MEASURING METHODS AND THEIR APPLICATION FOR DIAGNOSIS OF MACHINE TOOL SPINDLES

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Abstract:

Over the last years a gradual but nevertheless sustained increase in the production of machine tool spindles can be observed, especially for the needs of the automotive as well as aerospace industry. Along with this trend an increasing demand for maximum precision of spindles as well as their long-term reliability is evident. It is therefore necessary for the producers and users of these machines to monitor the quality of spindles. As for the producers, it is paramount that they manufacture products of high quality and in this way minimize both the financial loss incurred by complaints from customers and the loss of good reputation. As for the users of these machines, it is necessary that they maintain the required precision parameters in manufacturing and that they are able of suitable planning of their machinery maintenance. The requirements for the geometric quality and surface roughness are today commonly in the order of micrometers. Consequently, it is necessary to adjust machine tools and their components, especially spindles, to these requirements. The goal of appropriate assessing of the quality and the capability of long-term reliability of the spindle with a high standard of precision can be achieved only on condition of adequately accurate check. The following article describes a method and a measuring system which meets the above-mentioned requirements using a combination of several measuring methods and careful analysis including statistical evaluation. The basis of the method described is careful measurements of spindle vibration on the stator part of the spindle together with measurement of the arbor movement by means of proximity contactless probes. The arbor is clamped into the rotor of the spindle. Next, temperature in several places on the spindle and the rotating speed is measured including the angular position of the rotor. The data obtained in this way are subsequently analyzed using a variety of methods. The results are both scalar data and data depicted in various types of graphs. Using statistical methods, it is possible to determine limit values for miscellaneous types of spindles. These values can be compared with a next spindle under the test and can be plotted and highlighted in the report. The described method has been applied to a test rig developed in the Research Centre of Manufacturing Technology (RCMT) in cooperation with a producer of spindles and machine tools. The test rig is being used for final inspection of spindles in day-to-day operation. The presented article also includes a case study which demonstrates the practical applicability of methods used.

Keywords: (Final inspection; spindle; error motion, diagnostics, geometric accuracy of axes of rotation)

1. INTRODUCTION

In the first part, the paper sets out to briefly describe a tried and tested method used for quality measurement of machine tool spindles. The method, called Geometric accuracy of axes of rotation, (GAAR) uses non-contact measurement of spindle shaft movement. In the second part, a tailor-made test rig for final inspection of precise grinding spindles is presented. The test rig uses not only the mentioned GAAR method, but also methods of vibration and temperature testing. In the final part, a case study is presentedwhich demonstrates very good applicability of the test rig and the analysis used for the detection of issues concerning spindles. s

2. GEOMETRIC ACCURACY OF AXES OF ROTATION - TERMINOLOGY

2.1 Main error motions being analyzed

Total error motion TEM

It is a raw error motion which is recorded. It consists of the synchronous error motion and asynchronous error motion of the spindle and structural error motions.

Synchronous error motion SEM

It is a portion of total error motion which occurs at integer multiples of the rotation frequency. The SEM is calculated by synchronous averaging of all measured revolutions i.e. by averaging the values of TEM in every particular angle position of the rotor.

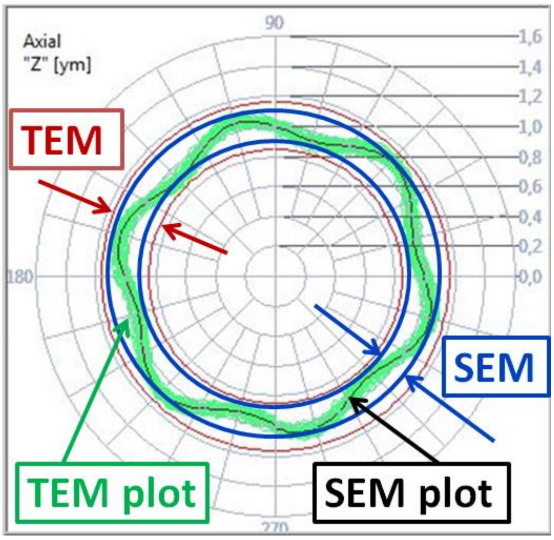

Fig. 1: Synchronous error motion AEM

The synchronous error motion is then calculated as a difference of the radii of two concentric circles – inscribed and circumscribed around the synchronously averaged orbit. The center of these circles is determined by the least squared circle (LSC) method from the synchronously averaged orbit.

Asynchronous error motion AEM

It is a portion of the total error motion that occurs at frequencies other than integer multiples of the rotation frequency. The AEM is evaluated as the maximum width of TEM measured (before averaging).

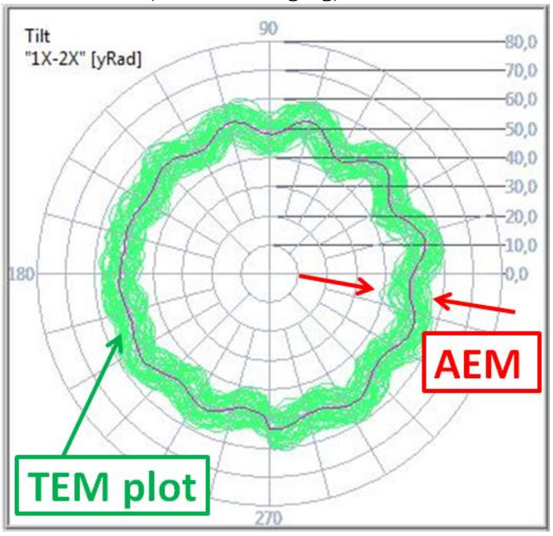

Fig. 1: Asynchronous error motion AEM

Residual synchronous error motion RSEM

It is a portion of the synchronous error motion which occurs at integer multiples of the rotation frequency other than the fundamental.

Fundamental error motion

It is a portion of the total error motion which occurs at the rotation spindle frequency.

Rotating sensitive directions RSD

These tests are performed in radial directions and they are suitable for machines that machine in a rotating sensitive direction such as drilling, boring, contour milling, contour milling etc.

Displacement sensors are positioned in one plane perpendicular to the axis of rotation. The angle between the sensors is 90 deg. The measuring artifact is centered, and an encoder or speed sensor is used in order to determine the precise angle of spindle tilting. A mandrel with deliberately increased eccentricity may be used as an alternative to the encoder. Revolutions and the phase angle is then picked up from the sinusoidal signal measured by displacement sensors. The registered sinusoidal signal is then phase shifted by 90 deg between sensors.

Radial error motion is identified from the record of radial displacements of the spindle rotor as a function of the spindle angle position related to static reference measured by two mutually perpendicular displacement sensors. Error motion is then determined using the formula

Fixed sensitive direction FSD

These tests are performed in radial directions and they are suitable for machines that machine in a fixed sensitive direction such as turning, cylindrical and surface grinding , certain types of surface milling etc.

Error motions in a direction perpendicular to the measuring direction of the sensor are not evaluated because they generally do not affect the machined surface quality. An exception is for example turning of small parts where even a small motion in the tangential direction may lead to a change in the diameter of the turned part. In such a case it is necessary to use the RSD method.

Polar graphs for RSD and FSD are not the same despite appearances. In the case of FSD measurement the value corresponding to the spindle angle position is generated using a computer or oscilloscope. The rotor angle position is identified from the encoder, eccentricity of the measured artifact or speed sensor. This means that FSD polar graphs express the motion of the rotation axis just in one direction (sensing direction of the appropriate sensor). Motion measured in this way is mathematically wound on an artificial circle, whose particular points represent rotor angle tilting. On the other hand, in the case of RSD the polar graph expresses a motion of the rotation axis in a plane (perpendicular to the axis of rotation). It means the RSD polar graphs represent a combination of the measured values from two mutually perpendicular sensors. In compliance with the ISO 230-7 standard several most important error motions (AEM, SEM, TEM) are evaluated.

Axial direction

Similar measurements are performed in the axial direction. They are evaluated in the same way as FSD measurements except the FSEM. In the axial direction the FSEM is really important contrary to the radial measurements because in this way it carries information about spindle condition. Therefore FSEM is evaluated separately every time the axial direction is measured. Unlike the radial direction measurements it is very important for the measured mandrel/ball (as well as the sensor) to be concentric with the axis of rotation.

Tilt

It is also possible to evaluate the tilt of the rotating axis. This analysis uses previous measurement in the radial directions. By means of this measurement it is possible to determine whether the source of error motion comes from front or rear bearings.

3 GEOMETRIC ACCURACY OF AXES OF ROTATION - METHODOLOGY

3.1 Mandrel (artifact) for proper measurement

At the beginning of GAAR tests it is necessary to clamp a precise mandrel into the spindle for all measurements. The mandrel may have the shape of a precisely ground cylinder or it may have the shape of a sphere in the place of measurement. Based on measurement requirements, the mandrel may be configured for measurement in one plane perpendicular to the axis of rotation or in planes that are some distance apart. This distance is dependent on the size of the main (front) bearings of the tested spindle. The mandrel for measurement in two planes is equipped with two spheres whose pitch corresponds to the distance of the mentioned measuring planes. Alternatively, the mandrel with spheres can be replaced by a cylindrical mandrel with ground and polished bands with a corresponding pitch. Due to its simplicity and therefore mechanical robustness, the mandrel with cylindrical surfaces is especially used for measurements of high speed spindles of approximately 50,000 rpm and higher. As another alternative to the previous mandrels, it is also possible to use a different shape of the measuring mandrel such as a disc with a ground face for measuring the tilt of a spindle rotor.

Mandrels with spherical surfaces are preferred because of insensitivity to rotor tilt during rotation. If mandrels with cylindrical surfaces were used, this phenomenon could lead to an incorrect evaluation of the rotor movement as an ellipsis instead of a circle. This effect would appear as the second harmonic of rotating frequency in the FFT spectrum. It is also necessary for the mandrel or more precisely its scanned surface to be of high quality. It is especially circularity which is a key parameter for correct measurement and subsequent evaluation. Therefore circularity values are in the order of tens of nanometers. Measuring mandrels in any form (cylindrical, spherical, two-spherical etc.) will be denoted in our text as a measuring artifact.

3.2 Measurement conditions and parameters

In compliance with the ISO 230-7 standard all measurements are carried out in three speed levels of 10%, 50% and 100% of the maximum speed. If it is not possible to set up 10% of the maximum speed, the minimum speed is chosen. It is necessary to warm-up the machine sufficiently before each measurement. The time of the warm-up procedure varies according to the type and size of the machine. 10 minutes for 50% of the maximum speed of the machine is given as the recommended minimum value in the ISO 230-7 standard.

It is necessary to carry out relevant measurement for each rotating speed. In order to meet repeatability conditions, it is necessary, in the case of spindles, to measure a minimum of 20 revolutions each time, from which individual types of errors are subsequently evaluated. In the case of spindles with ball or cylindrical bearings, it is recommended to measure an even higher number of revolutions – up to several hundred according to the above-mentioned standard. It is possible to divide such a high number of revolutions into a smaller number of e.g. 50 and next to average the resultant values of evaluated errors (AEM, SEM etc.). The averaged values are markedly more stable. This way, random events are eliminated and the measurement has significantly more repeatable results.

2.4 Nest for displacement sensor mounting

According to the type of measurement it is necessary to mount suitable displacement sensors into a special nest. The nest is clamped either to the machine table or to the spindle front face. It is important for the nest carrying sensors to ensure their correct position and enable convenient and precise sensor setup. A key property of the nest is also its stiffness of the clamping. If the stiffness of the clamping is insufficient, it may lead to imprecise measurement due to nest vibrations and subsequent incorrect evaluation. It is therefore advisable to check this parameter before each measurement.

3.3 Displacement sensors

Displacement sensors have to meet the following high requirements:

- High accuracy (in the range of fractions of micrometers depending on the spindle being monitored)
- Wide frequency range (the sampling frequency should be 100 times higher than the maximum rotor rotating frequency)
- Thermal stability
- Insensitivity to non-homogenities of the target
- Insensitivity to electromagnetic disturbance
- Insensitivity to grounding (especially in the case of measuring rotors with ceramic bearings)

4 TEST RIG AND ITS CAPABILITIES DESCRIPTION

The test rig has been developed in order to provide the capability of identifying the quality of newly produced spindles and to store important data about them. The test rig consists of a mechanical part and a measurement part.

The mechanical part consists of a fixing plate, a positioning mechanism with noncontact proximity transducers. The fixing plate is ready to carry every type of produced spindles. There are about 80 different types of spindles in production. The positioning mechanism makes it possible to set the proximity transducers in two translation directions and in one rotating direction. For precise adjustment of proximity transducers, there are five parallelograms with setting and arresting screws. All the mechanical parts are mounted on a heavy cast-iron plate which lies on four spring vibration insulators. See Fig. 3.

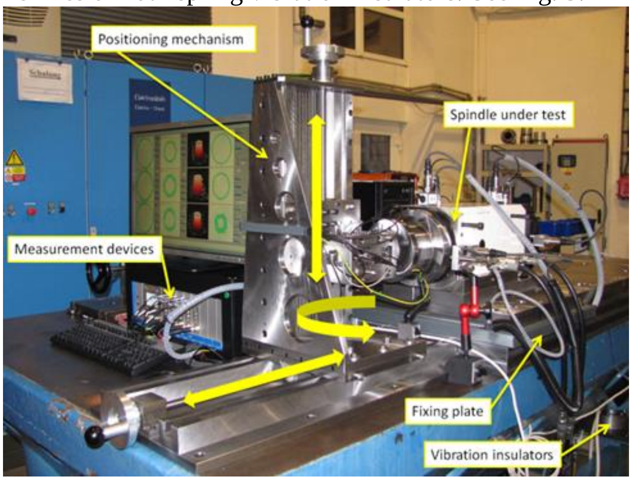

Fig. 3: The test rig in the plant

The electronic part consists of a case with data acquisition hardware, transducers and a computer. To assess quality of the spindle, its parts and quality of assemblage, the test rig is equipped with only highly precise sensors, accurate data acquisition hardware and a powerful computer. All signals are evaluated by specialized software, which has been custom-made at RCMT at CTU in Prague.

On the test rig there are 5 capacitive displacement sensors, 6 accelerometers, 4 thermometers and a tachometer. See Fig. 4. The proximity probes are used for the measurement of geometric accuracy of axes of rotation according to the ISO 230-7 standard.

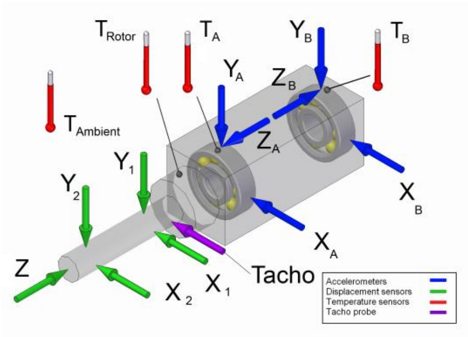

Fig. 4: Scheme of sensor application on the test rig

A measured target is an arbor clamped to the rotor of the spindle. Measured surfaces of the target are made in very high precision. It means that roundness cannot exceed 50nm. On the test rig vibration measurement is performed as well. In case of precise spindles it is common to use more than one bearing at both sides of the spindle. It means there are usually one, two or more pairs of bearings in the front and one or more pairs of bearings in the rear side of the spindle. Accelerometers are attached on the spindle case close to each bearing group. Since accelerometers have to be quickly removable, they are attached via magnetics pads. Vibration is measured in three axes, two radial directions X, Y and one axial direction Z. See Fig. 4.

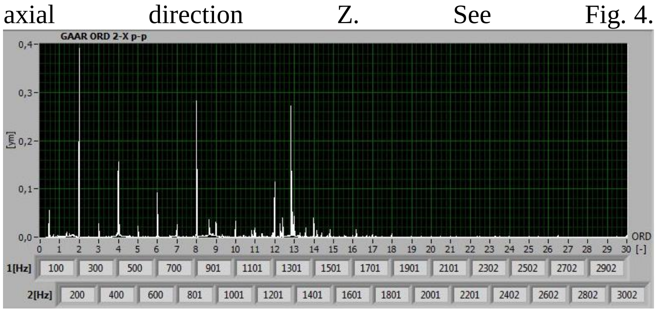

Fig. 5: Order analysis with corresponding frequencies

Measurement of temperatures is also important. There are four thermometers on the test rig. Two of them measure temperature at the case above bearings, one measures ambient air and the last one measures rotor temperature by a non-contact IR way. It was decided to measure rotor temperature in this way because of bad possibilities of rotor cooling. Therefore it is expected that temperature increase can be faster at the rotor then on the other parts of the spindle.

There are two basic approaches how to measure the quality of new spindles. The first one is spindle measurement in a static way or during very slow rotation. This approach has been used for many years and gives answers about spindle stiffness and provides some basic information about the quality of spindle assemblage and production. By using the static approach, it is not possible to reveal all the errors which can be included in such precise spindles. Therefore it is necessary to perform measurement whilst the spindle is rotating in working speed. Since the new test rig has been developed, it is possible to do so and to improve knowledge about spindles, to minimize failures and hopefully to extend their durability. All the measurements are performed after spindle warming up procedure.

The measurement sequence is divided into three parts according to spindle speed. Measurement is carried out at speeds of 10%, 50% and 100% of maximum spindle speed. It is possible to make a measurement at 10% and 50% of the speed in a cold state of the spindle as well.

When those test are finished, another two tests are pending. These tests are called run-up and coast-down analysis. They are usually shown as a waterfall or contour graphs. See Fig. 6. Run-up and coast down analysis is a very useful tool for finding resonances, bearing frequencies, their multiples and interactions with resonant frequencies or modulation of some harmonics of the rotor speed.

4 CASE STUDY OF MEASUREMENT ON THE TEST RIG

Before setting up the test rig at the plant, the test rig was used in RCMT to test its capabilities. During those tests some important spindle behavior was revealed. Some self-excited vibrations were observed during run-up and coast-down even during constant speed running. In quiet conditions the self-excited vibrations were even audible. Since the vibrations were presented even during free coast down, it means without electricity power, it was easy to exclude an influence of an integrated engine or some electrically generated noise. The self-excited vibrations were detected at one or two separated frequencies. In some cases the excited frequency is very sharp without any other excited frequency. See Fig. 6.

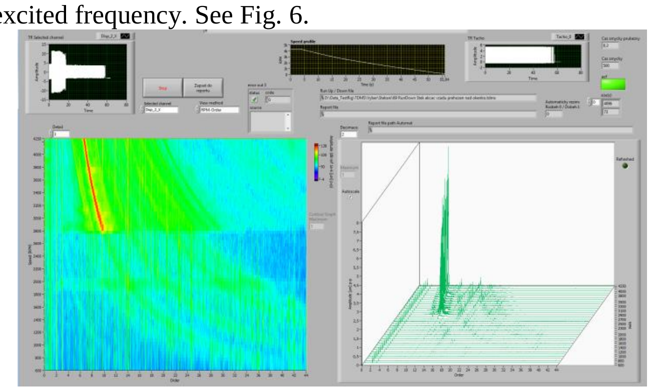

Fig. 6: Coast-down order analysis with continuously self-excited vibrations - measured by displacement sensors.

The excited frequency is about 480Hz, the running speed started at the speed of 4300 rpm. By switching off the power, the spindle speed started falling down in a free-way so the measurement of cast-down analysis started. The vibrations were excited from 4300 rpm to the speed of 2800 rpm. The excited frequency did not change during the whole time. In some other cases but at the same spindle, the self-excited vibrations occurred at frequencies of 370Hz and 480Hz together. See Fig. 7. There are four red fields which belong to the vibrations of the mentioned frequencies, but the excitation occurred at different running speeds. It started at the speed of 2600 rpm and stopped at 2100 rpm, then started again at the speed of 1800 rpm and finished at the speed of 1200 rpm. In some more important cases of the coast-down the vibration starts and stops even more often.

It means that the vibration excitement is independent of the speed. It is necessary to say that every test was performed at the same temperature of the spindle, without changing any condition.

In contour graphs it is possible to find bearing frequencies. They are shown as vertical lines between 8 to 12 multiple of running speed. Resonance frequencies as well as self-excited frequencies are shown as a rectangular hyperbola.

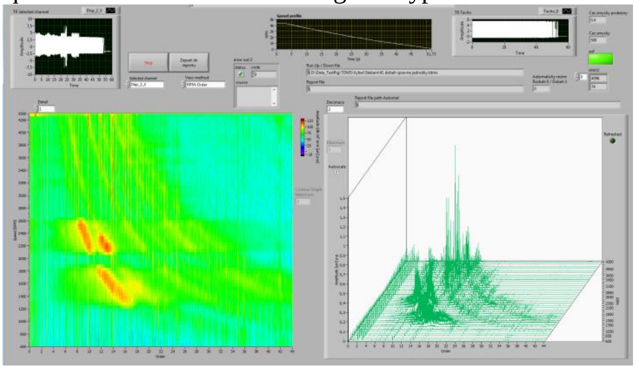

Fig. 7: Coast-down order analysis with intermittently self-excited vibrations - measured by displacement sensors

Very interesting information comes from the analysis of geometric accuracy of axes of rotation see Fig. 8. The difference between the state with and without the self-excited vibrations is very nicely visible. The speed of the rotor is the same on both sides of the figure. It was 2600 rpm. In the first case the asynchronous error motion is 0.2(0.5) um and in the second one it is 4.0(6.8) um. Both are related to the method which is called rotating sensitive direction (the bottom row). They are based on vertical and horizontal directions all together. The upper two rows are evaluated by the FSD method. It means that the orbits are based on an only probe.

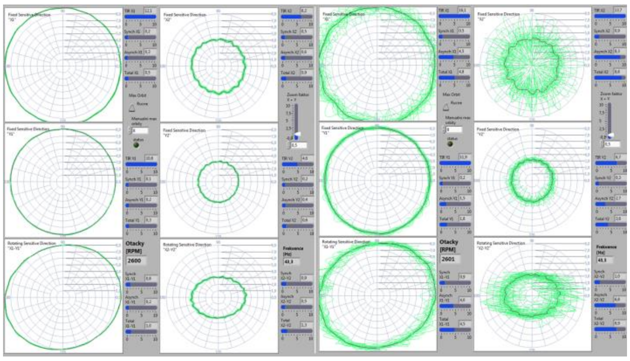

Fig. 8: Comparison of the state without self-excited vibrations (on the left side) and with the self-excited vibrations (on the right side).

It can be seen that the main movement of the rotor is not circular but ellipsoidal. It is probably caused by different stiffness in these two directions. It is even more expressive when self-excited vibrations start. The vibration movement mostly lies in a horizontal direction. It is quite visible in the right bottom graph of Fig. 8. Since the graphs in the upper row belong to the horizontal movements, the orbits there are bigger as well.

After finishing all the tests the rear bearings were replaced by new ones. Unfortunately, the old bearings were damaged during disassembling, so it was impossible to check their condition. After changing the bearings a new coaxial alignment of the whole spindle was performed and the self-excited vibrations dismissed. Since the vibrations were independent of the speed, it is unlikely that the bearings were the main source of the vibrations. At the time of writing this text the phenomenon was not explored satisfactorily. Hopefully, there will be a chance to investigate the problem more.

5. CONCLUSION

The methods used, especially the Geometric accuracy of axes of rotation, do not represent new methods of spindle testing. In its preliminary form, GAAR was developed more than 50 years ago by Prof. Tlustý. The important matter is the fact that contemporary machines with high speed spindles and high accuracy requirements need appropriate measurement equipment and software. These allow us to exploit the required information and to extend the traditional methods. Another task is to perform a satisfactory measurement in a very short time, which is determined by high productivity demands in current plants. To fulfill the mentioned requirements, only new computerized and automated methods with appropriate mechanical arrangement can be successful.

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