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Hydrostatic Spindles - When to Use Hydrostatic Spindles & Why
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The goal of this paper is to help manufacturing engineers determine and make the right decision on when it makes sense to use hydrostatic spindles for a particular application. Based on my personal involvement in the development and manufacture of hydrostatic spindles for more than 35 years, I like to share my thoughts about hydrostatic spindles' applications – when they **can** be used and when they **must** be used. On one hand, hydrostatic spindles effectively combine ultra-high rotational accuracy, high static stiffness and load capacity, extremely high vibration resistance, controlled thermal behavior, moderate thermal expansion and are virtually free of wear.

On the other hand, hydrostatic spindles are usually 30%-50% more expensive as compared to spindles with rolling elements and require large and expensive periphery support equipment, such as hydraulic power units used to provide high pressure liquid media to hydrostatic bearings, and chillers used to compensate power losses due to the share friction in the bearings as well as power losses caused by the pumping. As matter of fact, the share friction in hydrostatic bearings is a significant problem. Friction power grows very quickly depending on speed – proportionally to speed square if flow in the bearings is laminar, and even faster if flow starts to convert to turbulent regime. Wrongly designed, the hydrostatic spindle will serve as an oven rather than precisely rotating shaft.

The main advantage of hydrostatic spindles is not any one of separate features, but a unique combination of many different features. It gives us a powerful tool that provides for the correct technical and financial decision for particular applications.

Let's investigate some concrete examples that will help clarify the above statement:

1. Diamond Turning

Diamond turning is a kind of ultra-precision machining, with the goal to achieve mirror surface finish, by a turning process that uses a single crystal natural diamond tool for cutting. The main feature required from the spindle is ultra-high rotational accuracy, due to the cutting forces being very low. Air static bearings spindles are overwhelmingly used for this operation. They have extremely high rotational accuracy (same or even higher when compared to hydrostatic spindles); friction in bearings is minimal; no problems with oil leakage and they do not require expensive periphery equipment when compared to hydrostatic spindles.

But if a machined part is heavy, the load capacity of the spindle has to be taken into consideration and hydrostatic spindles excel. To reach the same load capacity as hydrostatic spindle, the bearings surface in air static spindles has to be 10-15 times bigger. This makes air static bearings spindles economically and technically not acceptable and hydrostatic spindles

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should be considered.

A good example is copper drums with mirror surface finish that are widely used in flat screen TV manufacturing, with weights varying from 1 to 3 tons.

2. Hard Turning & Hard Milling

Hard Turning is turning of the hardened steel and is often used to replace final grinding. To compete successfully with the grinding process, geometrical accuracy and surface finish after turning have to be close to the results achieved by grinding. In hardened steel turning, the cutting forces are expected to be relatively high. Because chips form while brittle material is machined, the cutting force is not steady and has sharp peaks, creating high frequency alternative force applied between the tool and the machined part. Spindles going to be used for hard turning must combine high accuracy, high stiffness and high vibration resistance. **The research conducted by the Institute of Production Technology (IPT) located in Aachen, Germany has proven that hydrostatic bearing spindles are the optimal choice for hard turning**. The usage of hydrostatic spindles makes possible to achieve sub-micron geometrical accuracy and excellent surface finish with Ra up to 0.05 microns and even better. Besides that, the life time of the cutting tool is significantly prolonged as a result of the powerful vibration suppression that comes with using the hydrostatic bearings.

Hard Milling is precision milling of hardened steel. One of the most common applications of Hard Milling is finish machining of high precision dies and molds, just before polishing, to compensate parts' distortion caused by heat treatment. Cutting depth is usually small and cutting forces are quite moderate. But because brittle material is machined, the force applied through the cutting tool to the spindle will contain sharp peaks generating a wide spectrum of vibrations. It means that a spindle used for this application has to be able to effectively suppress vibrations and to smooth sharp peaks in the cutting forces. Besides that, the spindle has to be very accurate and to provide as good surface finish as possible in order to reduce an expensive and time consuming polishing phase. **Only the hydrostatic spindle combines ultra-high accuracy and high effectiveness in vibrations suppression.**

3. Ultra-High Precision Grinding of Brittle Materials

There is a very wide range of applications related to high precision grinding of components made of brittle materials, one example is optical lenses. Materials like glass, quartz, tungsten carbide and ceramics are very brittle. To achieve excellent surface finish when grinding parts made of these materials is an extremely challenging task. The requirements for the spindle characteristics are even tougher when compared to Hard Turning and Hard Milling applications. In contrast to Hard Milling, the radial run-out of the grinding tool can be reduced by the truing process. The only imperfection left in the tool radial motion is caused by the non-repeatable portion in shaft rotation,

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i.e. totally defined by internal features of the spindle bearings. The rolling elements bearings would definitely not be the best choice due to their natural limit in rotational repeatability, i.e. after every revolution, the angular position of the rolling elements will be changed. The only spindles can be used are either air static or hydrostatic. **But because of sharp peaks vibrations generated by brittle material removal the hydrostatic spindle is preferable, featuring significantly more aggressive vibrations suppression when compared to air static spindle.**

There are interesting comparison results obtained during grinding of large size lithography lenses using air static and hydrostatic spindles:

a. Subsurface damages caused by grinding using hydrostatic spindle were substantially smaller when compared to air static one.
b. The time between grinding wheel dressings while hydrostatic spindle was used is about two times longer when compared to wheel dressings when grinding was accomplished using air static spindle

4. High Precision Internal Grinding in Mass Production

There are two spindles involved in the internal grinding process: the work head spindle holding a part to be ground, and the wheel head spindle holding an arbor with a grinding wheel mounted on an arbor. Generally speaking, the work head spindle is responsible mainly for the roundness of the ground opening, while the wheel head grinding spindle is responsible for the surface finish and productivity (i.e. for material removal rate). There is no need in hydrostatic spindles for a majority of internal grinding applications – high accuracy work head spindles with rolling elements bearings, and internal grinding spindles with rolling elements bearings, will provide reasonably good results for surface finish, roundness and productivity.

However the situation changes drastically when the size of the ground opening and the time given for grinding drops. As an example, let’s consider the gas fuel injector valve seat.

The small internal taper, with an average diameter of about 2-3mm, has to be ground to very tight tolerances - within 6 seconds or less - including in-feed and spark-out portions of the grinding cycle:

a. To remove the material as quickly as possible during the in-feed portion of the cycle, the speed of the wheel head spindle has to be very high in order to reach more or less a reasonable number for the surface speed, especially when CBN grinding wheels are used.
b. To reduce spark-out time, both spindles have to perform with extremely high rotational repeatability because the spark-out process, by its nature, is an averaging process. Whichever rotation is more repeatable, the shorter will be the averaging process. To achieve required out of roundness statistically (0.1 micron) the rotational accuracy of the

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work head spindle has to be at least two times better.

c. To reduce danger of chatter, wheel head spindle has to have good vibration suppression features.

It is easy to estimate that, to reach an optimal number for the surface speed while a 2mm diameter hole is ground using CBN wheel, the rotational speed has to be about 1,000,000 RPM. To achieve a more or less reasonable number for the surface speed, the rotational speed has to be as high as possible. Here the spindle lifetime comes into consideration:

a. When rotational speed is higher than 150,000 RPM, lifetime of rolling elements bearings drops significantly and can be as short as 6-8 weeks.
b. The average price for repairs of such a spindle is about $4,500. This does not include the cost of time while an expensive grinding machine is temporarily out of production.

It can therefore be concluded that the optimal choice for internal grinding of small precision parts in mass production environment would be combination of two hydrostatic spindles: work head grinding spindle with maximal speed usually up to 6,000 RPM and internal grinding spindle with maximal speed as high as possible (100,000 RPM and higher).

The typical parts are: gas and diesel fuel injector components; bearings rings for the small size precision ball bearings; components for computer hard disc bearings; precision servo valve components; fiber optic connectors; etc.

5. Increasing Spindle Rotational Speed

The real challenge is to find a right balance between spindle speed, stiffness, accuracy and lifetime. Increasing spindle speed is not free.

Stiffness is our "hard currency" that has to be paid to make spindle rotating faster. Speed, stiffness and accuracy have direct impact on grinding performance and productivity. The minimal bearings stiffness can easily be found when considering the complete dynamic system involved in machining. Often the weakest link in such dynamic stiffness is not the spindle itself, but the cutting tool (in milling process) or grinding arbor (in internal grinding process). Spindle bearings flexibility (compliance) can be safely increased without having significant impact on spindle performance, until its contribution to the total compliance is relatively small. Otherwise, by making a spindle much stiffer than the tool the total stiffness of the system will not increase, but it will increase friction losses and heating.