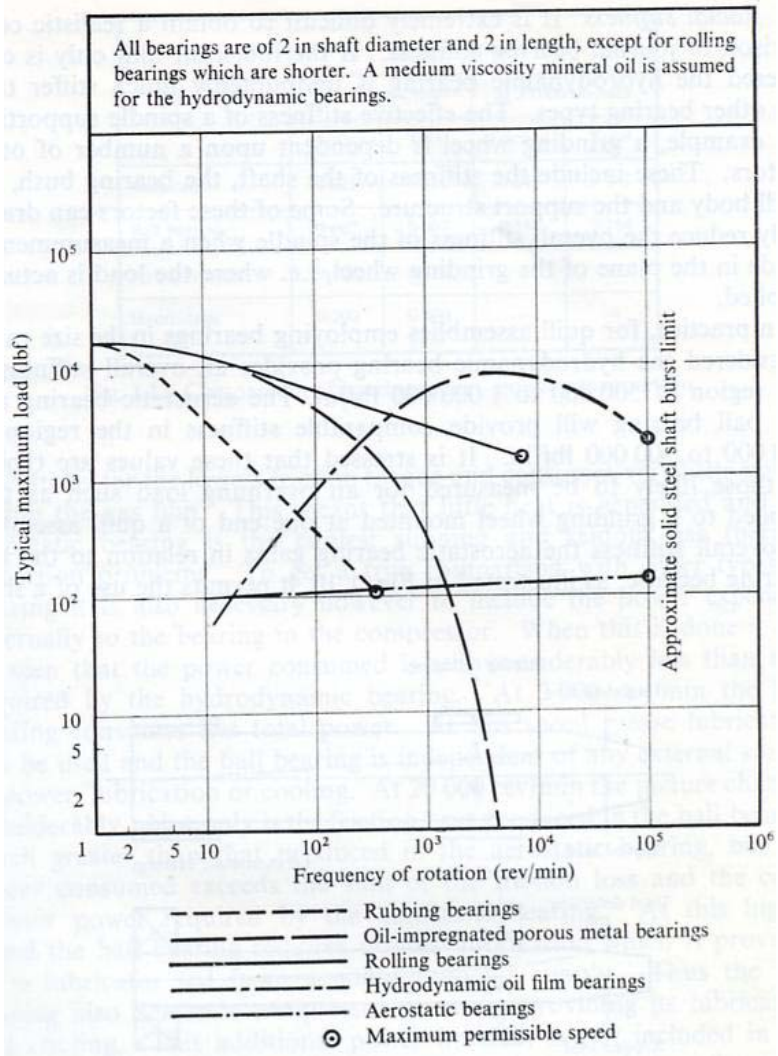


Figure 1. General Comparison of Bearing Types (rpm vs. load) [3]

## 4. Accuracy

Ceramic ball have a smoother finish than steel, so the vibration and spindle deflection is reduced allowing higher speeds and better performance.

Overall accuracy of motion of a hydrostatic/hydrodynamic bearing depends on the accuracy of the components. Hydraulic linear motion bearings have been built with submicron/meter accuracy.

Same as hydrostatic/hydrodynamic bearings, the overall accuracy of motion of an air bearing depends on the accuracy of the components. An air bearing averages out local irregularities to make it perhaps the smoothest running of all bearings.

Typically, achievable rotational accuracy is $50\mu m$ and $0.1\mu m$ system has been built. Since magnetic bearings depends on a close-loop servo system to a achieve stability, the performance of the position sensor and servo controller will directly affect the accuracy of the system.

## 5. Stiffness

Ceramic (silicon nitride) ball have a 50% higher modulus of elasticity (resistant to deformation) than steel, which means a 15 to20% increase in rigidity, improving stiffness.

Hydrostatic/hydrodynamic bearings can easily be in the Newton per nanometer range and do not have loss of contact problems that sliding or rolling contact bearings that are preloaded against each other have.

Air bearings stiffness can easily be in the 100 N/μm range and do not have the problem of loss of contact that sliding or rolling contact bearings can experience.

The steady-state stiffness of magnetic bearings can be essentially infinite, depending on how the close-loop control system is design. Magnetic bearing dynamic stiffness depends on the frequency of applied load and the bandwidth of the control system.

## 6. Damping Capability

Ceramic bearings have good damping capability because of the nice smooth finish of the ceramic balls.

The thin oil film in the bearing gap gives hydrostatic/hydrodynamic bearings excellent damping capabilities in both normal, via squeeze film damping, and tangential, via viscous shear, bearing directions.

The thin, low-viscosity air film in the bearing gap gives air bearings moderate to low damping capabilities in the normal and tangential bearing directions respectively.

A magnetic bearing's damping capability is attained from the closed-loop control system. Additional magnetic bearings modules can be added at various points along a shaft and used as vibration dampers. In this mode, the gap measurement signal is differentiated and used as a velocity feedback signal.

## 7. Friction

Ceramic bearings are "anti-friction" bearings and the friction is reduced drastically, and meanwhile the micro-weld problem is solved.

Hydrostatic/hydrodynamic bearings, air bearings and magnetic bearings have absolutely zero friction because of the "noncontact" characteristic.

## 8. Thermal performance

Because hardness and strength of silicon nitride do not deteriorate at high temperatures when compared to those of bearing steel, silicon nitride holds a lot of promise as bearing material for high temperatures. [4]

Energy is input a hydrostatic/hydrodynamic bearing in the form of a flow at a pressure. The oil oozes out of the bearing and into a drip pan. In the pan its flow rate and pressure are essentially zero, so all the power that is represented by the initial flow and pressure is expended in the viscous shear the fluid undergoes as it oozes out of the bearings. This power is dissipate as heat. The temperature rise of the oil depends on how much heat is conducted by the machine. One must be careful to consider this effect, which gives motivation for using as low pressure and flow rate as possible. In general, hydrostatic bearings are not used where speeds greater than about 2 m/s are encountered because viscous shear of the fluid in the bearing gap also generates too much heat.

The viscosity of air is very low, so air bearings are tolerant of small changes in bearing

clearance caused by viscous heating. But it is important to realized that air cools as it expands, and thus for a precision machine it is important to minimize flow and the resultant refrigeration effect.

Magnetic bearings can generate significant amounts of heat and therefore may require external cooling devices, such as recalculating chilled water jackets. For system where the load does not vary greatly, a large percentage of the load can be supported by permanent magnets which minimize coil size and current required to levitate load.

## 9. Size and Configuration

Ceramic bearings take small space as general steel bearings.

Hydrostatic/hydrodynamic bearings take up very little space themselves, but the plumbing requirements may be significant.

Same as hydrostatic/hydrodynamic bearings, the plumbing system of air bearings will take more significant space than the bearings themselves.

Magnetic bearings are typically 2-10 times than the rolling element bearings they can replace; however, in many applications, accommodating a magnetic bearing's larger size is not too much a problem.

## 10. Weight

Ceramic ball is 60% lighter than a steel ball.

Because of their simplicity, hydrostatic/hydrodynamic bearings have very high performance-to-weigh ratios, but only if one excludes the size and weight of the pump, oil collection and distribution system, and oil temperature control system.

Air bearings have moderate-to-high performance-to weight ratios.

Magnetic bearings are very heavy compared to the rolling element bearings they replace. In some applications, such as precision mechanical gyroscopes, the forces encountered by the bearing are so small that the weight of the required bearings is inconsequential anyway.

## 11. Maintenance and Requirements

Ceramic bearings generate less friction and require less maintenance than general bearings. Since ceramic balls will not cold weld to steel rings, wear is dramatically reduced, and wear particles generated by adhesive wear are not present in ceramic hybrids, lubricant life is prolonged. The savings in reduced maintenance costs alone can be significant. Some ceramic bearings are called “Zero maintenance ceramic bearings”.

In hydrostatic/hydrodynamic bearings system, oil level and cleanliness must be monitored and filter on the pump changed according to a fixed maintenance schedule. Oil quality should be monitored to make sure that its PH level remains within the desirable limits and that the oil dose not become contaminated with bacteria.

Air cleanliness must be monitored and filter changed according to a fixed maintenance schedule for air air bearings system. The air supply system should be inspected periodically for signs of contamination and the bearings rails for sign of wear that would result if a bearing pad’s flow restrictor becomes clogged and the pad staved for air. Properly maintained and serviced, and air bearing should never experience any wear. There are many examples which show no wear after 10 years continuous operation.

Magnetic bearings have virtually no maintenance requirements. This makes them especially suitable for equipment that must be kept continually running, such as pipeline compressors.

## 12. Required Life

Physical properties inherent to ceramic bearings contribute to their long-wearing capabilities, improved lubricant life and corrosion resistance. The presence of silicon nitride translates into a smoother surface and lighter weight than conventional bearings. These attributes enable ceramic bearings to operate at lower vibration levels, which in turn produce a longer service life. [5]

Since magnetic bearings, hydrostatic/hydrodynamic bearings and air bearings are noncontact devices, they can essentially infinite life.

## 13. Cost

Historically, one of the barriers to rapid expansion of the market of ceramic bearings was the high cost of ceramics relative to steel. In fact, it wasn't too long ago that the price ratio between the two was more than 1,000:1. But while the cost of steel balls has remained

relatively constant, the cost of ceramic balls has practically been in free fall. Two factors account for plummeting prices: improvements in the manufacturing process and higher volumes. [6]

The primary costs associated with hydrostatic bearings are those of the fluid supply system, the cost of machining all the oil supply holes, and the cost of machining long straight rails or very round bores.

The principal cost associated with the air bearings are those of machining all the air supply passages and machining long straight rails or very round bores with close tolerance. The cost of maintaining the air supply system should be considered. An air filter dryer unit, which can provide for dozens of air bearings, can cost on the order of $650.

Magnetic bearings are probably the most expensive type of bearing one can use; however, for the problem they solve, effective system cost can be low compared to design solutions that use other bearings.

## 14. Conclusion

Following the preceding discussions, the aerostatic bearing maybe the best choice of my project --- high speed spindle design which is under the moderate loads, moderates stiffness and high speed condition for the detail reasons listed below:

1. Capability of operating at very high speed rotational speed.
2. High accuracy.
3. Low friction giving low power loss and cool running characteristics. An air bearing averages out local irregularities to make it perhaps the smoothest running of all bearings.
4. Capability of operating at very high and very low temperatures. The viscosity of air is very low, so air bearings are tolerant of small changes in bearing clearance caused by viscous heating. And meanwhile, when using a high speed spindle, the temperature rise due to the friction within the bearing gap is offset by the refrigeration effects of the gas film as it expand in the gap after leaving the orifice. [2]
5. Little or zero need for periodic maintenance.
6. Low or zero wear rate giving a long life.
7. Low noise and vibration levels.

And there are some other advantages of aerostatic bearings such as:

1. Nice environmental sensitivity, because the air is always flowing out of the bearings,

aerostatic bearings are self-cleaning. Unlike bearings with oil lubrication, there is no mess associated with the air bearings. [2]

2. Aerostatic bearings are compatible with virtually all materials, and the presence of a small bearings gap usually leaves ample room for differential thermal expansion between components. [2]

It is therefore probable that there will be a greater need to utilize high quality spindle incorporation air bearings in the foreseeable future. As demand for spindle and carriage speeds and accuracy increases, greater use of aerostatic bearings in the precision machine tools can be anticipated.

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