

A COMPARISON OF ROLLING ELEMENT AND HYDROSTATIC BEARING SPINDLES FOR PRECISION MACHINE TOOL APPLICATIONS

Dr. Kevin L. Wasson
Hardinge, Inc.
Elmira, NY USA

INTRODUCTION

The type of rotary motion bearings principally used in machine tool spindles are rolling element bearings. Spindles with hydrostatic fluid film bearings can be more desirable for precision machining applications because they have much lower error motion, higher damping, and longer life than rolling element spindles.

Hydrostatic spindles also have higher system cost. The fluid supply system that is required for their operation is expensive, especially for high speed applications. The viscous drag caused by shearing of the bearing supply fluid consumes available motor power and generates heat which must be dissipated. The amount of viscous drag generated by a hydrostatic bearing is a strong function of spindle speed and bearing diameter. For small diameters and moderate to low operating speeds, the viscous power consumption of a hydrostatic spindle can be acceptable for many applications.

An examination of the hidden costs associated with building and maintaining rolling element spindles reveals a narrow gap between the true costs of the two spindle types. The added complexity of a rolling element spindle is readily apparent when the number of precision components is considered. The added difficulty of manufacturing and assembling rolling element spindles must be considered when the two spindle types are evaluated for an application.

ERROR MOTION

Spindles used in precision machine tool applications must have low error motion over a wide range of operating speeds. For example, parts manufactured on a precision turning center machine have roundness characteristics that directly reflect the spindle error.

In hydrostatic spindles, the bearing fluid film creates an averaging effect which tends to offset the impact of shaft nonroundness. The degree of

averaging is dependent upon the shape of the spindle shaft roundness profile; while there is little averaging if the shaft is oval, there can be a considerable averaging if the profile is multi-lobed. Shaft straightness between the front and rear bearings also plays a determining role in spindle error motion.

Pressure pulsations can also contribute to error motion of hydrostatic spindles. These pressure pulsations can be minimized by using a pump mechanism with low pulsations such as a screw pump. Proper use of accumulators can also reduce pump pulsations considerably.

Hydrodynamic whirl is a dynamic effect which occurs in fluid film bearings and also contributes to error motion in hydrostatic spindles. Hydrodynamic whirl can be minimized by using light viscosity oil and by designing the bearing to minimize hydrodynamic effects.

Rolling element spindles can be manufactured with error motions that are acceptable for a wide range of precision applications. However, the degree of difficulty in doing so is much higher. In contrast to hydrostatic spindles, there are many more factors which contribute to error motion in rolling element bearing spindles. Some of the primary contributors to error motion include bearing run-out, shaft roundness, shoulder squareness, spacer flatness and parallel tolerances, nut face flatness, housing bore roundness, shaft straightness, and concentricity between the front and rear housing bores. Due diligence must be paid to every single component which makes up a precision rolling element spindle.

Rolling element spindles are also sensitive to the manner in which their components are assembled. Small changes in assembly procedures can often dramatically affect the resulting error motion of a rolling element spindle.

STATIC STIFFNESS

Spindles used in precision machine tool applications must have high stiffness in order to be sufficiently reactive to excitation forces.

Generally, a hydrostatic spindle can be equally stiff as a ball bearing spindle, but each application must be analyzed individually. The hydrostatic supply pressure, bearing land design, and bearing clearance must be carefully chosen. Very often, the goal of high spindle stiffness is directly competitive with the cost of the hydrostatic fluid supply. For example, tighter hydrostatic bearing clearances will result in stiffer bearings, but choosing a tighter gap will also create more heat which must be dissipated. Choosing a higher supply pressure will enable bearings with higher stiffness but will result in higher pumping power.

The stiffness of a rolling element spindle is highly dependent on the bearing preload, which is a function of shaft fit, housing fit, and the manufacturing tolerances of the bearings. Variation in stiffness from spindle to spindle of +/-40% is common for rolling element spindles. In contrast, the stiffness of hydrostatic spindles typically vary by +/-10% or less when manufactured in production quantities.

DAMPING

The dynamic stiffness of a spindle is a measure of its ability to resist motion when subjected to dynamic (cyclical) forces such as forces generated by the machining process, forces caused by unbalance, drive belt vibration, and other vibrational forces. The dynamic stiffness of a spindle can be improved by increasing its static stiffness or its damping.

Hydrostatic bearings have excellent damping due to the squeeze film damping effect in the fluid film. Very often a hydrostatic spindle will be so well damped that it will have no measureable natural frequency. Rolling element bearings have comparatively very low damping. It is not uncommon for a ball bearing spindle to have a dynamic stiffness (stiffness at its resonance frequency) 1/10th to 1/20th that of its static stiffness.

RELIABILITY

Rolling element spindles have a finite life; their long-term failure is typically expected to be either raceway fatigue or grease break-down. The life duration of a spindle can be dramatically

shortened if it is used at elevated shop temperatures or subjected to excessively high machining forces.

Hydrostatic bearings have no mechanical contact and therefore infinite life, provided that the bearing supply fluid filtration is adequately maintained. Since hydrostatic bearings do not wear with time, the precision error motion does not degrade.

Rolling element spindles are very sensitive to contamination. A very small amount of contamination can cause bearing failure. It is essential to have clean procedures during assembly. Once in use, labyrinth seals and air purge methods are used to prevent coolant and machining debris from entering the bearings, with varied success. Even prolonged exposure to humid air can adversely affect bearings lubricated with grease.

Hydrostatic bearings have fluid continuously emanating from their gaps which prevents ingress of debris. An air seal is often used to prevent contamination of the hydrostatic supply fluid. If this air seal fails, and the hydrostatic fluid is contaminated by coolant, then the oil must be periodically replaced.

Rolling element bearings have multiple components spinning at high speeds. Each component can create noise under special conditions. Noisy spindles are considered failed and must be replaced.

Machine crashes can cause the raceways of rolling element bearings to be brinelled if the loads experienced during the impact are severe. The static load capacity of ball bearings are typically in the range of tens of thousands of pounds. Nevertheless, severe crashes cause spindle failures.

Hydrostatic spindles have much lower static load capacities than comparable ball bearing spindles. The static load capacity (the load at which the gap closes and contact occurs) of a hydrostatic spindle is typically in the range of thousands of pounds. In a crash, the force that is delivered to the spindle is an impact force that lasts for milliseconds. During the impact, the very high damping of the hydrostatic bearing prevents the gap from closing even when the spindle is subjected to an impact load of tens of thousands of pounds. If the impact is too severe

and bearing contact occurs during rotation, then there will be a total failure.

Most of the reliability risks inherent in a hydrostatic spindle are in the fluid supply system. The filter, pump, and other components require maintenance and have limited lives. A pressure switch interlock is required to ensure the bearings are fully pressurized prior to spindle rotation.

POWER CONSUMPTION

The primary drawback of hydrostatic spindles in precision machine tool applications is the drag caused by the viscous shearing of the fluid film. This drag consumes available motor power and generates heat which must be dissipated by the fluid supply system.

Consider an example hydrostatic spindle design with 70 mm diameter bearings. This spindle could be a turning spindle with a 42 mm bar capacity, a milling spindle with a size 40 taper, or a small grinding spindle. Figure 1 shows some calculation results for the expected performance of this spindle. A very light oil is used in order to minimize viscous drag. Bearing clearances of 0.0009" per side and a supply pressure of 1200 psig was chosen to provide enough stiffness and load capacity for this application while keeping the supply flow rate (and the size of the resulting fluid supply system) to a reasonable level.

Bearing Supply Fluid	Oil: Shell Pella A	
Fluid Inlet Temperature (°C, °F)	22	72
Supply Pressure (MPa, psig)	8.27	1200
Shaft Diameter on Radial Bearings (mm, in)	70	2.76
Radial Bearing Clearance per Side (µm, in)	22.9	0.0009
Radial Bearing Load Capacity (N, lb _f)	11034	2480
Radial Bearing Stiffness (N/µm, lb _f /µin)	1478	8.4
Thrust Bearing Outer Diameter (mm, in)	84.2	3.32
Thrust Bearing Clearance per Side (µm, in)	22.9	0.0009
Thrust Bearing Load Capacity (N, lb _f)	9719	2185
Thrust Bearing Stiffness (N/µm, lb _f /µin)	752	4.29
Total Spindle Flow Rate (lpm, gpm)	13.5	3.6

FIGURE 1. The design parameters for an example hydrostatic spindle design.

The power consumption (viscous drag) of the example spindle of Figure 1 is plotted versus spindle speed in Figure 2. As shown, the power consumption remains reasonably low for slower spindle speeds, but rapidly increases if higher spindle speeds are used.

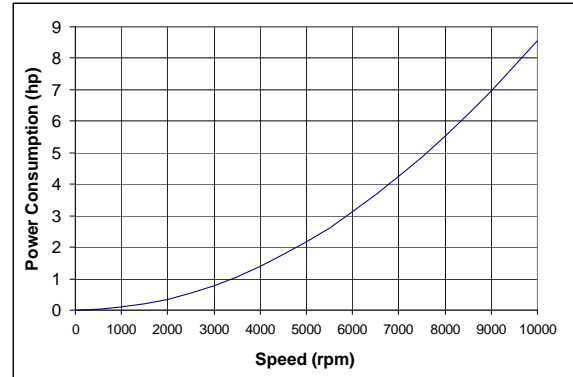


FIGURE 2. Power consumption of an example hydrostatic spindle as a function of spindle speed.

THERMAL ERROR CONSIDERATIONS

As a spindle housing heats up, it transmits heat to the rest of the machine. The structure is typically iron or steel which experiences thermal expansion. The spindle moves relative to the tool, causing thermal growth errors over the course of the day as the machine warms up.

Rolling element spindles consume very low amounts of power due to bearing friction. Nevertheless, if no means are provided to remove the heat that is generated, the spindle housing will warm up to approximately 20°F to 30°F above the shop ambient temperature in typical applications even if integral cooling fins and air blowers are provided. It is for this reason that machine builders sometimes provide an integral cooling jacket through which temperature controlled fluid can be pumped.

Hydrostatic spindles can generate a similar magnitude of thermal drift as rolling element spindles, depending upon how well the fluid temperature is controlled. The heat that is generated in a hydrostatic spindle is much greater than that generated in a comparable rolling element spindle; however, the fluid being pumped directly through the bearing is an excellent medium to absorb that heat and get it back to the fluid supply system where it can be rejected with the use of either an air-to-fluid heat exchanger or a chiller.

COST

The cost to manufacture a hydrostatic spindle assembly is substantially lower than that of a precision rolling element spindle assembly.

The number of parts in a rolling element spindle assembly can be approximately twice as many that are in a hydrostatic spindle assembly. All of the parts are precision parts that must be held to tight geometric tolerances. The precision bearings themselves are very expensive. The spacers, nuts, and retaining caps are all precision components that add considerable complexity and expense to the assembly.

In a precision rolling element spindle assembly, the bearings are match fit to the spindle shaft with an interference fit that must fall within a very narrow window of magnitude. It is for this reason that the spindle shaft of a rolling element spindle must be held to a size tolerance of 0.0001" on diameter. Spindle manufacturers alleviate this problem by carrying a large inventory of bearing sizes and carrying a large inventory of manufactured shafts with various sizes, with an unending goal of stocking shafts that match bearing sizes available. The cost of this inventory must be considered into the overall cost of a rolling element spindle.

The same strategy is employed to match the housing bore size to the rolling element bearing outer diameter size. Trying to match outer diameters to housings and inner diameters to shafts complicates matters further and forces even more inventory to be stocked.

In a precision hydrostatic spindle assembly, typical clearances between the shaft and housing are approximately 0.00018" diametrical clearance. In this case, the spindle shaft and the housing can each be made with 0.0003" diameter size control. Meeting this level of tolerance is relatively easily accomplished in a production environment where precision grinding is employed. If the parts are made to this level of tolerance, then all shafts will fit all housings with no matching required and no extra inventory need be carried.

Assembly cost must also be considered. The assembly of a precision rolling element spindle is expensive. Expert assembly personnel are required. Nuts are torqued and run-outs are checked at each step of the assembly process. The bearings must be heated to assemble them onto the shaft. The housing must be heated to fit the bearings into the bore. The time required for parts to heat up to the proper temperature adds considerable cost to the assembly process.

In hydrostatic spindle assemblies, there is ample clearance between the shaft and housing such that no heating of parts is necessary. There are no sensitive nuts that must be torqued and run-outs checked. The assembly time is dramatically less for a hydrostatic spindle.

Newly built grease-lubricated rolling element spindles require lengthy and careful run-in procedures in which the spindle speed is gradually increased to allow the grease to be properly broken in. Hydrostatic spindles do not require such a costly procedure.

The principal cost of using a hydrostatic spindle may be found in the required fluid supply system. A pump, filter, valves, chiller, reservoir, accumulator, and pressure switches are required. The magnitude of cost for this system is dependent upon the system pressure, flow rate required for the hydrostatic bearings, and the amount of heat that has to be rejected. In general, the higher the rotational speed and the greater the bearing diameter, the more expensive the required fluid supply system.

CONCLUSION

Spindles with hydrostatic fluid film bearings can be more desirable for precision machining applications although they have higher system cost. The fluid supply system that is required for their operation is expensive, especially for higher speed applications where the viscous drag in the fluid film consumes excessive motor power and generates excessive heat which must be dissipated external to the machine.

The results of calculations for a representative application indicate that a hydrostatic spindle is a reasonable alternative to a rolling element spindle in slow or moderate speed applications even when cost considerations are important. Furthermore, an examination of the hidden costs associated with building and maintaining rolling element spindles reveals a narrow gap between the true costs of the two spindle systems.

REFERENCES

- [1] Wasson, Kevin L. Hydrostatic Machine Tool Spindles. Doctoral Thesis. Massachusetts Institute of Technology. 1996.
- [2] Stansfield, F. M. Hydrostatic Bearings for Machine Tool and Similar Applications. The Machinery Publishing Co., LTD. London: 1970.