SPINDLE FACTS

PART I – SPINDLE FACTS

PART II – DYNOMAX INFORMATION

1. Introduction

A Precision spindle that will be used in a machine tool must be designed to provide the required performance features. The major performance features include:

1. Desired Spindle Power, Peak and Continuous
2. Maximum Spindle Load, Axial and Radial
3. Maximum Spindle Speed Allowed
4. Tooling Style, Size and Capacity for ATC
5. Belt Driven or Integral Motor-Spindle Design

Although these criteria may seem obvious, for the spindle designer they represent a wide array of needs that are quite difficult to meet and optimize in one design. As we will discover, many of the criteria are contradictory to one another, and eventually a compromise must be chosen to provide the best design.

The machine tool, also, will present design constraints to the spindle. The amount of available space, complexity will affect the ultimate spindle design. Cost will also have a significant impact on the final spindle design. A very sophisticated and capable spindle design will not be acceptable on a low-cost machine tool. Consequently, an advanced machine tool design can justify the higher cost of a more capable and complex spindle package. In fact, a fast and accurate machine tool will demand a reliable high-speed spindle system.

We will give a brief overview of the major components required in a Precision spindle design. Emphasis will be on commercially available components that are available at reasonable cost and most commonly used today on existing machine tools. Future trends will also be mentioned.

In addition to the Precision spindle system design, maintenance and reliability issues will also be discussed.

2. Precision Spindle Design

2.1 List of Major Components

The major components required for Precision Spindle design include:

1. **Spindle Style**- Belt Driven or Integral Motor-Spindle
2. **Spindle Housing**- Size, Mounting Style, Capacity
3. **Spindle Bearings**- Type, Quantity, Mounting, and Lubrication Method
4. **Spindle Motor**- Belt-Type, Motor-Spindle, Capacity, Size
5. **Spindle Shaft**- Including Tool Retention Drawbar and Tooling System Used

Each of these components will be discussed, with emphasis on selection criteria and effectiveness for a given machine tool specification. The machine tool we will assume is a modern CNC machining center with automatic tool changing ability (ATC).

2.2 Basic Spindle Styles

- **Belt and Gear Driven with external Drive Motor**
- **Integral Motor-Spindle**

The first decision which must be made is if a belt-driven spindle or integral motor-spindle design will be required. This must be determined by evaluating the requirements of the machine tool, including the maximum speed, power and stiffness required.

Belt and Gear Driven Spindle Design

A belt-driven Spindle is quite similar in design to a conventional speed spindle design, with some noticeable differences. A typical belt driven spindle assembly consists of the spindle shaft, held with a bearing system and supported by the spindle housing. The spindle shaft incorporates the tooling system, including the tool taper, drawbar mechanism and tool release system. The mechanism that provides the force to provide a tool unclamp is usually externally mounted

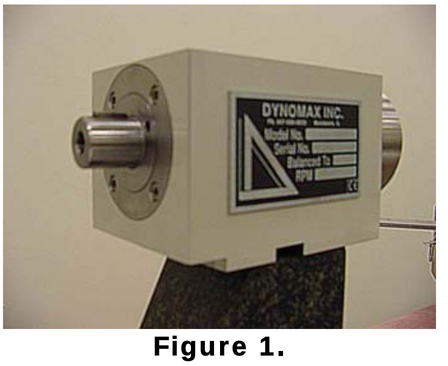


Figure 1.
Belt driven spindle Design
Dynomax Model No. #06-2A-B-0580

Power and rotation are supplied to this spindle by an external motor. The motor is mounted adjacent to the spindle, and the torque is transmitted to the spindle shaft by means of a cogged or V-belt. The power, torque and speed of the spindle will therefore depend upon the characteristics of the driving motor, and the belt ratio used between the motor and the spindle.

The principal advantages of the belt or gear driven spindle design are as follows:

1. Reasonable Cost: As the spindle itself is comprised of a few basic parts, the cost is relatively low, when compared to alternative solutions.
2. Wide Variety Of Spindle Characteristics: As the spindle power, torque and speed are dependent upon the driving motor, to a large degree, the final specifications can be modified for a particular application by using a different motor or belt ratio. In some cases, gears are also used to provide multiple speed ranges in addition to the fixed belt ratio.

3. High Power and Torque Possible: The spindle motor is mounted externally from the actual spindle shaft. Therefore, it is often possible to use a very large motor. A large motor, particularly one of large diameter, can provide very high torque and high power for spindle use. This is much more difficult in an integral motor-spindle design, as available space is always limited.

However, there are also some limitations of a belt and gear driven spindle design, particularly when a High Speed spindle is required:

1. Maximum Speed is Limited: A belt or gear driven spindle will be limited in maximum rotational speed due to several factors. The mechanical connection, which transmits the torque to the spindle shaft, the belt and pulley system, is limited in maximum operating speed. If a poly V-belt system is used, high rotational speeds on the pulleys tend to stretch and disengage the belts, reducing their contact and ability to transmit torque. Cogged belts eliminate the slipping problem, however, at higher speeds these belts produce unacceptable levels of vibration. At gear driven spindles much higher torque is possible, but Gears are very limited in maximum speed, and will also produce high levels of vibration and heat if operated at very high speeds. These will be further discussed in subsequent sections of this catalogue, as they are similar to methods used in motor spindles.
2. Belts Utilize Bearing Load Capacity: In order to be able to transmit the necessary torque, belt-driven spindles utilize a belt and pulley connection on the end of the spindle shaft. The required tensioning of these belts will exert a constant radial force on the rear spindle shaft bearing set. As the power and speed of the spindle increase, the applied tension and consequent force will increase, using up much of the available radial loading capacity of the bearings. Substituting larger bearings, or adding additional bearing sets will not be feasible, as these methods will only further reduce the spindle abilities to reach high rotational speeds.

Therefore, it is evident that a belt and gear driven Precision spindle will be limited to certain applications. Typically, belt-driven spindles will be used up to maximum rotational speed of 12,000 - 15, 000 RPM. Gear driven spindles even less. To accomplish this, other means must be used to allow the higher speeds, including different bearings types, setups, or bearing lubrication. These will be further discussed in subsequent sections of this report, as they are similar to methods used in motor-spindles. Power for this type of spindle may reach as high as 30 HP, however, it is sometimes difficult to provide high torque at the top speed. This will depend very much on the driving motor characteristics.

Integral Motor-Spindle Design

The integral motor-spindle does not rely upon an external motor to provide torque and power. The motor is included as an integral part of the spindle shaft and housing assembly. This allows the spindle to rotate at higher speeds as a complete unit, without the additional limitations of belts or gears.

In general, a complete motor-spindle is comprised of the spindle shaft, including motor element, and tooling system. The spindle shaft is held in position by a set of high precision bearings. The bearings require a lubrication method, such as grease or oil. The spindle shaft then will

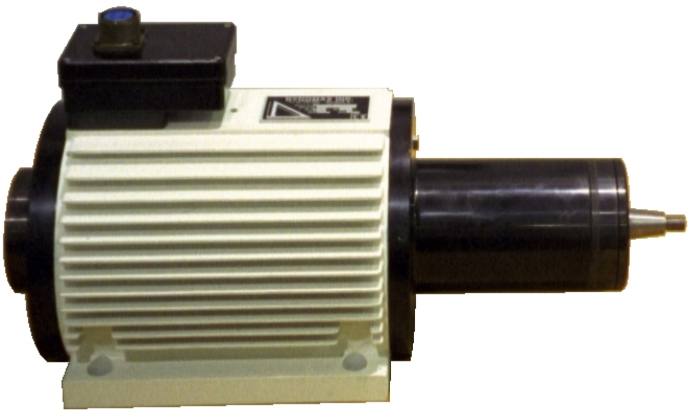


Figure 2. - Integral Motor-Spindle Design
Dynomax Model No. #08-3A-FM-5.0-0427

rotate up to the maximum speed, and exhibit the power characteristics of the motor type that is used. The selection of a particular component will, of course, depend upon the requirements of the machine tool. Also, compromises must be made in order to provide the best combination of speed, power, stiffness and load capacity. The following sections will describe in more detail the design and selection criteria used for the major components of a High Speed motor-spindle.

2.3 Spindle Housings

The spindle shaft and motor must be held in a housing. The housing may be an integral part of the machine tool, or it may be block, foot mount or a flange mount cartridge housing. Many high speed spindle designs utilize a cartridge type housing, as this is the simplest to service, and the tolerances required for high speed are easier to obtain when the housing can be produced as a cylinder.

The primary function of a spindle housing is to locate the bearings. The spindle housing must support and locate the bearings accurately, and provide the utilities needed by the spindle system. It must be robust and stiff, as the housing transfers all forces from the spindle to the machine tool.

High precision bearings, being run at top dN values, must be positioned exactly in terms of geometry and size. In addition, the housing will provide the lubrication, air seal, cooling water or oil, and other utilities required by the spindle. If the spindle utilizes oil lubrication, the housing will include drilled passages to deliver the oil or oil mist to each bearing, and out of the bearing to a return line. A cooling liquid is often used to remove heat produced by the spindle motor stator, as this heat would affect the size and accuracy of the spindle as a complete unit.

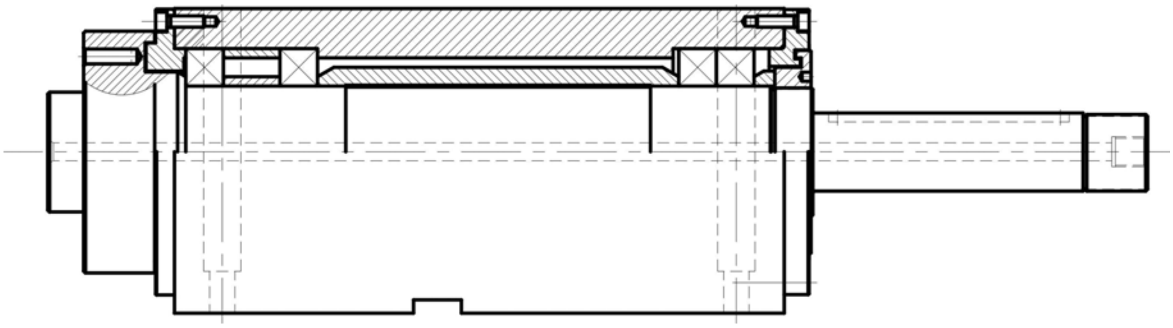


Figure 3. BLOCK HOUSING
Dynomax Model No. #14-2A-B-0630

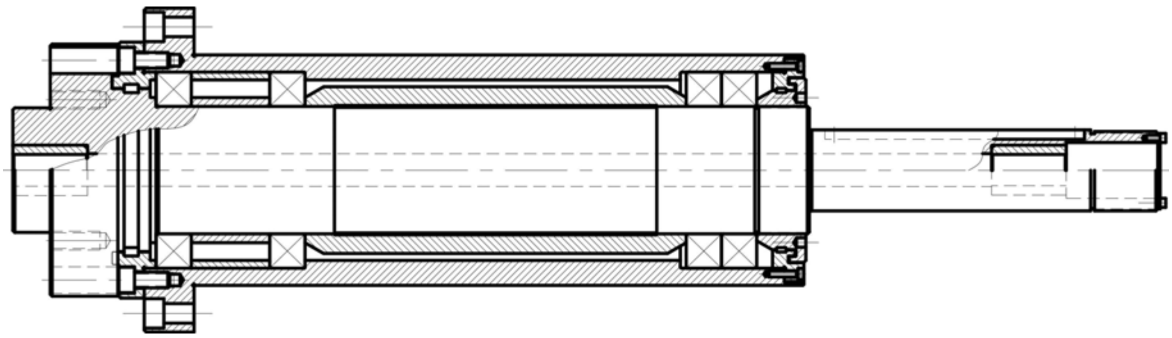


Figure 4. CARTRIDGE HOUSING
Dynomax Model No. #13-2A-C-0710

2.4 Spindle Bearings

Introduction

One of the most critical components of any high speed spindle design is the bearing system. Our design requirements state that the spindle must provide high rotational speed, transfer torque and power to the cutting tool, and be capable of reasonable loading and life. The bearing type used must be consistent with these demands, or the spindle will not perform.

High precision bearings are available today from a variety of manufacturers worldwide. The type of bearings available for high speed spindles include roller, tapered roller and angular contact ball bearings. The selection criteria of which type to use will depend upon the spindle specifications, as each will have an impact, or impact upon the bearing selection, as the following table explains.

Requirement	Best Bearing Type	Design Impact
High Speed High Stiffness Axial Loading Radial Loading High Accuracy	Small Contact Angle Large Roller High Contact Angle Low Contact Angle ABEC 9 (ISO P2)High Preload	Small Shaft, Low Power Low Speed, Large Shaft Lower Speed Higher Speed Expensive, Low Speed

As you can see, there are many factors that determine the final decision. A spindle that is desired to have the highest speed will not have the maximum stiffness possible, and, the spindle with the highest stiffness cannot run at high speeds without sacrificing bearing life. So, as designers, compromises must be made in order to arrive at the most efficient design possible.

Angular contact bearings features

Angular contact bearings are most commonly used today in very high speed spindle designs. This is due to the fact that angular contact ball bearings provide the precision, load carrying capacity and speed required for metal cutting spindles. In some cases, tapered roller bearings are used, due to their higher load capacity and greater stiffness over ball bearings. However, tapered roller bearings do not allow the high speeds required by many spindles.

Angular contact ball bearings utilize a number of precision balls fitted into a precision steel race. They are designed to provide both axial and radial load carrying capacity, when properly pre-loaded.

An important concept to consider is the maximum speed a bearing, and ultimately, the spindle will be able to achieve. This is determined, theoretically, by considering the type of bearing, lube method, pre-load, loading, etc. In practice, a bench mark is used, referred to as the dN number. The **dN number** is derived by multiplying the bearing bore diameter by the speed in RPM.

For a high speed spindle, utilizing ball bearings, there is the upper level of dN = 500,000. With oil lubrication, special care in design and choosing the right components, **dN numbers up to 1,500,000 are possible.**

Bearing Contact Angle

Angular contact ball bearings are manufactured to a specification that includes a **contact angle.** The contact angle is the nominal angle between the ball-to-race contact line and a plane through the ball centers, perpendicular to the bearing axis.

The contact angle determines the ratio of axial to radial loading possible, with radial loading being the primary benefit. Typically, contact angles of 12º, 15º, and 25º are available. The lower the contact angle, the greater the radial load carrying capacity, the higher the contact angle the higher the axial loading capacity will be. Therefore, it may be desirable to use a bearing with a contact angle of 25º for a spindle that will be used primarily for drilling, and a contact angle of 15º for a spindle that will primarily be used for milling.

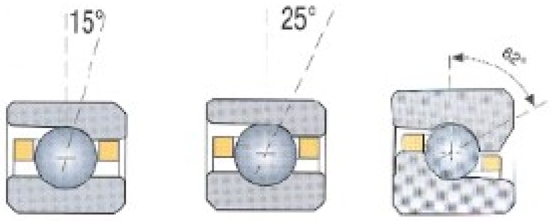


Figure 5. Different Contact Angles

Bearing Precision

All precision bearings are manufactured to a tolerance standard. The tolerances for dimensional, form and running accuracy of High precision Spindle ball bearings are specified in international (ISO 492) and national standards (DIN 620).

The most commonly used standard in the United States is the ABEC standard (America Bearing Engineers Committee) This standardization has been accepted by the American National Standards Institute (ANSI) conform essentially with the equivalent standards of the International Organization for Standardization (ISO). ABEC standards define tolerances for major bearing dimensions and characteristics. They are divided into mounting dimensions (bore, I.D. and width) and bearing geometry. Accuracy ratings range from a low of ABEC 1, for a general purpose bearing, to a high of ABEC 7 and ABEC 9, which describes a high precision bearing suitable for use in a high speed spindle. Typically, spindle bearings are manufactured with geometry accuracy of ABEC 9, to provide minimum run out and rotational accuracy. Bore, O.D., and width are manufactured to ABEC 7, which allows for a more reasonable fitting and installation.

The precision of a spindle bearing does affect the guiding properties or life, especially with applications at max. speed.

The relationships between the various standards are explained below.

ISO	DIN	AFBMA
class 4	P4	ABEC7
class 2	P2	ABEC9

Table 1.

Bearing Preload

Angular contact ball bearings are available with a choice of pre-loading magnitude, typically designated as light, medium and heavy.

Light pre-loaded bearings are designed to allow maximum speed and less stiffness. Light pre-loaded bearings are often used for very high speed applications, where cutting loads are also light, and top RPM is needed.

Heavy pre-loading allows less speed, but higher stiffness.

In order to provide the required load carrying capacity for a metal cutting machine tool spindle, several angular contact ball bearings are used together. This way, the bearings can share the applied loads, and increase the overall spindle stiffness. The bearings can be installed several ways, depending upon the desired characteristics.

Angular contact ball bearings must be pre-loaded in order to provide axial and radial capabilities. One simple way to do this is to mount the bearings in groups of two or three, such that the pre-load is correctly applied to the bearings. This is possible by using duplex bearings, which are manufactured for this purpose. The inner or outer bearing races are ground, such that when clamped together the bearings will have the proper amount of pre-load.

Bearing Mounting Configurations

Face to Face Configuration

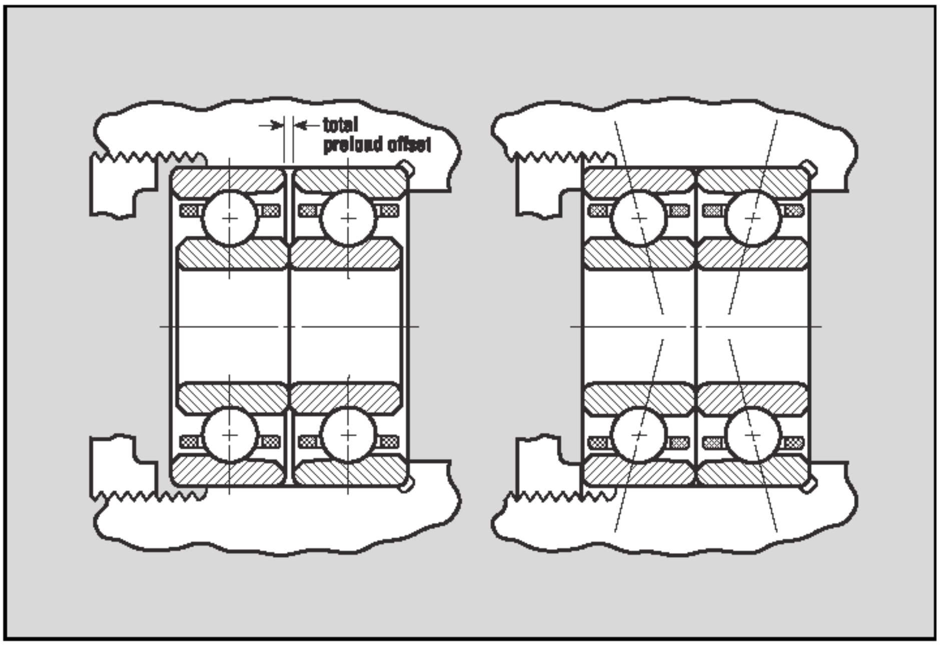


Figure 6. FACE TO FACE DF-Mounting

If the bearings are mounted face to face, this is referred to as "Face-to Face" or "X" configuration. In this configuration, the outer races are relieved When the outer races are clamped together, the relief clearance is eliminated, resulting in the correct pre-load. This mounting technique is not very common; however, it does provide the proper pre-loading, such that the bearing pair is capable of withstanding both axial and radial loading.

Back to Back Configuration

The most common technique used is back to back, "O", or "DB " mounting. In this configuration, the inner races are relieved. When the inner races are clamped together, the relief clearance is eliminated, resulting in the correct pre-load. This configuration is suited for most applications and provides good accuracy and rigidity.

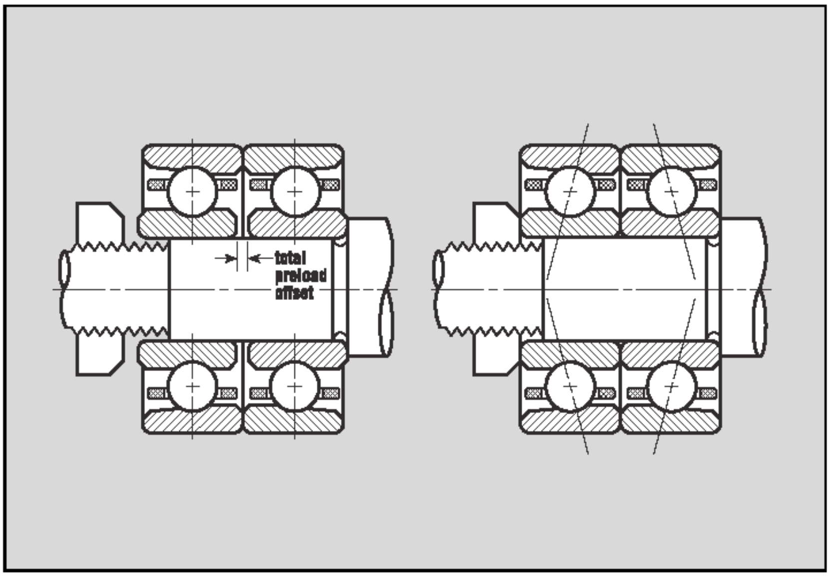


Figure 7. BACK TO BACK DB-Mounting

Tandem Configuration

Generally, a combination of mounting techniques is used in a spindle assembly. In many cases, two or three bearings are placed near the spindle nose, with a pair mounted near the rear of the spindle shaft. This mounting is known as "Tandem" or "DT". Tandem mounting does not allow forces in both directions, unless another pair of bearings are used on the spindle shaft, facing in the opposite direction. To increase moment loading capacity and spindle performance, spacers are used to separate the bearing sets. This is generally the case in most motor-spindle designs. The spindle designer will use two or three bearings in the front in a tandem setup. At the rear of the spindle shaft, another bearing pair, of equal size or smaller, will be used in a tandem arrangement as well. Together, the bearing sets form an overall "DB" or Back-to Back setup. The spindle shaft and spindle housing locate the bearings.

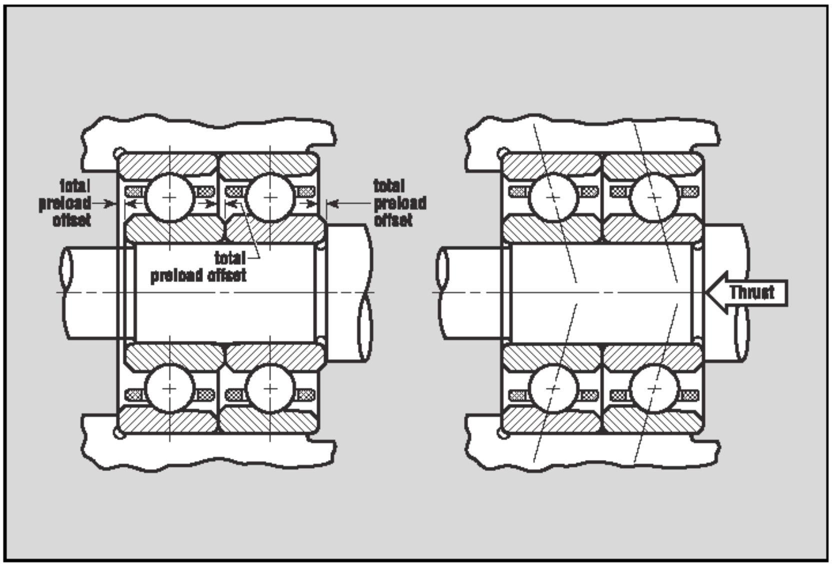


Figure 8. TANDEM DT-Mounting

Specialized Configuration

Sets of three or more bearings are sometimes used in special cases having requirements for increased stiffness or capacity, where the shaft or housing size cannot be changed to accommodate larger bearings. (See Figure 7.)

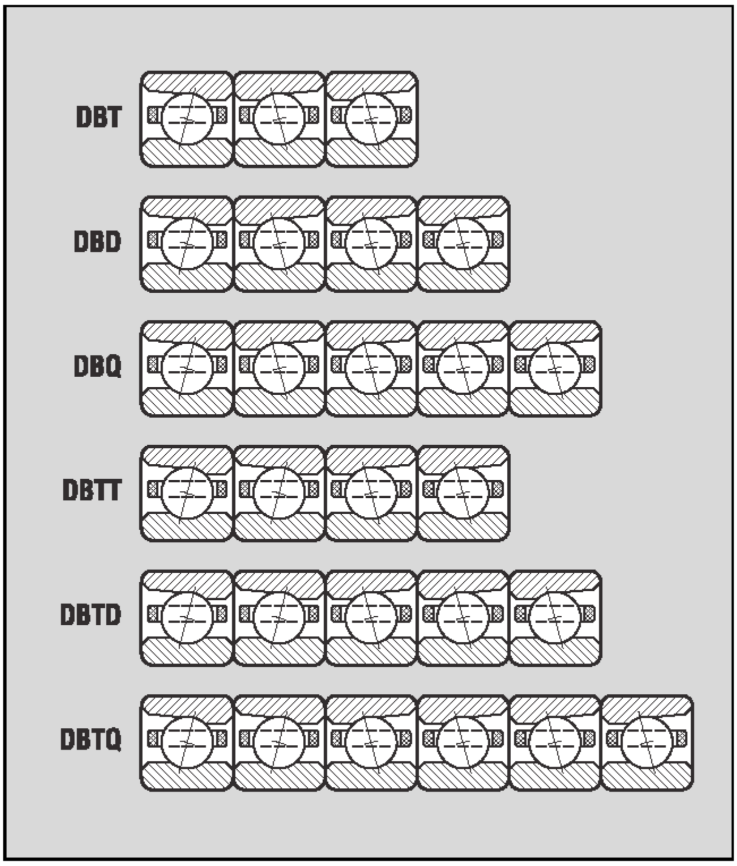


Figure 9. Mounting the bearings in sets

Rigidity

To achieve the best possible rigidity:

- minimise the distance between the front support position and the spindle nose.
- bearing spacing (between rear and front supports) should be fairly short. As a guideline, a ratio l/d = 2,5-3 provides the best compromise, where are:

  l= distance between the rearmost bearing row and the first front side bearing row;
  d= bore diameter of the first bearing

Motor-Spindle with Tandem Bearing Pairs and Spring Pre-Loading

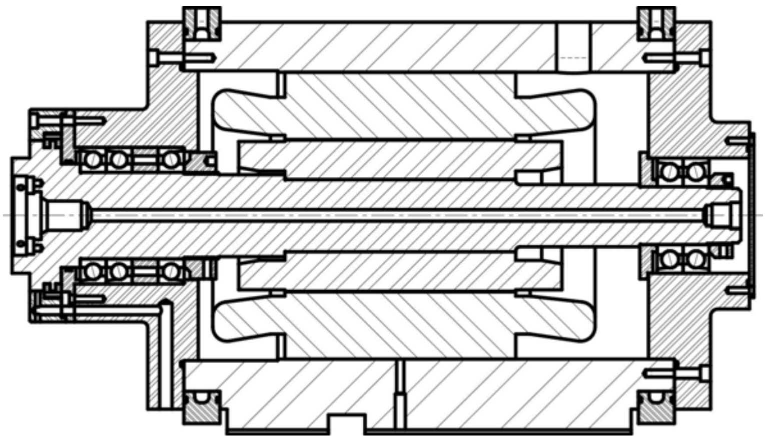


Figure 10. TANDEM BEARING PAIRS
Dynomax Model No. #12-3A-FM-10-0428

Motor-spindles experience temperature increases due to bearing heat and motor losses. This heat results in thermal growth of the spindle shaft. As illustrated, a tandem pair of bearings used both in the front and rear of a spindle will initially have an affixed pre-load based upon the location of the bearings in reference to the spindle housing. When the temperature is increased, the spindle shaft will grow in length. This change in dimension will be seen by the bearings as an increase in pre-load, as the inner race is forced into the bearing. This is most undesirable, since it can cause rapid failure of the bearings.

To compensate for this change, it is often necessary to mount the rear spindle bearings in a floating housing with springs. The floating housing is mounted in a precision bore, or ballcage, that is free to move in an axial direction only. Springs are used to provide a constant pre-loading force against the spindle shaft in the axial direction. As the spindle grows due to thermal expansion, the rear bearings are also free to move. In this way, the pre-load seen by the bearings does not change, as it is maintained by the force exerted by the springs. This technique is used for high speed milling spindles and grinding spindles, and does add a degree of cost and complexity to the spindle system.

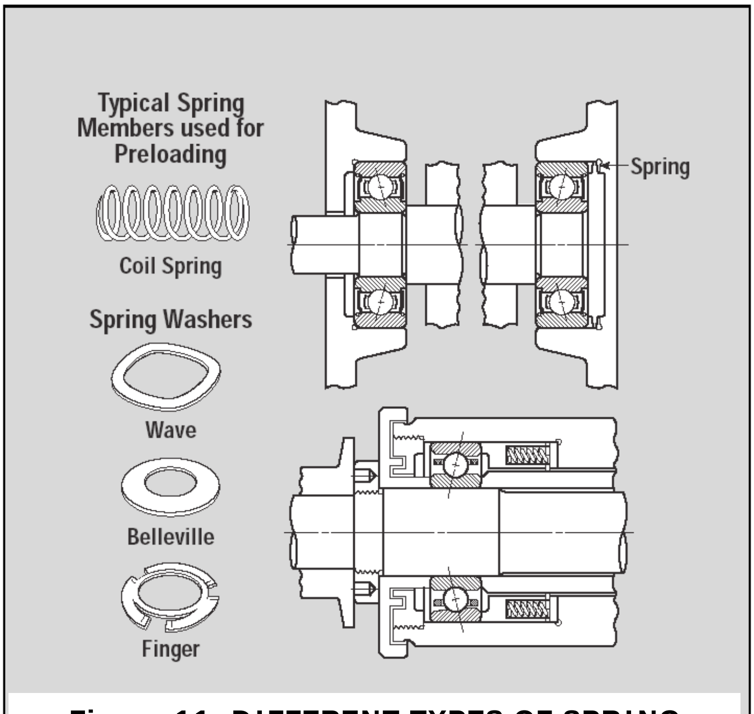


Figure 11. DIFFERENT TYPES OF SPRING PRELOADING

Bearing Construction: Hybrid Ceramic

Figure 12.
HYBRID CERAMIC BEARING

Newer bearing technologies using ceramic balls. The ceramic balls, when used in an angular contact ball bearing, offer distinct advantages over typical bearing steel balls.

The ceramic balls have 60% less mass than steel balls: This is significant because as a ball bearing is operating, particularly at high rotational speeds, centrifugal forces push the balls to the outer race, and even begin to deform the shape of the ball. This deformation leads to rapid wear and bearing deterioration. Ceramic balls, with less mass, will not be affected as much as steel at the same speed. In fact, the use of ceramic balls allows up to 30% higher speed for a given ball bearing size, without sacrificing any bearing life.

Ceramic Balls Do Not React with The Steel Raceways: One of the most prominent mechanisms of bearing failure is surface wear created by microscopic "cold welding " of the ball material to the raceway. The cold welds actually break as the bearing rotates, creating surface roughness, which leads to heat generation and bearing failure. The ceramic material drastically reduces this mechanism, resulting in longer bearing life.

Ceramic Ball Bearings Operate At Lower Temperatures: Due to the nearly perfect roundness of the ceramic balls, hybrid ceramic bearings operate at much lower temperatures than steel ball bearings. This results in longer life for the bearing lubricant.

Ceramic Bearings Operate at Much Lower Vibration Levels: Tests have shown that spindles utilizing hybrid ceramic bearings exhibit higher rigidity and have higher natural frequencies, making them less sensitive to vibration.

Roller Bearings

Roller bearings are mostly used at lower speed application, but with higher Loads. They are usually used in pair of two, opposite oriented to allow a high assembly's stiffness.

Ususally, those kind of bearings are grease lubricated.

Bearing Lubrication Methods

Angular contact ball bearings require some form of lubrication to operate properly. The function of lubrication is to provide a microscopic film between the rolling elements to prevent abrasion and skidding. In addition, lubrication protects the surface from corrosion, and protects the working area from particle contamination.

Grease Lubrication

The most common and simplest method of lubricant is grease. The grease is injected into the space between the balls and the races. It is permanent and therefore requires minimal maintenance. Grease lubrication, however, does have limitations.

Grease packed spindles generally are not run above dN values of approx. 850,000 for continuous operation. As speeds increase, operating temperatures increase, and begin to break down the grease. Most grease is rated to operate at temperatures under 300° F. The grease type that can tolerate high speeds generally has an ester oil base. With regard to the quantity of grease, **more is not better**. Excessive grease can cause overheating due to churning, causing the grease to deteriorate. Approximately 20% to 30% of the open area between the races should be filled. Following the grease fill, a careful run-in period is required to distribute the grease within the bearing.

In general, high speed spindles that utilize grease lubrication do not allow for replacement of the grease between bearing replacements. During a bearing replacement, clean grease is carefully injected into the bearing. Positive air overpressure is typically used to prevent contamination from entering the bearing, which could lead to rapid bearing failure.

Oil Lubrication Techniques

In many cases, particularly when high rotational speed is required, lubrication of the bearings with grease is not sufficient. Oil is then used as a lubricant, and delivered in a variety of ways. As previously mentioned, grease can support bearing speed up to a dN value of approx. 850, 000.

Oil lubrication can support speeds at much higher speed than grease

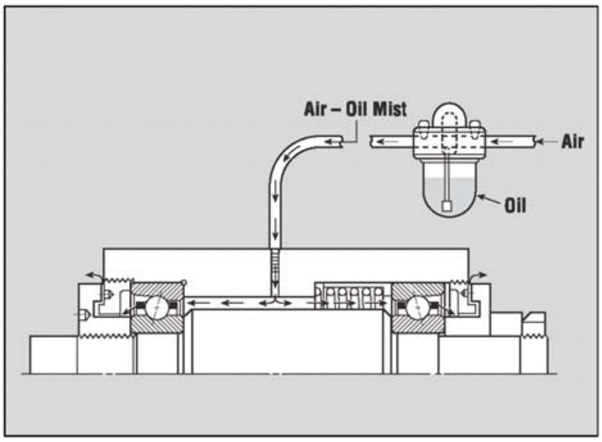


Figure 13. AIR/OIL MIST LUBRICATION SYSTEM

One common method of oil lubrication is oil mist. An oil storage tank is used, and compressed air is mixed with the oil. This creates oil droplets that are carried by the airflow to the bearing area. The major benefits of oil mist are: it is a good supply of lubricant, oil mist is simple to use, and it also cleans and cools the bearings. This system is best applied to spindles having high speeds and relatively light loads. Oil mist is somewhat difficult to measure and control, so if the quantity of oil delivered to the bearings must be very accurate, oil mist may not be the best system to use.

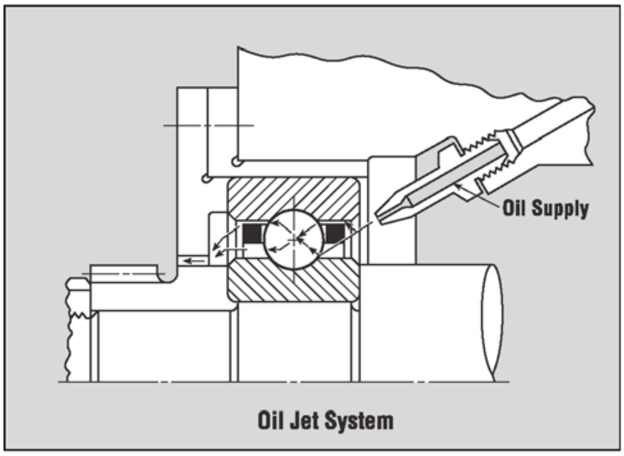


Figure 14. OIL JET LUBRICATION SYSTEM

Another common method of oil lubrication is an oil jet. The oil jet utilizes a high pressure pump that delivers oil directly into the bearing race. This system is suitable for spindles that must tolerate high loads, high speeds, and high temperatures. Care must be taken to insure that the oil can be quickly routed through the bearing, or oil churning will develop. This system requires a complex pump, storage tank and temperature control system. Sometimes, though, it is necessary to support very high performance spindles.

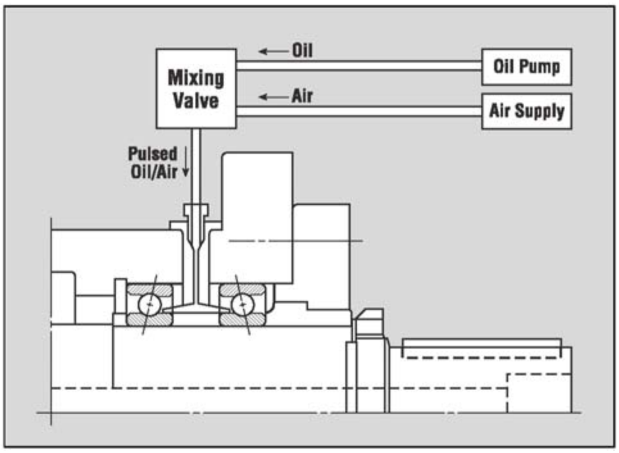


Figure 15. PULSED AIR/OIL LUBRICATION SYSTEM

Another system, pulsed oil-air, injects oil in very small quantities with compressed air, into the bearing cavity. The frequency of injection may be related to the spindle operation, or simply on a timed basis. Experience has shown that this is the lubrication system that gives the most precise oil quantity control. An additional benefit from this system is that the airflow helps to exclude contaminants from the spindle. Optimum flow may need to be established experimentally. A guide value for the delivery rate can be estimated from the expression:

V=0,15 x b x w -in cubic mm/hour
where b= bearing bore in mm
w= bearing width in mm

The air used must be clean (5micron filter) and dry (40° dew point). The oil must be of high quality with a viscosity of 150 SUS at 38°C.

Direct oil injection through the outer bearing ring

This type of lubrication is a newly developed system, typical for high speed applications. The holes allow the lubricant to directly reach the ball raceway contact and ensure the presence of an oil film even at high speed.

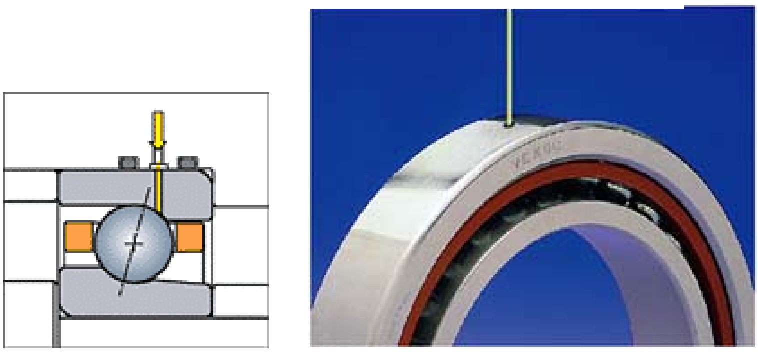


Figure 16. DIRECT OIL INJECTION

There are many oils available on the market today that are effective for use in high speed bearings. Please, refer to your Spindle manual for details and recommendations.

Bearing Lubrication Summary

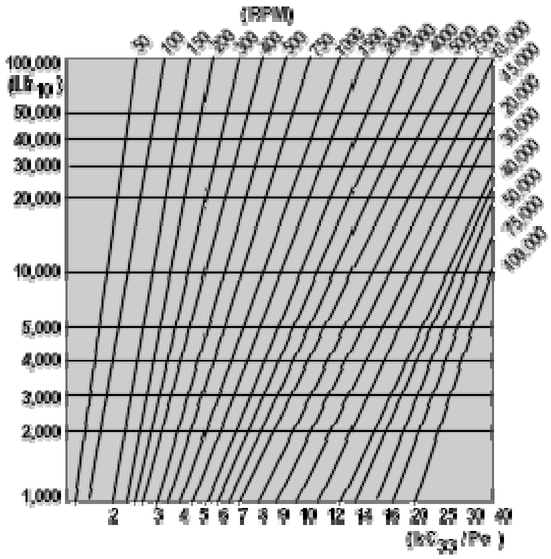
Bearing lubrication is a critical component in the complete high speed spindle system. Depending upon bearing size, type, and speed, bearing lubrication may be permanent grease or some type of oil system. The maintenance of the lubrication system is vital, and so it must be closely monitored to insure that proper bearing conditions are maintained. Oil mist, oil jet, and pulsed oil-air systems require a continuous supply of clean and dry air. Also, use of the correct type, quantity, and cleanliness of lubricating oil is critical.

Bearing Life Calculation

This following graph illustrates theoretical bearing life based on speed and bearing loading factors. (Courtesy SNFA)

All bearings will have a useful life, defined as operation time until the bearing specifications are lost, or a complete failure of the bearing occurs. The most common cause of bearing failure is fatigue, when the races become rough, leading to heating, and eventual mechanical failure. Bearing life, in general is affected by the following parameters:

1. Bearing Loads, Axial and Radial
2. Vibration Levels
3. Quality and Quantity of Lubrication
4. Maximum Speed
5. Average Bearing Temperature



L10 Bearing Life (Courtesy SNFA)

Figure 17. BEARING LIFE

Bearing life is typically expressed as L_{10} life.
This is defined as the minimum life, in revolutions, for 90% of a typical group of apparently identical bearings. The calculation for this is expressed as follows:

$$L_{10} = \left[\frac{KC_{33}}{P}\right]^3 x10^6 \quad \text{(Revolutions)}$$

Where: C_{33} = Basic Dynamic Load Rating
K = Factor for Multiple Bearings
P = Equvalent Radial Load

And: P = XR + YT
R = Radial Load
T = Thrust Load
X = Radial Load factor relating to contact angle
Y = Axial Load factor depending upon contact angle, T, and ball complement.

If we take into consideration time, a life can be expressed in terms of hours of operation:

$$L_{H10} = \frac{L_{10} \ x\ 10^6}{60 \ x \ n} \quad \text{(hours)}$$

Where: n = RPM

In general, bearing life, and ultimately spindle life, will depend upon many factors, including speeds, loading, lubrication, and bearing size. Computer models are often used to forecast life; however, a typical spindle bearing life for very high speed operation should be in the range of 5000 - 7000 hours, assuming the spindle is not crashed or misused.

2.5 Spindles with Integral Motors

Spindle Electro Motor Design

Integral motor spindles must utilize an electrical motor as part of the rotor shaft. Therefore, the motor size and capacity will depend strongly upon the available space. As we have discussed earlier, bearing size is critical in a Superprecision spindle design, so the motor shaft will affect the bearing size that can be used. The bearing size also affects the loading capability, stiffness, and maximum speed, so the motor characteristics must match the bearing capability.

The most common type of motor used in Superprecision motor spindles is an AC induction motor. In this design, the rotor is attached to the spindle shaft, either with an adhesive or thermal clamping. The rotor and stator, the winding in which the rotor revolves, are generally provided by a motor or drive supplier. The rotor is attached to the shaft during assembly. Following this, the bearings are mounted to the front and rear of the shaft, and the shaft is then fitted into the spindle housing.

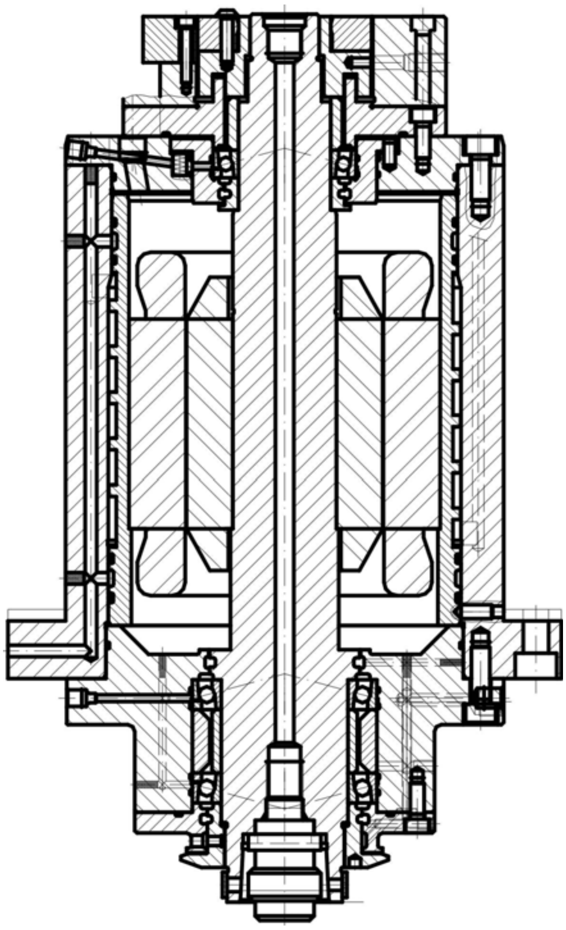
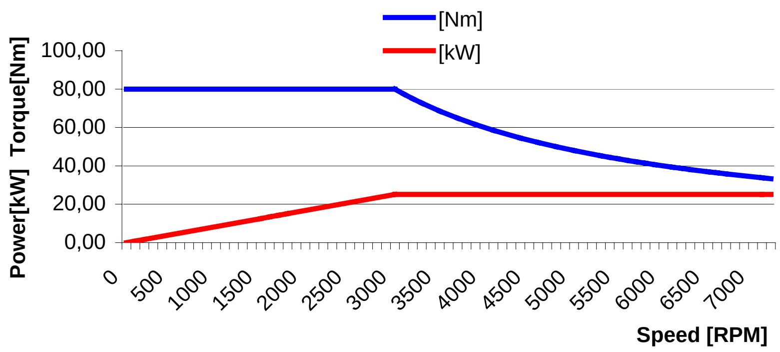


Figure 18. MOTOR SPINDLE DESIGN
Dynomax Model No. #07-2A-FL-3.0-0500

The spindle shaft is quite important because it must transfer the power from the motor to the cutting tool. The shaft must locate and support the bearings, as well as contain the complete tooling system. One important design consideration for the shaft is bending. During high speed operation, the shaft will exhibit bending characteristics. The frequency at which the shaft will bend depends on the diameter and length of the spindle shaft. It is often tempting to design a very long spindle shaft, as this increases the load carrying capacity of the spindle and allows for a more powerful motor. However, care must be taken as the spindle grows in length, the first bending mode will approach frequencies in the operating zone. This is not tolerable for spindle operation, and must be resolved by either re-designing the shaft with a larger diameter (bearings will be larger and slower!) or decreasing the shaft length.

Spindle Motors Power and Torque characteristics

Figure 19. TYPICAL POWER & TORQUE DIAGRAMS FOR INTEGRAL MOTOR SPINDLES



Used induction motors exhibit power and torque curves determined somewhat by the winding design. However, due to limited available space, and centrifugal forces acting on the laminated rotor, power is related closely to speed.

Spindle motors will generally provide constant torque up to the base speed, and constant horsepower after the base speed. As power is a function of speed multiplied by torque, the above curves are typical. Conventional spindle heads multiply available torque by using mechanical components such as gears and pulleys.

Motor-spindles, however, must rely upon a single motor characteristic to provide the power and speed needed for machining across a full range of operations. Generally, these spindles are designed for intended use at or near full speed. Below this, as power falls off, little heavy machining is feasible.

Integral AC induction motors are typically three phase, requiring a special electronic drive to provide the electrical power source. The drive is a high frequency type, providing a variable voltage and variable frequency to the spindle motor. The speed of an AC motor is determined by the following formula:

Speed (RPM) = (Frequency in Hz x 120) / (# of motor poles)

This would dictate that a two pole spindle motor, having a top speed of 30,000 RPM, would require a drive with the capability to provide full motor voltage at an output frequency of 500 Hz. If this motor were a four pole type, then a maximum frequency of 1000 Hz would be required.

Very high speed drives utilize an open-loop concept, providing voltage and current to the motor without any real-time feedback to close the velocity or position loop. Many drives, however, do use magnetic or optical feedback to the spindle drive. This is used to regulate speed, provide programmable positioning of the spindle shaft, and, in some cases, rigid tapping. Orientation is required for many tooling systems for ATC operation. DC brushless and Flux vector are examples of closed loop systems.

Synchronous Spindle Motor :

AC asynchronous motors are used as the standard. Recently, more spindle manufactures are attempting to use a Synchronous motor type, where the rotor is made from permanent magnetic material, with much less thermal dissipation and, consequently, a lower bearing temperature rise and expansion.

The main advantages given with Synchronous motors use:

- Simpler spindle design
- 90 % less power loss in the rotor, e.g. significantly lower bearing temperature rise / spindle expansion
- Higher efficiency
- More compact machine design
- Higher torque (approx. 60 %) for the same active part volume
- Better machining results
- Higher productivity

Comparison between Synchronous/ Asynchronous motors :

Comparison of Power and Torque characteristics

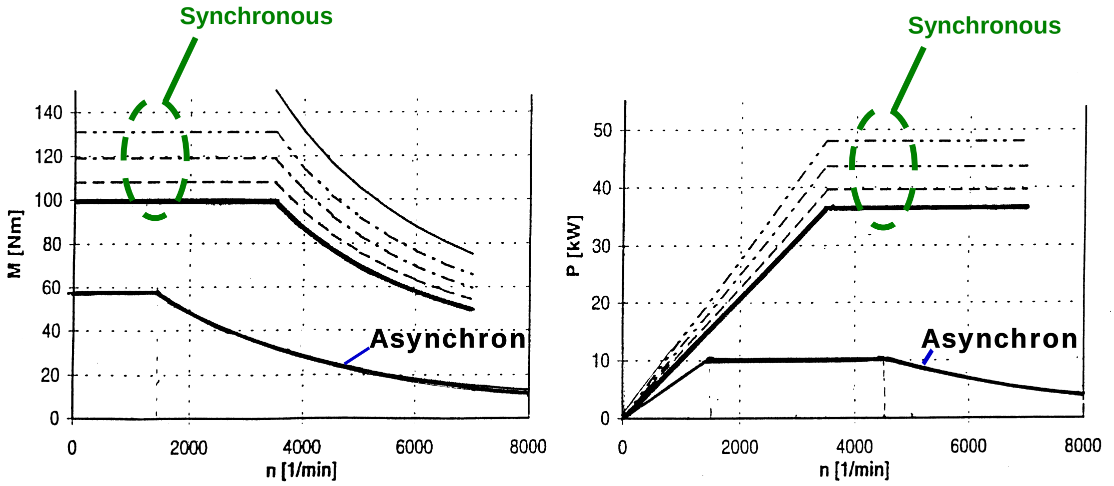
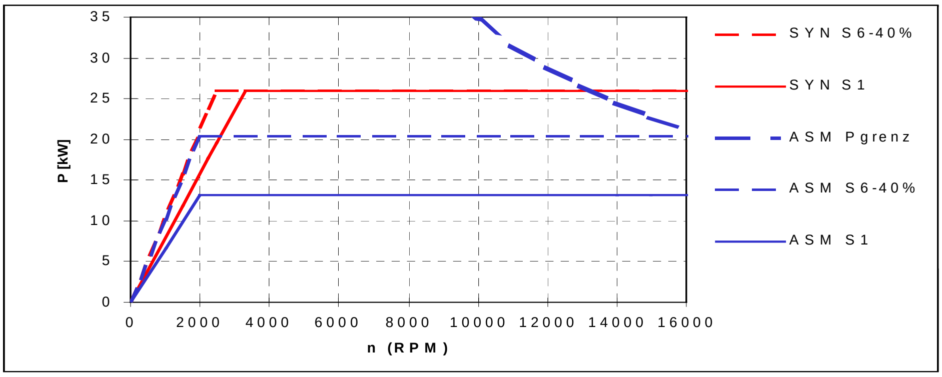


Figure 20. COMPARISON BETWEEN SYNCHRONOUS AND ASYNCHRONOUS MOTORS CHARACTERISTICS

Comparison of Acceleration time
(4-pole, n_{max}= 16,000 RPM)

Basis of the comparison:
-n_{max} = 16,000 RPM
-identical frame size: 90 , l_{FE} = 150 mm
-identical power module S6-40%, current 90A



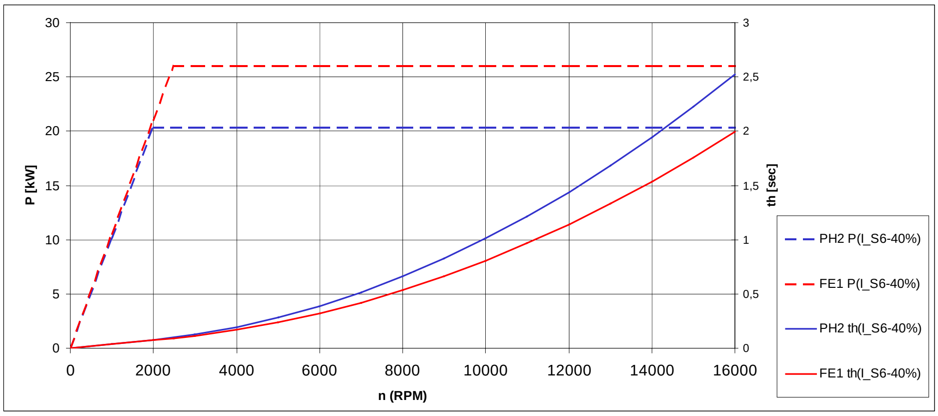


Figure 21. ACCELERATION TIME OF SYNCHRONOUS AND ASYNCHRONOUS MOTORS

Advantage at Synchronous motor spindle

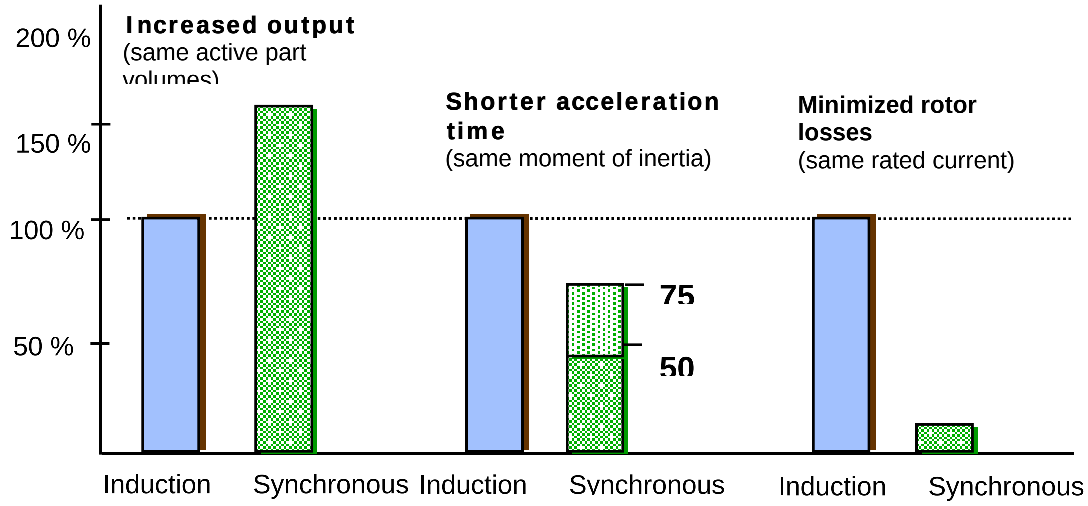


Figure 22. ADVANTAGE AT SYNCHRONOUS MOTOR SPINDLE

The synchronous motor built in spindle:

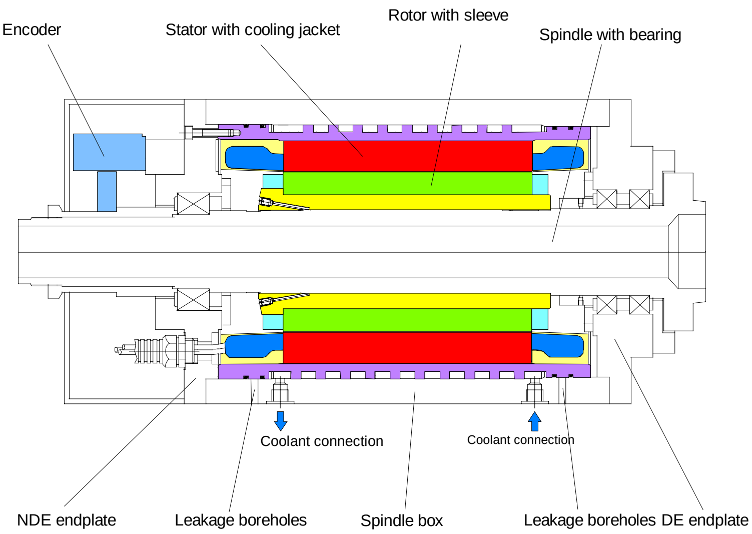


Figure 23. SPINDLE WITH SYNCHRONOUS MOTOR BUILT IN

Benefits Summary:

-High torque over the complete speed range
-Constant output up to max. speed
-Compact construction - high output
-Electrical field weakening
-Automatic pole-position-identification
-Low load moment of inertia due to small rotor
-Short acceleration and deceleration times n Relatively cold rotor - bearing temperature does not have to be monitored
-Large diameter hollow shaft and low rotor mass - high natural frequency and stiffness of the system
-Applications: High performance cutting on general purpose machines, tools and castings, aerospace industry
-High efficiency one-chuck machining as no changeover is required between roughing and finishing spindle

2.6 AC Variable Frequency Motor Drives

AC drive operation begins with rectifying the alternating line voltage to produce DC. But because an AC motor is used, this DC voltage must then be changed back, or inverted, to an adjustable-frequency alternating voltage. The drive's inverter section accomplishes this. In years past, this was accomplished using SCRs. However, modern AC drives use a series of transistors to invert DC to adjustable-frequency AC.

This synthesized alternating current is then fed to the motor at a frequency and voltage required to produce the desired motor speed. For example, a 60 Hz synthesized frequency, the same as standard line frequency in the United States, produces 100% of rated motor speed. A lower frequency produces a lower speed, and a higher frequency a higher speed. In this way, an AC drive specialized for the High Speed Spindles, can produce motor speeds from, approximately, 15 to 5000% of a motor's normally rated RPM by delivering frequencies of 9 Hz to 3200 Hz, respectively.

Today, AC drives are becoming the system of choice in many industries. Their use of simple and rugged three-phase induction motors means that AC drive systems are the most reliable and least maintenance prone of all. Plus, microprocessor advancements have enabled the creation of so-called vector drives, which provide greatly enhance ramp response down to zero speed and positioning accuracy.

By far the most popular AC drive today is the pulse width modulated type. Though originally developed for smaller-horsepower applications, PWM is now used in drives with hundreds or even thousands of horsepower, as well as remaining the staple technology in the vast majority of small integral and fractional horsepower "micro" and "sub-micro" AC drives.

Pulse width modulated refers to the inverter's ability to vary the output voltage to the motor by altering the width and polarity of voltage pulses. The voltage and frequency are synthesized using this stream of voltage pulses. This is accomplished through microprocessor commands to a series of power semiconductors that serve as on-off switches. Today, these switches are usually IGBTs, or isolated gate bipolar transistors. A big advantage of these devices is their fast switching speed resulting in higher pulse or carrier frequency, which minimizes motor noise.

AC Drive Application Factors

As PWM AC drives have continued to increase in popularity, drives manufacturers have spent considerable research and development effort to build in programmable acceleration and deceleration ramps, a variety of speed presets, diagnostic abilities, and other software features. Operator interfaces have also been improved with some drives incorporating "plainEnglish" readouts to aid set-up and operation. Plus, an array of input and output connections, plug-in programming modules, and off-line programming tools allow multiple drive set -ups to be installed and maintained in a fraction of the time spent previously. Some of the modern drives can be preset for different motors and user can easy switch connection on each of them with principle “one at a time”. On the other hand, a few motors with the same characteristics, can be used simultaneously with single drive. All these features have simplified drive applications. However, several basic points must be considered.

Torque: This is the most critical application factor. All torque requirements must be assessed, including starting, running, accelerating and decelerating and, if required, holding torque. These values will help determine what current capacity the drive must have in order for the motor to provide the torque required. Usually, the main constraint is starting torque, which relates to the drive's current overload capacity. (Many drives also provide a starting torque boost by increasing voltage at lower frequencies.)

Perhaps the overriding question is whether the application is variable torque or constant torque. The torque required in applications decreases as the motor RPM decreases. Therefore, drives for variable torque loads require little overload capacity. Constant torque applications, require the same torque regardless of operating speed, plus extra torque to get started. Here, high overload capacity is required.

Speed: As mentioned, AC drives provide an extremely wide speed range. In addition, they can provide multiple means to control this speed. Many drives, for example, include a wide selection of preset speeds, which can make set-up easier. Similarly, a range of acceleration and deceleration speed "ramps" are provided. Slip compensation, which maintains constant speed with a changing load, is another feature that can be helpful. In addition, many drives have programmable "skip frequencies." Particularly with some spindle systems, there may be specific speeds at which vibration takes place. By programming the drive to avoid these corresponding frequencies, the vibration can be minimized.

Current: The current required for a motor to provide needed output is the basis for sizing a drive. Horsepower ratings, while listed by drive manufacturers as a guide to the maximum motor size under most applications, are less precise. Especially for demanding constant torque applications, the appropriate drive may, in fact, be "oversized" relative to the motor. As a rule, general-purpose constant torque drives have an overload current capacity of approximately 150% for one minute, based on nominal output. If an application exceeds these limits, a larger drive should be used.

Power Supply: Drives tolerate line-voltage fluctuations of 10-15% before tripping and are sensitive to power interruptions. Some drives have "ride-though" capacity of a second or two before a fault is triggered, shutting down the drive. Drives are sometimes programmed for multiple automatic restart attempts. For safety reasons, plant personnel must be aware of this. Manual restart may be preferred.

Most drives require three-phase input. Smaller drives may be available for single-phase input. In either case, the motor itself must be three-phase.

Drives, like any power conversion device, create certain power disturbances (called "noise" or "harmonic distortion") that are reflected back into the power system to which they are connected. These disturbances rarely affect the drive itself but can affect other electrically sensitive components.

Control Complexity: Even small, low-cost AC drives are now being produced with impressive features, including an array of programmable functions and extensive input and output capability for integration with other components and control systems. Additional features may be offered as options. Vector drives, as indicated previously, are one example of enhanced control capability for specialized applications.

In addition, nearly all drives provide some measure of fault logging and diagnostic capability. Some are extensive, and the easiest to use display the information in words and phrases rather than numerical codes.

Environmental Factors: The enemies of electronic components are well known. Heat, moisture, vibration and dirt are chief among them and obviously should be mitigated. Drives are rated for operation in specific maximum and minimum ambient temperatures. If the maximum ambient is exceeded, extra cooling must be provided, or the drive may have to be oversized. High altitudes, where thinner air limits cooling effectiveness, call for special consideration. Ambient temperatures too low can allow condensation. In these cases, or where humidity is generally high, a space heater may be needed.

Drive enclosures should be selected based on environment. NEMA I enclosures are ventilated and must be given room to "breath." NEMA 4/12 enclosures, having no ventilation slots, are intended to keep dirt out and are also used in washdown areas. Large heat sinks provide convection cooling and must not be obstructed, nor allowed to become covered with dirt or dust. Higher-horsepower drives are typically supplied within NEMA-rated enclosures. "Sub-micro" drives, in particular, often require a customer-supplied enclosure in order to meet NEMA and National Electrical Code standards. The enclosures of some "micro" drives, especially those cased in plastic, may also not be NEMA-rated.

Motor Considerations With AC Drives

One drawback to pulse width modulated drives is their tendency to produce voltage spikes, which in some instances can damage the insulation systems used in electric motors. This tendency is increased in applications with long cable distances (more than 50 feet) between the motor and drive and with higher-voltage drives. In the worst cases, the spikes can literally "poke a hole" into the insulation, particularly that used in the motor's windings. To guard against insulation damage, some manufacturers now offer inverter-duty motors having special insulation systems that resist voltage spike damage. Particularly with larger drives, it may be advisable to install line reactors between the motor and drive to choke off the voltage spikes. In addition, some increased motor heating will inevitably occur because of the inverter's "synthesized" AC waveform. Insulation systems on industrial motors built in recent years can tolerate this, except in the most extreme instances. A greater cooling concern involves operating for an extended time at low motor RPM, which reduces the flow of cooling air, especially in constant torque applications where the motor is heavily loaded even at low speeds. Here, secondary cooling may be required.

2.7 Spindle Cooling Systems

Heat is the number one enemy of machine tools. The machine tool spindle is one of the prime sources for generating heat in a machine. Before the introduction of integral spindles, most machine tool spindles were driven via belts or gearboxes attached to a remotely mounted drive motor. For the most part, integral motors have replaced these arrangements. Integral spindles are used on turning centers, machining centers, grinders and most other machine tool variations.

On integral motors, the motor shaft pulls double duty as both the electric motor rotor and the machine's spindle. A cartridge that holds the windings surrounds this shaft. It's a nice clean, compact package that is easily integrated into machine tool design.

However, integrating the electric motor into the spindle creates a heat source that in precision machining applications must be controlled. The cutting tool is in direct contact with the spindle, and as the spindle dimensions change due to thermal growth, the cutting tool's position is affected.

The following figures show how much the temperature influences the dimensions of certain parts of the spindle.

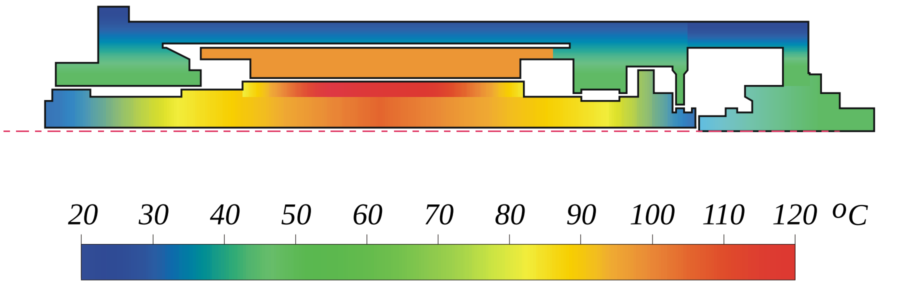


Figure 24. Temperature in Motorized spindle

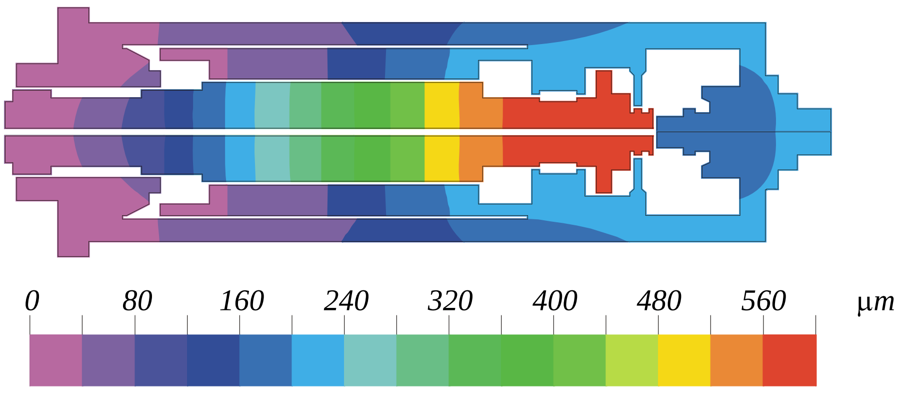


Figure 25. Dimensional thermal effect

This explains why many builders use an active system to stabilize the temperature of the machine spindle. When indirect drive motors were used to run the spindle through a gearbox, the gearbox was directly cooled by oil. Most integral spindles use a cooling jacket around the outside of the stator housing with water or coolant as the cooling medium.

The water jacket that surrounds cylinders in an automotive engine block indirectly removes heat from the combustion chamber. Therefore, coolant would not work inside the cylinder.

Likewise, a spindle cooling jacket indirectly removes heat created by the moving rotor and internal winding that has transferred to the stator. The drawback is, of course, that the cooling media cannot contact the inside of the motor, particularly the ends of the windings where heat is greatest. In addition, the cooling water has to be pumped through a separate heat exchanger, adding to the cost.

Depending upon the spindle design, estimated cooling system capacity can vary. The next charts show informative relations between heat dissipation and cooling water flow quantity:

SPINDLE MOTOR COOLING RECOMMENDATIONS		
Heat Removal Requirements kW	Flow l/min	Inlet Liquid Temp. to Spindle (°C)
5.0	12.0	26 °C
5.5	13.5	
7.0	18.0	
4.0	10.0	
6.5	16.5	
7.5	19.0	
12.5	32.0	

A spindle can be furnished with internal passages for thermal bearing control:

THERMAL BEARING CONTROL RECOMENDATIONS		
Heat Removal Requirements kW	Flow l/min	Inlet Liquid Temp. to Spindle (°C)
0.50	2.0	30
0.75		

Another possible system involves using air as the cooling medium.

This system blows cool outside air simultaneously around the stator and through the motor. It allows for a very effective method of cooling both the inside and outside of the integral spindle motor.

The effectiveness of this system allows the motor to run cooler, thereby generating more power. This system effectively keeps the heat away from the machine resulting in reduced dimensional thermal effects.

The cold outside air is typically sucked through a filter from the rear of the machine through the motor. The exhaust typically goes to the top of the machine, blowing the warm air away from it.

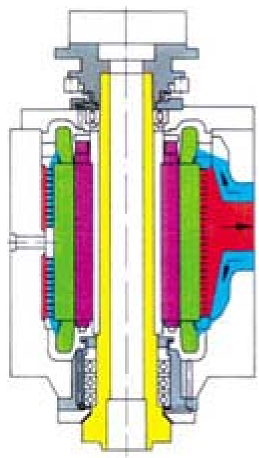


Figure 26. Air cooling

2.8 Seal Types

High precision bearings are quite sensitive to external contamination. Chips, dust, dirt, coolant, and other foreign material polluting the bearing surfaces, result in pre-mature failure, particularly in grease packed bearings.

To protect against this condition, spindle designers utilize some type of seal to prevent contamination from entering the spindle. The simplest type is a contact seal design. But, contact seals are usually not feasible, due to the high speeds. Instead, labyrinth seals are used. A labyrinth seal is a non-contact sealing system comprised of a fixed and rotating part. Both parts have channels and grooves machined into them, so they fit together to form a series of passageways between the spindle bearing and the outside air. It is very difficult for a particle of dirt in the coolant liquid to pass through a labyrinth seal. Labyrinth seals, used in conjunction with positive air over-pressure, provide very good protection for a high speed spindle. Compressed air is directed into the spindle housing at low pressure. The air feeds outward to the front and rear of the spindle, providing a low flow of air. This flow prevents contamination from entering into the spindle.

This is particularly important for motor-spindles, due to a "chimney affect" which often occurs. As a motor-spindle operates, losses in the rotor will produce heat. As the only contact between the rotor and the spindle housing is through the bearings, the shaft will increase in temperature. When the spindle is stopped, the hot rotor will heat the adjacent air, which will rise. This movement of air, as in a chimney, will draw outside air into the spindle, often bringing contamination with it. This can be very damaging if the material being cut is graphite or carbon. A positive air over-pressure will protect the spindle from this effect.

One of the most vulnerable areas in a spindle is near the spindle nose. In this area, the front bearings are very close to the machining area, and are subjected to the coolant splashing and chips. Therefore, it is important to provide an extra measure of care to protect the sensitive spindle bearings.

We have two basic seal types:

1. **Contact seals**
2. **Non-contact seals**

Contact Seals

Only in the case of relatively small diameters and relatively small rotational speed, is it possible to use a contact seals.

The lip of a radial shaft seal must always exert a certain pressure on the counterface to obtain efficient sealing. The friction resulting from this lip pressure is only part of the total friction in the contact and thus of the total power loss at the sealing position. The other contributing factors include

- the type of medium being sealed
- the pressure differential across the seal
- the circumferential speed
- the surrounding temperature
- the lubrication
- the condition of the counterface

Figure 27 illustrates the frictional losses that may be expected when a radial shaft seal with conventional sealing lip is properly installed and fully lubricated.

During the running-in phase for the sealing lip, which lasts a few hours, the frictional losses are somewhat higher.

For the seals intended for high pressure differentials, the losses are generally higher than shown in the diagram. For Waveseal designs, on the other hand, the losses are generally lower than indicated.

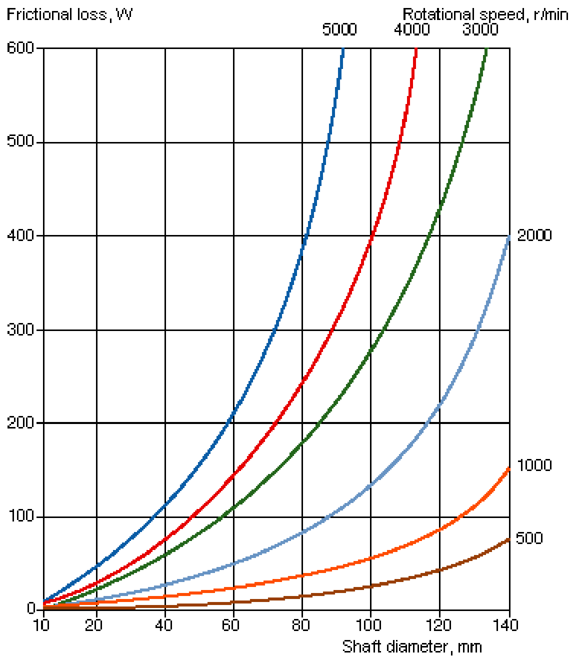


Figure 27. Contact Seal Frictional loss

Permissible speeds

Guideline values for the permissible rotational and circumferential speeds for the different Contact seal designs are given on **Figure 28.**

It will be seen in **Figure 29** that higher circumferential speeds are permitted for large-diameter shafts but not for shafts with smaller diameters. This is because the cross section of the shaft does not increase linearly with the increase in diameter but by the square of the increase in diameter, so that the heat removal capacity of a large shaft is much better than a small shaft. The diagram gives circumferential and rotational speeds related to the material of the sealing lip.

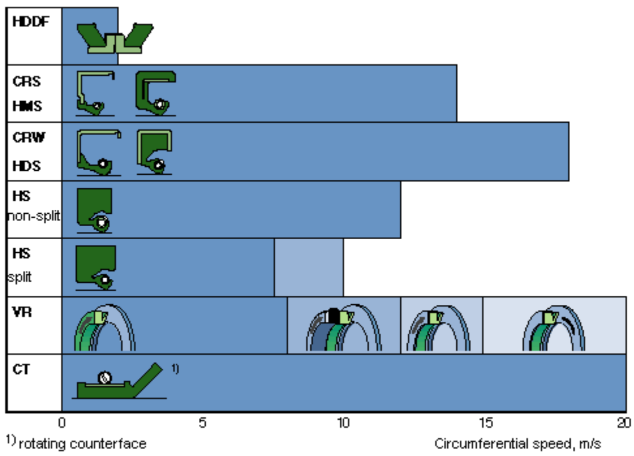


Figure 28. Permissible circumferential speeds for various seal designs

The values are valid for spring-loaded lips which are well lubricated by a mineral oil, where adequate lubricant supply ensures that heat does not build up and where the pressure is the same on both sides of the seal (pressure differential = 0). If in doubt, e.g. when the circumferential speed of the sealing lip is relatively high and there is no experience available in house, it is advisable to consult the manufacturer.

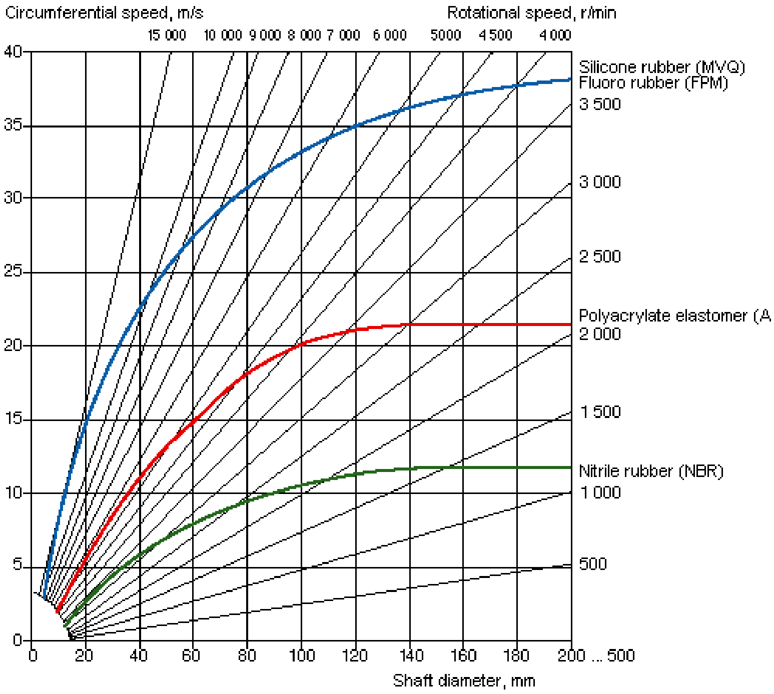


Figure 29.
Permissible speeds for spring-loaded seal lips where no pressure differential exists across seal in operation

The values obtained from Figure 29 should be reduced if:

- Radial shaft seals with a secondary rubbing lip are used
- Lubrication is poor or grease lubrication is used, i.e. when there is little cooling of the sealing lip and poor heat transfer
- The counterface does not meet the demands in respect of surface finish or running accuracy
- There is a pressure differential across the seal

To obtain higher circumferen-tial speeds, it is possible to use Waveseals lip instead of standard straight type edge. The differential between those two types is shown in Figure 30.

The Waveseal design from CR represents one of the most important developments in radial shaft seals during the past 25 years. The sealing lip is pressed and its special form produces a relative movement of the sealing lip on the counterface, imparting hydrodynamic properties. CR Waveseals are suitable for both directions of rotation; they pump the lubricant back into the bearing arrangement and expel contaminants. The sinusoidal form of the sealing lip considerably extends the path on the counterface and at the same time reduces the specific surface pressure in the sealing lip/counterface contact. As a consequence, CR Waveseals produce up to 20% less friction and up to 30% lower temperatures than conventional seals. These advantages prevent the formation of deep tracks in the counterface and provide much longer service lives.

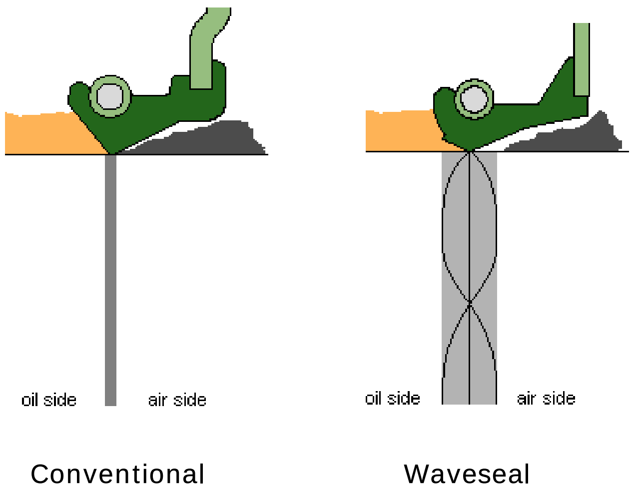


Figure 30.

Table 4.

Comparison of Contact Seals to Non-Contact Seals

The table below shows the most important advantages of Non-Contact Seals compared with lip seals.

Criteria	Lip seal	Non-Contact Seal
Wear	by friction	none
Power loss	by friction	none --> savings of energy --> may lead to smaller driving units
Temperature increase	yes	none
Speed limit	depending on material	none
Live	limited by wear	unlimited
Lubrication	required at the sealing location	no lubrication required for the seal
Mating parts	Hardening and grinding required for the shaft at higher speeds to reduce wear	Hardening and grinding not necessary
Temperature range	limited due to material (plastic or rubber)	from very low to very high - 40° C - 140° C (plastic material) - 40° F - 340° F (metallic material steel + aluminium)
Space requirement	small	formerly large - customer designed labyrinth seals;
Field of applications	Grease lubrication	Grease lubrication
	Oil lubrication	Oil lubrication if oil level below sealing diameter Oil mist lubrication
	water - limited, as water may increase the friction at sealing location	water - with the use of rust proof materials and level below sealing diameter
	fine and coarse granular contamination not possible, as this environment causes rapid wear of the lips	fine and coarse granular contamination can be sealed reliably if applied to horizontal shaft.

Because of the friction, contacting seals will raise the temperature of the system and therefore cannot be considered for the majority of machine tool spindles. Thus, in general, contacting seals are used only where low speeds are involved

dN value below 200.000

and the influence of higher temperature has no important effects on the spindle working conditions.

Non-contact seals

Non-contact seals are the most commonly used arrangements in machine tool applications, even though they are more difficult to manufacture, more expensive and more complex. Some examples of non-contacting seals are shown in the next Figures.

Among the non-contacting seals, labyrinth seals are the most widely used in spindle applications. They make access to bearings and thus contamination difficult, and prevent cutting fluids from entering the bearing area. The main design features of a labyrinth seal, starting from the external side, are: splash guard, narrow gaps, large drainage chamber(s), and if there is adequate room, further gaps and drainage chambers. The splash guard prevents the fluids from gaining access directly to the first gap. The gaps prevent most of the fluid from proceeding further in. The drainage chambers also serve to reduce the velocity of the fluid arising from the rotation of the shaft.

In order to avoid pumping effects inward, the labyrinth components should progressively decrease in diameter from the outside to the inside. Machining spirals than can direct the fluid inwards should be avoided. If the spindle is designed to rotate in both directions- clockwise and counterclockwise- spirals have to be avoided.

Additional protection is achieved by creating an overpressure inside the spindle. This is the case when oil spot or oil mist lubrication systems are used.

Under severe conditions, an air barrier can be created by blowing air into the labyrinth. It is important that the flow is balanced so that the dominant flow is outwards. An air barrier can provide a reasonably efficient sealing even with a fairly simple labyrinth design.

The following is an example of a sealing system.

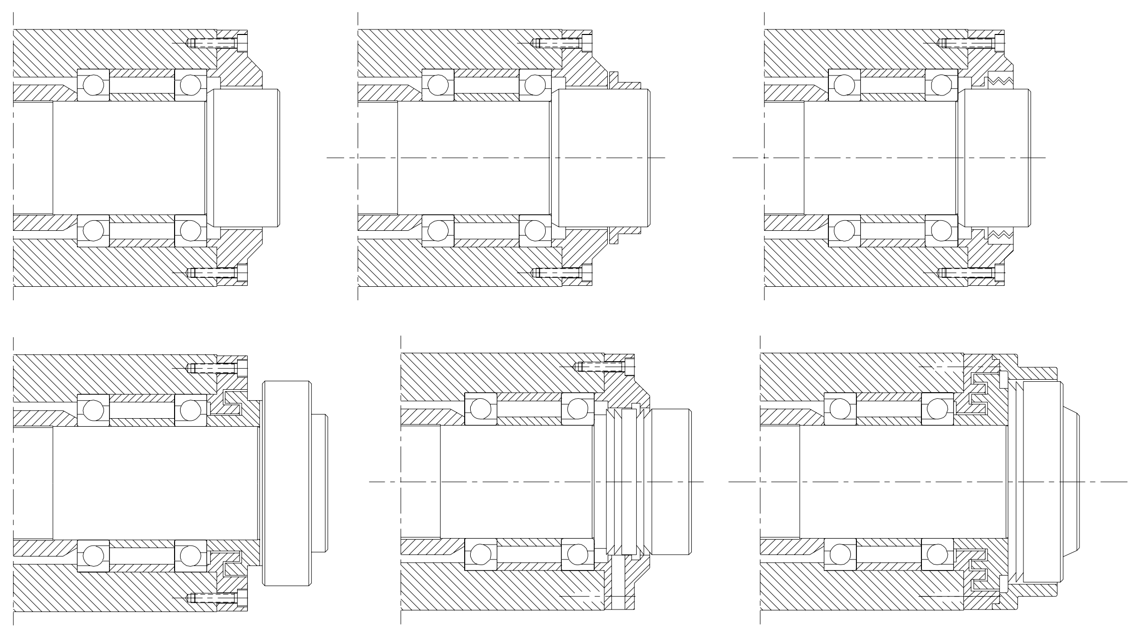


Figure 31. Some examples of non-contacting seals

Preventive stages

The sealing system can be divided into the following preventive stages shown in Figure 32.

1. Direct access to the labyrinth of fluid washing over the spindle housing is prevented.
2. Splash guard, designed as a labyrinth together with the housing cover, throws fluids outward. Both the splash guard and the housing cover are provided with one or several annular grooves to direct the fluid. When positioned on a rotating body, the grooves have little influence during rotation.
3. Gap with a heigh of 0,1-0,2 mm
4. Groove or grooves on the shaft to direct the fluid under non-rotating condition
5. Large drainage chamber where the velocity of the fluid is reduced. The chamber should be relatively large as the amount of the fluid at this stage can be important.
6. Drainage using large outlet area around 250 mm², so that no fluid stays inside the chamber (5)
7. Labyrinth with the gap heights of 0,2-0,3 mm.
8. Chamber for fluid retardation
9. Collector to guide the fluid to the lower side and prevent it from penetrating further
10. Drainage using an area of 100-150 mm².
11. Chamber with collector and drainage as in steps (8)-(10). Very little fluid should be present here and a drainage area of around 50 mm² should be adequate.
12. Gap with a height about 1 mm to avoid capillary action.

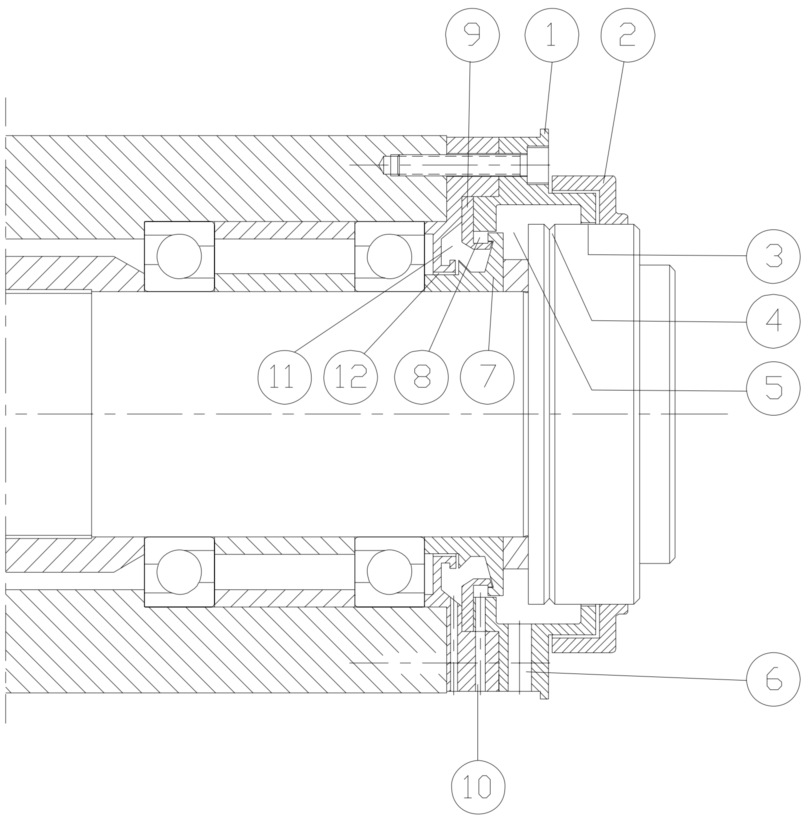


Figure 32. Preventive stages

This design is rather complex and more costly than conventional labyrinths. However if the environmental conditions are severe, a very efficient sealing should be considered. The service life of the spindle will otherwise suffer, and downtime and replacement costs can be very high. A sealing system that takes up considerable space axially is favourable, as large drainage areas and collectors can be designed, thus improving sealing efficiency. However, the larger the space taken axially, the longer the overhang from the front bearing and cutting force position, thus making the spindle radially less rigid.

2.9 Tool Retention System

A high speed spindle designed for use in CNC machines must be able to automatically change tools, which is done by incorporating a tooling system. Common tooling systems include CAT, BT and ISO styles. More recently, a new DIN and ISO tooling standard has been developed with particular application for high speed, known as HSK.

The CAT, BT, and ISO standards are questionable as tooling choices for very high-speed. As these tooling standards were developed prior to high speed cutting, the tolerances allowed do not always match the strict requirements of high speed machining. If one of these styles is used, accuracy, cleanliness, and most importantly balance are very critical issues to consider.

HSK: Characteristics And Capabilities

How HSK Differs From Standard Tool Holders And What Advantages It Offers

Despite its growing use and acceptance in the United States, HSK technology remains widely misunderstood. This primer examines how HSK differs from standard tool holders and what advantages it offers.

Despite its growing use and acceptance in the United States, HSK technology remains widely misunderstood. Questions about its proper use have created substantial resistance among those who are accustomed to traditional, steep-taper shanks, including CAT, SK and BT. Although a significant portion of the machine tools imported to the United States from Europe incorporate HSK spindles, steep-taper shanks still represent the most widely used tooling interface.

The acronym "HSK" is the German abbreviation for "hollow taper shank." An HSK shank has a ratio of 1:10, compared to CAT (BT, SK) shanks that have ratios of 7:24 (**Figure 34, below left**). HSK shanks must be connected to machines by means of compatible HSK spindle receivers. Whereas steep-taper shanks were developed prior to standardization, HSK shanks were developed to address performance problems associated with the traditional interfaces, particularly in high speed machining applications.

After five years of testing, by a working group that comprised educators, machine tool builders, end users, cutting tool manufacturers and standards organizations, the HSK standards were created. The preliminary standards included six types of HSK shanks designated as A through F (**Figure 35, below right**) and a total of 35 sizes. Final standards have now been published for Types A, B, C and D, but the most popular types for high speed machining--Types E and F--are covered by the working group's "preliminary standards."

HSK shanks cover three different application categories. Types E and F are designed for low torque and very high spindle speeds on machines that incorporate ATCs. Types A and C serve applications requiring moderate torque and moderate-to-high spindle speeds. (Type A is for automatic tool changing, and Type C is for manual changing.) Types B and D are designed for high torque applications with moderate-to-high spindle speeds. (Type B is for automatic changing and Type D is for manual changing.)

Figure 34. Comparison of HSK and CAT (SK) Shanks.

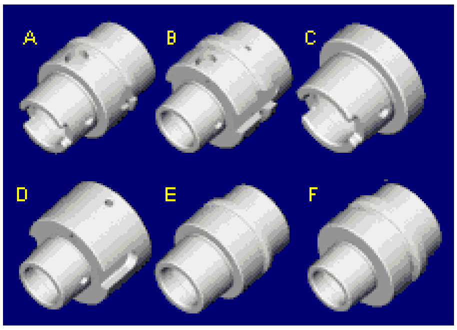


Figure 35. Overview of six types of HSK Shanks, per DIN 69893.

Comparison HSK With Steep Taper

Although HSK has become the primary choice for newly developed machine tools in Europe, substantial scepticism remains in the United States. To alleviate some of this doubt, it is important to explain some fundamental differences between HSK and conventional tooling interfaces.

The first category of comparison is radial and axial stiffness the most important aspects of any machining operation. Unlike conventional shanks, an HSK shank is hollow and the clamping mechanism operates from the inside. The end of a typical, HSK Type A shank incorporates two drive slots that engage milled drive keys in the spindle receiver. The wall of the hollow shank deflects slightly when it's clamped into the receiver. Radial access holes in the shank's wall allow the clamping mechanism to contact an actuation screw. The inner surface of the shank wall also incorporates a chamfer to facilitate clamping.

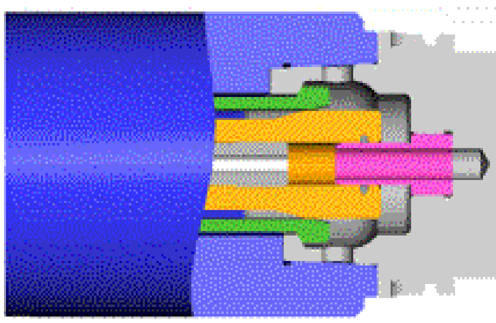


Figure 36. HSK shank clamping mechanism operates from the inside.

Although different clamping methods are available depending on the tooling manufacturer, all HSK receivers incorporate segmented collets that expand radially under drawbar pressure to bear against the inner wall of the shank. Because the collet's chamfer matches the chamfer of the shank's inner wall, the shank is locked securely into the receiver when the drawbar is actuated. When this occurs, elastic deformation of the shank's walls creates firm metal-to-metal contact around the shank, as well as mating the shank's flange with the receiver. (**See Figure 36, above right**.)

Assuming that equivalent force is applied to the drawbar, twice as much clamping force is exerted on the flange of an HSK shank compared to a steep-taper shank. This extra clamping force makes the radial stiffness of HSK tool holders up to five times greater than the value for CAT, SK or BT (**Figure 37, at right**). This makes the tool more resistant to bending loads, thus allowing deeper cuts and higher feed rates in milling and boring operations. Higher rigidity also translates to a higher natural frequency for the cutting system. This allows a tool to be operated at higher speeds before resonance or "chatter" commences. Because tool deflection is reduced, machining accuracy and surface finish also improve.

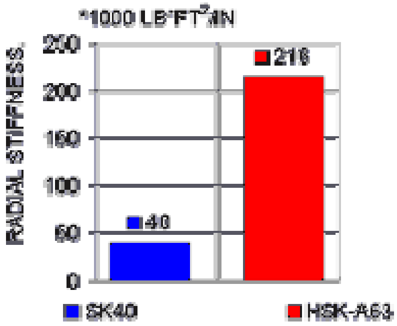


Figure 37.
Radial stiffness of SK40 and HSK-A63 Shanks.

With firm contact between the HSK shank's flange and the receiver, the axial position of the interface remains constant during boring and drilling operations that exert the strongest Z-axis forces. With its stronger clamping mechanism, HSK tooling is also considerably more resistant to pull-out forces than conventional interfaces.

In terms of torsional stiffness, the HSK interface is comparable to the CAT (SK, BT) connection. But HSK transfers significantly greater torque than conventional shanks (**Figure 38, at right**).

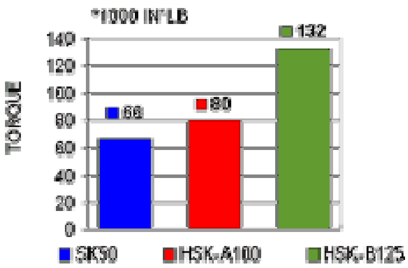


Figure 38.
Torque transmission of SK50 and HSK-A100 and HSK-B125

Regarding accuracy and resistance to tool runout, the HSK interface is equivalent to CAT (SK, BT) in radial accuracy, while providing significantly better axial accuracy. In the axial direction, the accuracy of a CAT (SK, BT) connection can vary up to 0.004 of an inch compared to an HSK shank. This affects the repeatability of machining operations.

Another factor that affects accuracy is tool presetting. With a CAT (SK, BT) interface, variation between the machine spindle and the pre-setter spindle changes the axial position of the tool tip. This is particularly true in cases where bell mouthing of the machine spindle has occurred as a result of wear.

Conversely, the HSK interface (with metal-to-metal contact both radially and axially) maintains a constant tool tip position that does not depend on physical differences between the machine and a pre-setter spindle. As the HSK connection wears during operation, therefore, the tool's rigidity is affected--but not its static accuracy.

The HSK interface also offers some key advantages in relation to high speed machine spindles, tool collisions and maintenance. Using a conventional interface (CAT, SK, BT) at spindle speeds greater than 8,000 rpm, the spindle receiver expands at a much higher rate than the tool holder shank. This causes the shank to be pulled back axially into the spindle under the force of the drawbar. This changes the Z-axis position of the tool tip and often locks up the tool holder inside the receiver, thus making tool-changing difficult. However, the design of the HSK connection prevents the shank from pulling back into the receiver during high speed operation.

When a tool collision occurs using a conventional, steep-taper shank, the potential damage can be considerably greater than when using an HSK shank. Because a CAT (SK, BT) shank is solid steel, most of the collision load (and damage) transfers to the spindle. With its hollow design, however, the HSK shank acts as a fuse during collisions. When a cutting tool crashes, the toolholder breaks off and protects the spindle, thus reducing repair costs and machine downtime.

CAT (SK, BT) spindles may be reground to restore proper performance. Although regrinding must be done by a professional, many companies offer this service. On the other hand, regrinding of an HSK spindle is considerably more difficult, requiring a highly skilled operator, an extremely precise grinding machine and the proper gauging equipment. Because this work is beyond the capabilities of many machine shops, the cost is higher than is true for regrinding steep-taper spindles.

The tool-changing capability of HSK is another improvement when compared to steep-taper shanks. Because of the short length of the HSK taper (approximately one-half the length of a CAT shank) and the lighter weight of its hollow shank, tool changes can be completed more rapidly than is true with conventional toolholders. Part of this time savings results from the fact that the HSK interface does not require a retention knob to clamp the shank.

Variable cutting conditions can adversely affect the CAT (SK,BT) interface. This applies particularly to modern CNC machining centers that are used in flexible manufacturing systems. Under these circumstances, machines may operate at low speed and high torque, as well as high speed and low torque. Because conventional toolholders are clamped from the outside, centrifugal force causes the spindle walls to expand faster in relation to the shank at spindle speeds higher than 8,000 rpm. Consequently, the draw bar force pulls the shank deeper into its receiver, changing the position of the tool tip and frequently locking up the tool.

The HSK interface is not subject to this problem because of firm contact between mating components. This contact is enhanced at high speeds because, as the collet segments in the receiver rotate inside the hollow shank, centrifugal force increases the clamping force.

Additional Performance Factors

In terms of tool balancing, HSK and SK adapters are similar. HSK adapters are normally sold unbalanced but, if balancing is required, the customer should specify this when placing an order. Two methods are used to balance HSK tooling. The first method balances by using a cutting tool to remove excess material from the adapter housing. This method is recommended for heat-shrink tooling, and both the tool and toolholder must be balanced (usually by the manufacturer).

The second method incorporates adjustable components such as screws that allow fine-tuning of the tooling assembly prior to use. Although this method is more accurate, it also requires frequent user intervention to make balancing adjustments.

Both HSK and steep taper shanks allow for use of an internal coolant supply. At spindle speeds exceeding 20,000 rpm, however, internal coolant may destroy the static balancing of the spindle/toolholder assembly. This can occur because of asymmetrical coolant channels in the tooling or by contamination with air and oil. In these cases, using external coolant may be necessary.

HSK tooling is manufactured according to more rigorous specifications than steep-taper tools. One reason for tighter tolerances is because the force of the clamping mechanism improves as the clearance between toolholder and receiver is reduced. As a result of its minimal clearances, the HSK interface requires even greater attention to cleanliness of shank surfaces than is true when using conventional toolholders. HSK tools are also more sensitive to wear than other types of tooling. This means that users must have their own gauging systems or use outside inspection services to control tooling quality. A shop's workforce also must be properly educated regarding the care and maintenance of HSK tools.

2.10 Tool clamping

Tool clamping – Drawbar systems

The spindle must provide a means to house and clamp the toolholder. This is accomplished by machining a taper in one end of the spindle, manufactured to match the appropriate taper angle and diameter required by that tooling specification. In addition, a clamping mechanism must be provided to hold the toolholder in the taper during machining operations. This device, a drawbar, must provide sufficient pulling force to overcome all forces created by cutting that would tend to pull the tool out of the spindle. The most common technique used in drawbar construction is to stack belleville washers to create a long tension ring. The end of the drawbar grips the toolholder retention knob, and holds the toolholder in position in the taper. When a tool change must occur, a hydraulic or pneumatic cylinder compresses the drawbar, and the toolholder is released

SK-Gripper- The optimal universal gripper

Gripper sizes SK 30, SK 40, and SK 50 can be mounted into the OTT universal contour. This allows for grippers of different standards to be used in the same spindle.

Figure 39. SK Grippers

SK Drawbar shaft

OTT-JAKOB has been designing and manufacturing power drawbars for the machine tool industry for over 20 years. Rotary unions and unclamp units in various designs for unclamping of the clamping system and for medium transfer are designed and manufactured.

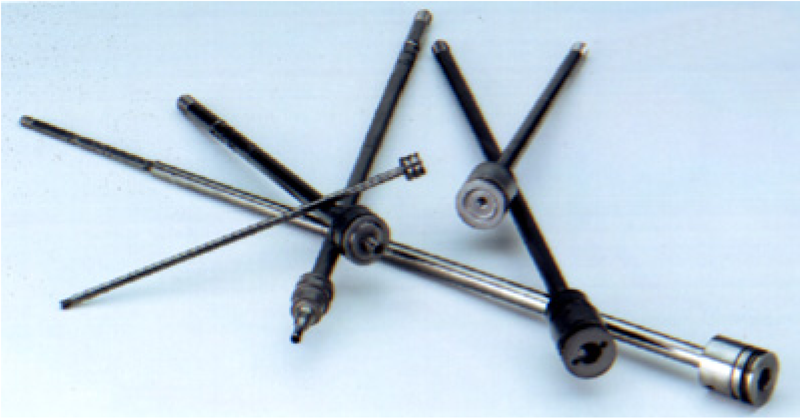


Figure 40. SK Drawbar shafts

HSK Clamping - Principle of force amplification

The geometry of grippers and clamping tapers amplify the pull force. Therefore, high forces occur mainly in the front part of the spindle. The patented HSK-clamping unit offers safety, high pull force and high life expectancy. The axial stroke is converted into a radial/axial movement of the clamping cone towards the gripper segments. This enables the amplification of the spring force. The gripper unit moves parallel, increasing surface contact and constant amplification of the pull force.

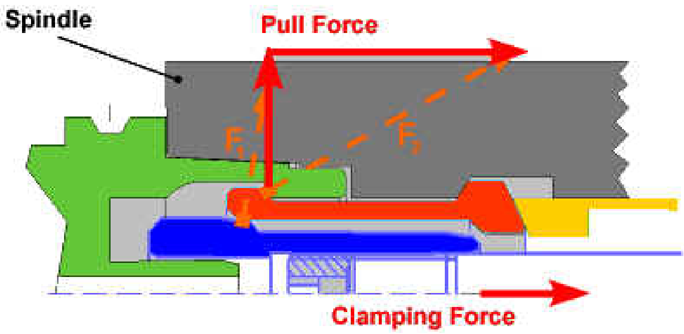


Figure 41. Principle of force amplification

HSK advantage

The HSK-interface shows significant advantages in precision and stiffness compared to the steep taper interface.

- Higher positional accuracy of the tool due to axial face and taper positions
- Ideal for high speed machining. Easy tool handling due to low weight and dimensions of the short tapers.
- Heavy duty chip removal can be achieved through total stiffness of the interface, high pull forces and the resulting transmittable torque.

The automatic interface HSK 25 - HSK 160 are available in 4 forms:

- Form A is the most common tool standard with internal drive keys
- Form B has external drive keys, a larger flange diameter, and is used mainly for heavy duty chip removal
- Form E without drive keys is used for high speed operations

Form F has no sealing against coolant and is used mainly in the woodworking and the plastic industry.

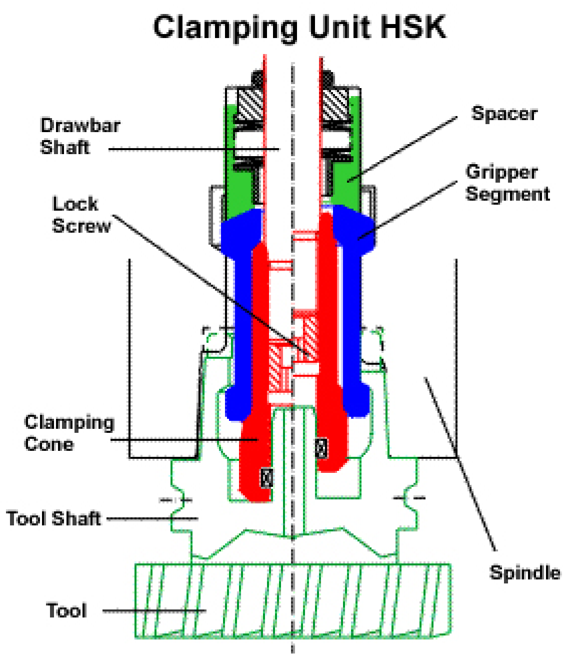


Figure 42. HSK Clamping Unit

Over the past years, thousands of employed HSK units became known for their reliability, long tool life and high precision. Especially the parallel moving gripper segments ensure uniform force amplification and subsequently a 100% reliability of the interface. The spring in the spacer enables the gripper segments to hold tools changed with radial offset clamping units and the necessary contour guarantee perfect sealing of the inside spindle intensifier against dust and coolant.

HSK-Clamping Unit / Design B

- A newly designed coating optimizes the life span 50 times in the case of insufficient lubrication.
- The guiding of the gripper is done by means of a specially formed locating sleeve, which sits the tool directly into the taper.
- New also are the geometry and the coating of the spacer. The position of the individual gripper fingers are securely held and guided to ensure a perfect balance at high speed.

Quickest clamping now depends only on the machine tool control and its software

With regard to spindle design, the drawbar presents some challenges. A drawbar is a movable device, and with each actuation the springs may end up in slightly different locations. This can create a balance problem, which could cause unwanted vibration at high speeds. To overcome this, drawbar components should be manufactured to close tolerances, and with guide bushings positioned internally.

Figure 43. HSK Clamping unit – Design B

Also, as speeds increase, the holding force required also increases. It is not practical to increase the holding force by simply increasing the number of washers, as this would require a longer spindle shaft. It is also not always practical to increase the diameter of the washers, as this may require the shaft to be larger imposing on spindle speed.

Mechanical locking systems

The mechanical clamping system offers the highest pull forces. Special features of the power drawbar are the amplification mechanism for transmission of the pull force and locking the universal spindle's inside shape. The drawbar uses belleville washers to pull the toolholder into the taper. Once seated, however, a mechanical locking system then is actuated. The locking components may be small balls or cams.

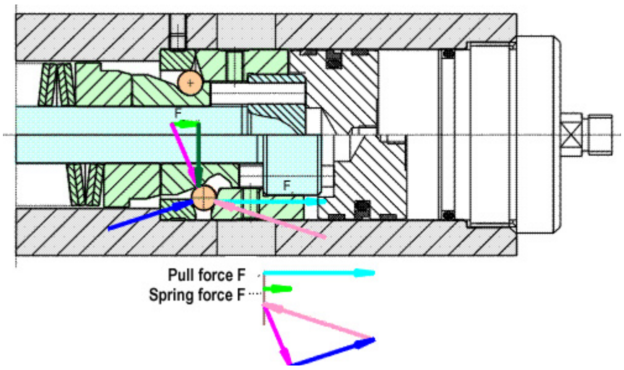
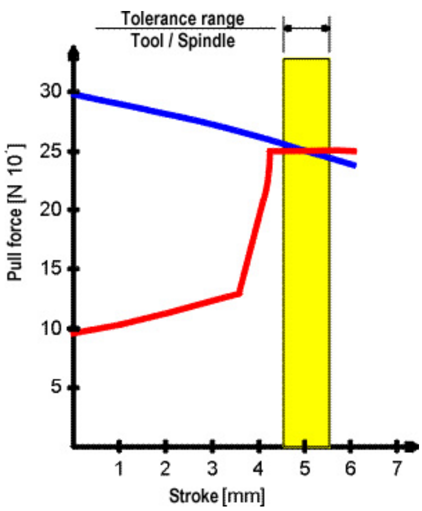


Figure 44. Mechanical locking system

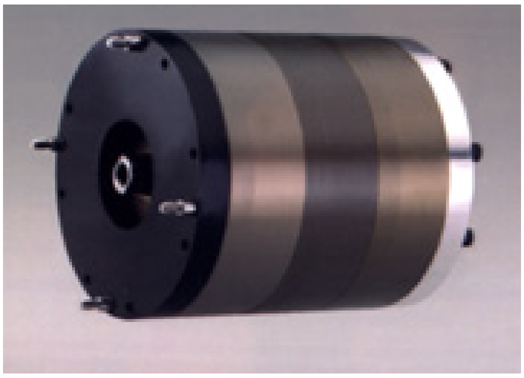


After the locking mechanism is in place, all cutting forces are directed against the solid steel shaft, not against the belleville washers. This system provides very high holding force and rigidity, which is critical to the high speed cutting process.

As the spindle will be used with an ATC (Automatic Tool Change) magazine, it is necessary to have electronic sensors or switches built-in to indicate to the control logic when a tool is clamped, unclamped, or missing. These signals must be derived by monitoring the position of the drawbar.

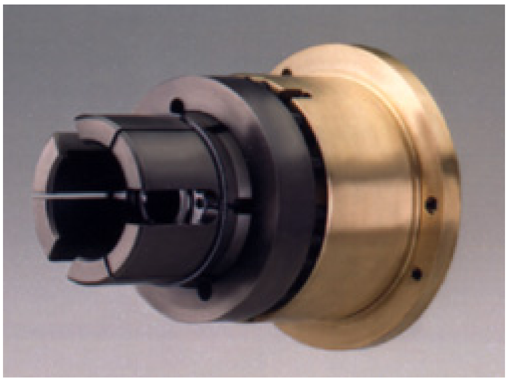
Unclamping Units

Figure 45. Pneumatic unclamping unit



- low bearing load
- enclosed housing
- modular
- RPM independent

Figure 46. Hydraulic unclamping unit



- purge passage
- low bearing load
- easy mounting
- RPM independent

3. Conclusion and Future trends

A high speed Superprecision Spindle Design must take into consideration the desired end result: the required power, speed, torque, tooling system used, accuracy, and life. From this design specification, the needed components can be selected including bearings, shaft design, motor, lubrication system, tooling style, drawbar system, housing and cooling system.

As we have seen, bearings will impact a spindle design to the greatest degree. High speed spindle designs most often run bearings systems up to a predetermined limit, in order to be the most productive. And, as integral motors are limited in maximum torque available, higher speeds will yield higher power. To reach these speeds, and maintain a reasonable life, precision bearings must be used, along with complex bearing lubrication systems. Oil jet or mist systems not only boost the speed of the bearings, they also provide cooling and cleaning functions as well. Maintenance is critical to the performance of precision bearing systems. Positive over-pressure and labyrinth air seals also should be used to protect the bearing environment.

In addition to the bearings, the spindle shaft design must be capable of providing a strong motor, suitable tooling retention system, and stiffness without developing bending problems. And, all rotating components must operate in a balanced condition.

The spindle housing must support and locate the bearings accurately, and provide the utilities needed by the spindle system. It must be robust and stiff, as the housing transfers all forces from the spindle to the machine tool.

In general, a high speed spindle design will be the result of many compromises. Bearing size and type will dictate the maximum speeds possible. Increasing pre-loads and additional tandem bearings will increase stiffness, but speed will be sacrificed High power motors will not fit into the design envelope, and more complex drive systems are required. Higher speeds require higher precision tooling systems, better balance, and cleanliness to obtain the desired results. Shop discipline must be strict. Operators should be well trained and encouraged to learn more about the machine tool.

Future Trends

In the opinion of any spindle designer, the ultimate spindle would have the following characteristics:

1. Unlimited Speed
2. High Power
3. Long Life
4. Self-Balancing
5. Self-Diagnostic

As unattainable as these qualities may sound, they will be fulfilled in the future. High speeds can be accomplished through the use of magnetic or fluid bearings. These non-contact bearing systems will exhibit no mechanical wear, so their life will be very long. Electronic sensors will monitor all aspects of the spindle operation, including cutting loads. Imbalance can be compensated for as the spindle runs. Diagnostic information can be relayed to the CNC for action. Superconducting materials and new motor technologies will provide compact, high power motor system's that produce little heat. Thermal affects on the spindle shaft can be compensated for electronically.

DYNOMAX INFORMATION

1. Corporate Overview

Established to offer manufactures high quality, customizable spindles to meet unique machining needs, Dynomax offers manufacturers the design, manufacturing and service of machine spindles. With more than 400 modular spindles each designed to offer countless options, Dynomax spindles are engineered to accommodate a variety of applications and environments. Offering spindles including belt and gear driven, integral motor, high speed and robotic, Dynomax is dedicated to spindles. An ISO 9001:2000 certified company, our spindles are found in industries ranging from aerospace to stone to medical.

Today, Dynomax operates within a 10,000 sq ft facility that provides the in-house equipment necessary to manufacture and service precision tolerance spindles.

2. Offering Overview

Dynomax's offering can be broken down into three distinct areas, each briefly introduced below.

2.1 Design Offering

As a niche focused spindle design, manufacturing and service facility, Dynomax has insight into all faucets of a spindle's life. We know what it takes to develop a spindle with integrity. Engineering a new spindle to meet a variety of specifications requires combining time-tested theories and new technologies, with careful consideration to practical application, to design a spindle for new or existing machinery.

In addition to designing new concepts, Dynomax, because of our modular designs, can customize standard spindles to meet special requirements without significantly increasing the delivery schedule. Working cooperatively with customers to design spindles that outperform the competition, Dynomax engineers review performance specifications and design limitations before engineering the ideal spindle. Our spindle design process includes:

- Application review/Application consulting
- Spindle Engineering
- New Spindle Design
- Design Approval
- Available finite element analysis (FEA)

Our experience has taught us that a good spindle is one that spins, but a great spindle is one that consistently spins, requires minimal maintenance and is quick and easy to restore when and if the time comes. Dynomax designs great spindles because we know spindles.

2.2 Manufacturing Overview

New robotic arm spindles. Spare cartridge spindles. High speed motorized spindles. When it comes to spindles, Dynomax does it all. Dynomax, an ISO 9001:2000 registered company, has invested heavily in the tools, talent and training necessary to manufacture new high quality spindles.

Dynomax's dedication to new spindle manufacturing has enabled us to better service our customers. Our experience has taught us how to determine the spindle best suited to customer requirements as well as how to manufacture that spindle to perform on the shop floor. We work with our customers to make sure they get the machine tool spindle they want, when they want it!

All new Dynomax spindles...

- Are manufactured to precision tolerances and assembled by trained technicians under controlled conditions
- Complete maximum speed run-in's to ensure the spindle meets performance requirements
- Complete balancing and vibration analysis testing
- Are processed and fully documented under ISO standards
- Come with a 1-year warrantee on craftsmanship and parts

Dynomax spindles are precision machine components. Dynomax has put rigorous standards in place to ensure spindles that leave our shop floor are ready to operate on yours. Dynomax offers more than 400 spindles, offering manufactures a variety of different sizes, styles and characteristics. Each spindle has been devloped to accomidate a variety of applications and tooling, offering our customers countless options.

Our extensive product line includes hundreds of standard spindles, each designed to allow customization with minimal impacts on delivery schedules. Our lines include:

- Block Spindles
- Cartridge Spindles
- Quill Spindles
- Motorized Spindles
- High Speed Spindles
- Robotic Spindles
- Dresser Spindles
- Speciality Spindles

Within each line we have spindles covering a large variety of operating characteristics, tooling set-ups and applications. Details on each spindle can be found on our website at www.dynospindles.com or our experienced engineering staff can help you determine the spinldle best suited to fit your needs.

2.3 Service Offering

Dynomax knows the quickest way back to maximum production is a timely, high quality service. Our step-by-step ISO 9001:2000 documented service processes are focused on detail with built-in quality control measures to ensure precision and quality craftsmanship. Experienced in spindle design, manufacturing and service. Dynomax applies fundamental spindle concepts and proven processes to service, regardless of application, in order to put value back into your machine tool spindle. Whether you need a complete spindle rebuild, a spindle repair or spindle enhancements, Dynomax has your solution. At Dynomax we make the best and repair the rest!

DYNOMAX RFQ

Need a new spindle design?

For quote and more spindle information, please fill out the following and fax us at 847.680.8838 or complete online at www.dynospindles.com/rfq.html.
(If you do not have the answer to a question, please leave it blank and go to the next question.)

Company ______________________________ Date ______________
Name ______________________________ Quote needed by ______________
Address ______________________________ Spindle needed by ______________
Email ______________________________ Customer's Machine: ______________
Phone ______________________________
Fax ______________________________

Type of Spindle *(Check One)*
☐ Belt Driven ☐ Motorized ☐ Other
- ☐ Base Mount
- ☐ Cartridge
- ☐ Flange Cartridge
- ☐ Block Style
- ☐ Other

Application
____
____
____
____

Operation to be performed
☐ Grinding ☐ Drilling
☐ Milling ☐ Boring
☐ Turning ☐ Facing
☐ Other

Axial Load: ______________
Radial Load: ______________
Radial Load (distance from the nose) ______________

Operating Characteristics
Operating RPM
☐ Horizontal
☐ Vertical
- ☐ Nose Up
- ☐ Nose Down
- ☐ Angle to Horizontal ________ °

Rotation of Spindle (Front View):
☐ Clockwise
☐ Counter Clockwise

Coolant
Type of coolant ______________ Pressure ______________

Type of Drive
Motorized:
H.P. ________ RPM ________ Voltage ________ Cycle ________ Phase ________
T.E.L.C. ________ T.E.F.C. ________ T.E.N.V. ________ Other ________
Belt Driven:
☐ Flat Belt ☐ "V" Belt ☐ Timing Belt ☐ Poly "V" Belt ☐ Other

Tooling interface
☐ HSK
☐ CAT
☐ Other ______________

Bearing Lubrication
☐ Grease Lube
☐ Oil Mist
☐ Air/Oil Lube

Define the requirements and any expectations you have for the spindle. Note any limiting factors such space or power.
____
____
____
____
____

Thank you for giving us the opportunity to work with you on your design project. We will contact you shortly.