

SPINDLE PRELOAD MEASUREMENT AND ANALYSIS

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ABSTRACTS

A spindle preload is one of the major factors effecting on machine tool spindle performances. The spindle preload affects its stiffness, rotating accuracy, temperature rise cutting depth and spindle life. The preload force is generated inside of spindle system by negative setting of bearings. We discuss a new method to analyze the preload quantitatively in practical manner.

CONVENTIONAL METHODS

There are many methods which have been suggested and used to monitor and control the machine tool spindle preload.

Dimensional Control method

The dimensional control method is popular method among spindles builders. A set assembly of multi rows bearing and spacer is precisely controlled for major dimensions and internal bearing clearances (end play). The spindle OD is ground matching with the bearing bore to get the exact fitting within one or two μm tolerances. The preload amount is analyzed from the calculated dimensional preload and bearing deflection characteristics. This method may be combined with a push pull checking and/or a natural frequency method. Normally once the bearing set is assembled on the spindle, the preload adjustment is limited. It is normally required to remove bearing from the spindle for the adjustment of the spindle setting.

Starting Torque Method

The starting torque method has been used for long time at machine tool builder as well as machine tool operators for slow spindle speed and/or high stiffness application. The starting torque can be measured by a simple tool, a scale with string. However this is not applicable for a high speed spindle which preload is much smaller. The torque difference can not be detected within the light and precise preload control required for the high speed spindle.

Axial Static Stiffness Method

The bearing deflection curve is non-linear at light load area because of Hertz contact between rolling elements and race ways. The spindle stiffness is calculated by measuring an axial displacement of spindle under a static thrust load. The preload amount is analyzed from the stiffness characteristic chart of the bearing set. This method is commonly used for machine tool spindle builders combined with dimensional control method.

Natural Frequency Method

This method is also common method for the machine tool spindle assembly shop for monitoring preload after bearing are assembled on spindle. A natural frequency is measured by impact hammer method with acceleration sensor on the spindle. The natural frequency is converted to spindle stiffness. Theoretically this should work, when the preload is within the non-linear range of spindle deflection character. However, many cases, a mounting fixture of the spindle would effect on the natural frequency. This makes difficult to analyze the quantitative preload from the frequency. This method is used to monitor the spindle setting by comparing each natural frequency within same model of spindles mounting on the same fixture.

Strain Gauge Method

The preload force is measured as the internal force built up with in the assembly by installing strain gauges on outer spacer of the bearing assembly in the spindle. There are several applications measuring and monitoring the internal preload force with this method. These are mostly academic study purpose application because of complexity of the system.

Issues of the Conventional Methods

All of these methods are an indirect way to measure the preload force except strain gauge method. The accuracy and repeatability are not sufficient to satisfy the requirement of the high speed spindle. There are several sources of major errors with conventional methods.

Dimensional Tolerances

The dimensional control method provides certain range of the preload but the range is far out from the requirement. For example, typical machining center taper 40 spindle bearing, the spindle stiffness would be between 10Kg/ μm and 20Kg/ μm . The targeting preload deviation for the high speed spindle would be $\pm 10\text{Kg}$. This means we would need to control dimensional axial preload within $\pm 0.5\ \mu\text{m}$ to $\pm 1\ \mu\text{m}$. It is impossible to maintain the scatter of the dimensional preload within the range by controlling dimensions of related parts including bearings. Most cases, each component has a dimensional tolerance larger than $1\ \mu\text{m}$. The scatter of a fitting between bearing bore and spindle OD would be within 1 to $2\ \mu\text{m}$ when the spindle OD is ground matching with bearing ID. The effect of fitting deviation on axial dimensional preload is a few times larger in case of angular contact ball bearings. Bearing internal clearance is controlled within $2\ \mu\text{m}$. This deviation will effect on dimensional preload direct. There are many other tolerances involved. Considering all of machining errors in practical world, it is impossible to control the preload for high speed spindle with this method.

Rolling Elements

Another issue is spindle character measurement with static spindle. Rolling elements between the bearing raceways are seated to an appropriate location when the elements are moving. It is squeezed between raceways when load applied at static condition. Once it clamped between raceways, it is not seated in the appropriate location unless the rolling element move. This is common knowledge for bearing industry. This common knowledge is not applied for machine tool spindle application because of inconvenience of measurement with rotating spindle. There are studies and analysis about spindle character based on the stiffness measured under the static spindle. This includes the axial static stiffness method and natural frequency method. The static spindle measurement does not represent the spindle deflection and stiffness character accurate enough for high speed spindle because of the rolling element squeezed effect. FIGURE 1 shows a spindle setting measurement comparing between a rotating spindle and a static spindle. The test is conducted using same spindle measuring 10 times each the rotating and static conditions alternatively to eliminate other factors. The

average of the rotating spindle is $19\ \mu\text{m}$ End Play (axial clearance) and standard deviation of σ is $0.5\ \mu\text{m}$ while static spindle's average is $15\ \mu\text{m}$ and standard deviation of σ is $1.5\ \mu\text{m}$. From the average and standard deviation values, standardized normal distribution chart is generated with $0.2\ \mu\text{m}$ increment. This test indicates that static spindle displacement accuracy can be offset by a few μm with wider deviation range. This magnitude of error is beyond acceptable concerning the high speed spindle preload analysis.

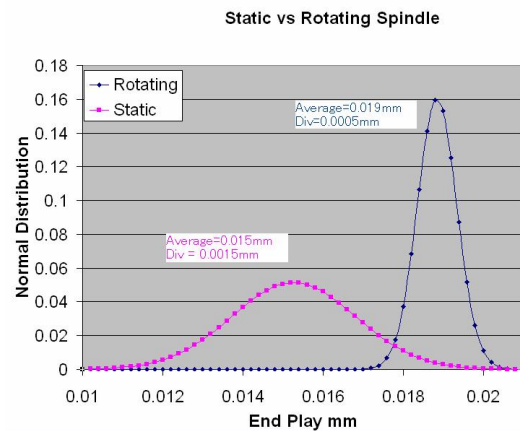


FIGURE 1) Normal Distribution ($0.2\ \mu\text{m}$ increment) of average and standard deviation for Rotating and Static spindle.

Zero Point Scatter

A finding and determination of zero point of deflection curve is an issue to achieve the dimensional preload control with $1\ \mu\text{m}$ accuracy. We can plot the spindle deflection curve on a chart by applying axial loads on spindle and measuring axial deflection of spindle. The determination of the zero point is challenge at the level of the accuracy required. Zero point represents the zero load on spindle at zero displacement of the spindle. Measured data scatter widely at zero point area as example of measured data shows in FIGURE 2. Normally such zero point is determined by human judgment which caused wider range of zero point. There are several reasons for it. One is bearing stiffness become weak at zero load area and small load change generates a large displacement changes. Another is the fact that zero point does not exist while it should be considered as zero zone. The rolling element in the bearing is not necessary to start contact at the same time when a small load applied. This is because of the various dimensional errors of many parts involved as like off square of

housing and/bearing shoulder. A precision machining of housing would cause shoulder off square of a few μm . This causes contact point of rolling elements one by one inside of the bearing.

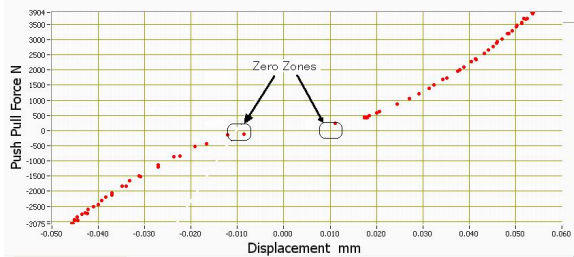


Figure 2) Example of spindle deflection curve. Vertical is axial force and horizontal is spindle axial displacement.

NEW METHOD, MASTER CURVE METHOD

We acquire data for the spindle deflection characteristic curve by applying axial load and measuring axial displacement simultaneously with the rotating spindle. We analyze the spindle setting quantitatively by establishing a spindle axial deflection curve. We defined the curve with zero end play/zero preload as the Master Curve. The Master Curve is generated by an algorithm built in the program.

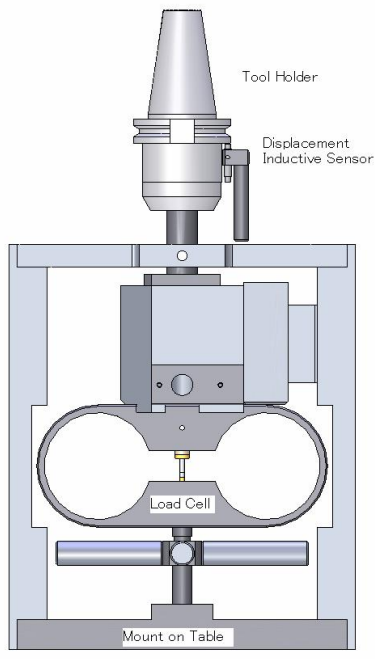


FIGURE 3) Spindle Setting Analyzer Model SC3 unit to be mounted on machine tool table.

Hardware

A bottom frame of measuring unit is mounted on a machine tool table. (Figure 3) The spindle of the unit is connected to the targeted machine tool spindle. A displacement sensor is non-contact type inductive sensor and is mounted on the targeted spindle housing. The axial load is measured by a load cell located just behind the spindle unit. The load is applied by changing the distance of the 8 figured load cell spring. The distance of the spring is measured by LVDT which is installed in the load cell unit. The distance can be changed by a handles with a thread jack in the unit or changing distance between the table and the spindle. Analog voltage signals are converted to digital signal and transferred to portable PC through PMCIA DAQCard. The measuring unit spindle is supported with tapered roller bearings lubricated by grease.

Analysis Program

We have developed a new PC program for the data acquisition, analysis and simulation. The measured data and analysis result is instantly available at the machine site. It displays a graphic of spindle deflection curves on screen which help visually understand the spindle characteristics. The program can simulate the deflection curve at any setting conditions. This is a good visual tool verifying the analysis result as well as comparing with targeted setting value.

Principle of analysis

The data spots locate wider in displacement direction (X axis) than the Master Curve for the spindle with end play. The total displacement difference represents the amount of the end play. (Figure 4) The displacement data spots locate narrower than the Master Curve for the preloaded spindle. (Figure 5) The total displacement difference between the Master Curve and data spot represents the dimensional preload. From the Master Curve Character, we can convert the dimensional preload to a preload force. We named this measurement and analysis as the Master Curve Method.

Master Curve Generation

There are two ways to generate the Master Curve. Both cases, the Master Curves are generated by an algorithm in the program from measured data. First method is by measuring an endplay spindle. The program determines the zero point from the data according to an algorithm. This provides repeatable and

consistent analysis result eliminating the zero scatter errors. The Master Curve is generated subtracting the analyzed endplay portion. (FIGURE 4) This Master Curve method provides the most accurate analysis result. A drawback is we need to prepare a spindle with endplay in advance to measure the preloaded spindles.

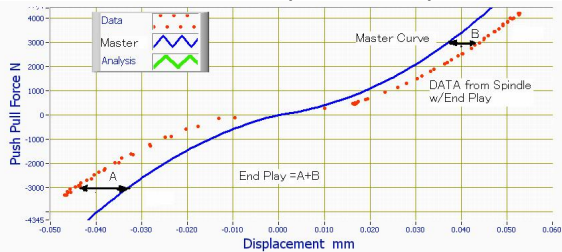


FIGURE 4) Master Curve generation from Spindle w/End Play

The second method is generating the Master Curve automatically just after data is acquired. The curve is called as Temporally Master Curve (TMC). (FIGURE 5) This is applicable for spindles axial stiffness higher than 10Kg/μm. The TMC is generated by an algorithm built in the program. The algorithm generates it based on the stiffness analysis of high load ends assuming it locates outside of preload range. This portion of data represents a portion of original Master Curve. It is important to apply a load high enough to reach the out side of preloaded area at both push and pull sides. The TMC can be generated for the most of spindle taper 40, 50 and higher or HSK 63 and 100 or higher applications as today. This is convenient method since it is not required any preparation of Master Curve and the analysis result is available just after the measurement.

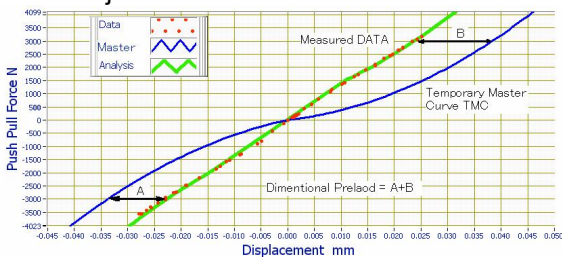


FIGURE 5) Temporally Master Curve Generation from Preloaded spindle DATA

There are many components involved for the spindle axial deflection character. It is a combination of components like bearing, spindle, housing, cap plate, bolts etc. The Master Curve Method includes all of these factors by utilizing the measured data for each

model. It represents the character of the spindle system. The Master Curve character can be utilized not only for the preload analysis but also for a spindle characterization in general.

Applications

We can utilize this new method on existing machine tool spindle by simply mounting a loading unit on a table, a displacement sensor on housing and connecting two spindles by a collet chuck. (FIGURE 6) The measuring time is normally about a minute. The spindle speed is 1,000 rpm. This unit can be used many purpose by measuring and analyzing quantitative preload for an inspection, a maintenance, a machine performance monitoring, a field services and a R/D applications.

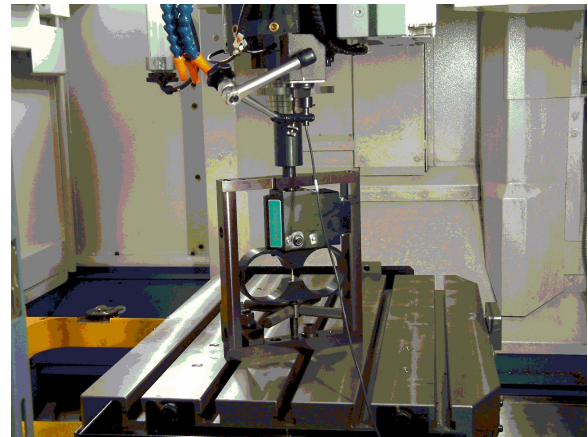


FIGURE 6) Mounting the Spindle Setting Analyzer on Vertical Machining Center

The program includes many features for user's convenience. One example is the analysis for a spring or hydraulic preloaded spindle. (FIGURE 7) The program analyze the cross point of the spring deflection and spindle deflection curve to determine the spring preload amount.

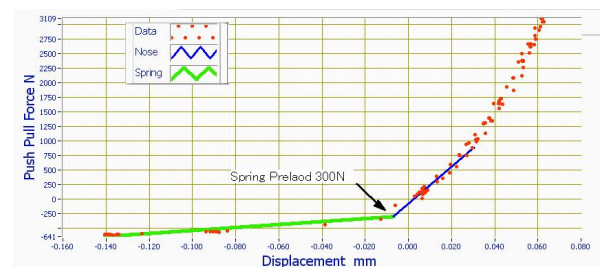


FIGURE 7) Measurement and Analysis of Spring Preloaded Spindle