ERROR MOTION ANALYSIS OF MACHINE SPINDLE UNDER LOAD

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The present paper deals with a novel approach to the analysis of machine tools under load; it identifies the parameters of machine tool spindles simulating a real cutting process. The main focus of the paper is on evaluation of synchronous and asynchronous error motions and their dependency on spindle speed and load. To investigate the errors, a hydraulic load unit is used. This unit exerts a uni - or bidirectional force located between the spindle and the machine table. Behaviour of the load unit was also investigated. For the purposes of simulating a real cutting process, working conditions between 500 - 5000 rev / min and loads in the range of 50 - 500 N were analysed. Results can be used for evaluation of spindle parameters, prediction of machining accuracy and improvement of the cutting process.

KEYWORDS

Spindle error, measurement, load unit, spindle modelling

1 INTRODUCTION

Machine spindle rotates either cutting tools or the workpiece, transmitting the required energy to the cutting zone for metal removal [Abele et al. 2015]. Therefore the spindle is a critical part of the machine tool and its parameters define to a large extent the machining quality. However, its motion is associated with many sources of errors which result in surface waviness and often in workpiece damage. These errors also have a significant impact on wear and degradation of cutting tool.

Error motions can be divided into short-term error motions and long-term spindle thermal drifts. Error motions correspond to degrees of freedom and can be divided into radial, axial, and tilt errors. Radial error motions are measured in X and Y directions located at a specific axial distance on the Z-axis. The axial error motion is the error motion collinear with the Z-axis [Castro 2008]. Tilt error motions are angular changes relative to the Z-axis in the XZ and YZ planes.

Generally, error motions can be synchronous or asynchronous in relation to spindle rotation. A synchronous error motion consists of harmonics that occur at integer multiples of the spindle rotational frequency; therefore they can be found by averaging the measured data. An asynchronous error motion occurs on other frequencies. Figure 1 shows the result of error motion measurement in the form of a radial plot. The asynchronous error motions can be determined by subtracting a synchronous error motion from the measured data.

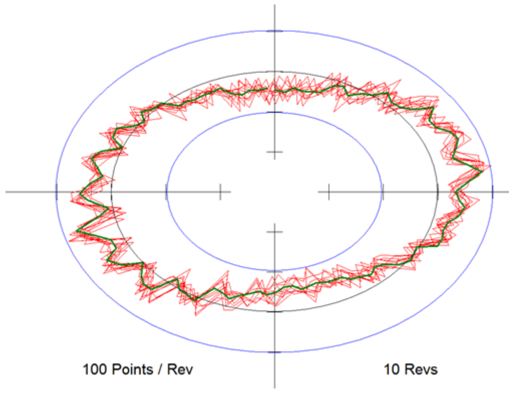

Figure 1. Radial plot of synchronous (green) and asynchronous (red) errors [0.5 µm/div.]

Error motions in their nature alter in time. To calculate error motions, the number of revolutions and the sampling frequency must be defined. These two parameters can significantly impact the results. Further, artefact eccentricity should be excluded from results. With the known value, eccentricity can be easily subtracted; otherwise, Fast-Fourier Transform or other optimization methods must be implemented.

Identification of geometric and kinematic errors and prediction of accuracy behavior of vertical lathe are described in [Holub 2014]. A new concept of a universal measuring stand, developed for monitoring of the headstock error motions in relation to changing load conditions, is dealt with in [Holub 2011].

[Castro 2008] identifies radial and axial error motions based on interferometric method. The spindle was evaluated without load. A high-precision sphere is in this case used as an optical reflector. [Matsubara 2014] investigated dynamic stiffness of the spindle using a non-contact magnetic loading device. This device provides swept-sine-wave load and the spindle displacement is measured with eddy-current sensors. The load is estimated both from the coil current and the dynamometer. The results showed to be dependent on the device and dummy tool temperature.

Stiffness measurement in radial direction in the end milling process using four eddy-current sensors is described in [Sarhan 2015]. This system is implemented directly on the spindle unit. The work investigates the impact of temperature on the spindle stiffness and finds out that in this case the temperature increase has a negligible impact on spindle stiffness.

Displacement measurement of a subtle part by conventional contact methods is difficult because auxiliary sensing devices mounted on this subtle part would increase the weight of the measured part resulting in degradation of the measurement results. In contactless optical methods only the intensity of the light reflected from a moving surface is measured and calibrated in terms of distance. [Kotek 2014]

The method described in this paper was first presented in [Holub et al. 2015]. The paper deals with identification of stiffness under different machine operation conditions, between 500 - 5000 rev / min and loads in the range of 50 – 500 N. The measurement method is suitable for evaluation of both spindle stiffness and stiffness of the machine structure. Subsequently, the acquired stiffness is compared with Multi-body system analysis.

2 TASK FORMULATION

A great deal of emphasis is placed on running accuracy of machine tool spindles. Therefore, suitable measurement and inspection method are necessary during their entire life cycle.

Although measurement methods of spindles under load have been published, most of them are too complex to be regularly implemented in practice and standard procedures still identify spindle parameters in unloaded state. However, this does not represent cutting conditions and results diverge from the real machining. Furthermore, some defects do not have to be seen.

A novel load unit for testing the spindle under load was first presented in [Holub et al. 2015]. This unit can be easily implemented on different types of machine tools. The aim of this paper is to analyse the error motions under different load conditions using the load unit. The emphasis is placed on synchronous, asynchronous and total error motions because these errors have a significant impact on machining quality. The parameters to be studied are spindle speed and spindle load. Furthermore, a survey of impacts of the load unit itself on the results should also be considered.

Concerning small milling machines, depending on depreciation of the tool, cutting force ranges from 300 to 800 N, passive force from 50 to 150 N and normal force from 250 to 500 N. In the case study, further conditions are cutting speed of 35 m/min, displacement speed of 140 mm/min, feed per tooth of 0.05 mm, radial width of the cutting edge of 16 mm, axial width of the cutting edge of 2 mm, milling cutter with a diameter of 16 mm and workpiece material with a diameter of 1. 8159.

The maximum load capability of the unit was estimated as follows: 1000 N and 2500 rpm. Based on the specified cutting conditions, the spindle load in the test varies between 0-500 N and spindle speed between 50 – 1550 rpm.

3 DESIGN OF MEASUREMENT

The design of the load unit is shown in Figure 2. The unit is arranged for loading and evaluation in two perpendicular directions in order to identify error motions of the spindle under multi-axial static load. However, a different configuration enables evaluating a displacement in the machine spindle itself or in the entire machine. Another configuration allows evaluating the static stiffness or the stiffness during rotation with predefined load. Tilting around the X and Y axes and axial movement in Z axes can also be measured. .

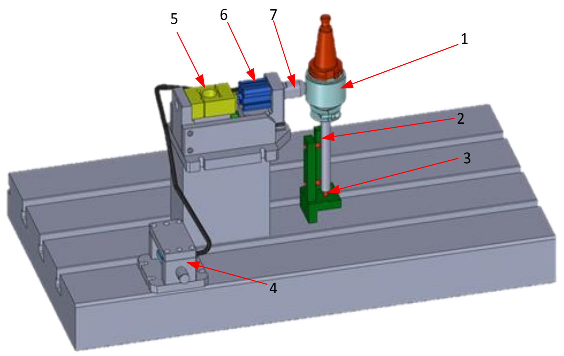

Figure 2. Design of measurement

Generally, it is difficult to apply constant impact force to a running spindle (Matsubara 2014). In this case, the external force is acting over a precise ball bearing (1). The force of the load unit (6) can be controlled through the pressure exciter (4). The load unit is directly linked with a tensor unit (5) and a contact pin (7). Displacement in the X, Y and Z axes is measured on a high precision double-ball artefact (2) by proximity sensors (3).

For the purpose of this work, the unit is set only in an uniaxial configuration (Figure 3). Displacement of the artefact is measured using two sensors; however up to five sensors can be arranged in parallel with the machine coordinate system.

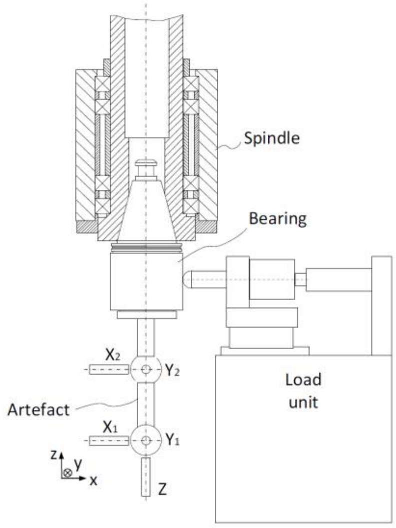

Figure 3. Principle of evaluation method [Holub 2015].

Proximity sensors can be of an arbitrary type. However, because of the size of artefact and high static and dynamic resolution, capacitive sensors were preferred for this test.

The unit was used on a three-axis machine tool (Figure 4). The machine spindle is constantly preloaded and designed to use the following bearing configuration – the angular contact ball bearing at the front of the spindle, the cylindrical roller bearing at the rear.

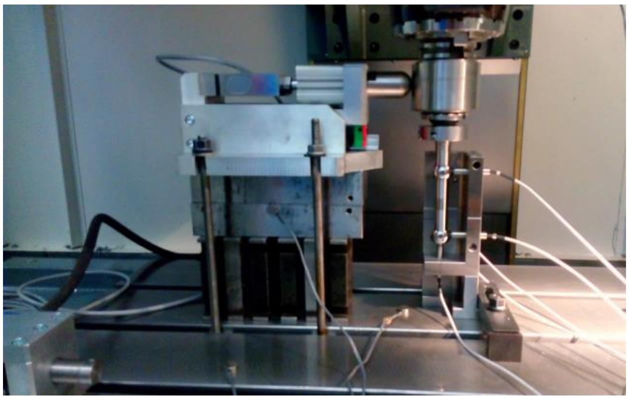

Figure 4. The load unit used on a machine tool

4 RESULTS

The test was carried out in order to analyze the error motions of the spindle under load. First, it was necessary to analyze the impact of the acting ball bearing on the error motions. During the test, the acting force was recorded. The observed variance was almost negligible relative to the absolute value and most probably did not influence the results. The force remains constant due to damping in actuator hydraulic system and the precise ball bearing used in the design

Figure 5 shows asynchronous error motions, which are partly random and are related to surface quality of a machined part. The diagram represents an asynchronous error in relation to the acting load and spindle speed.

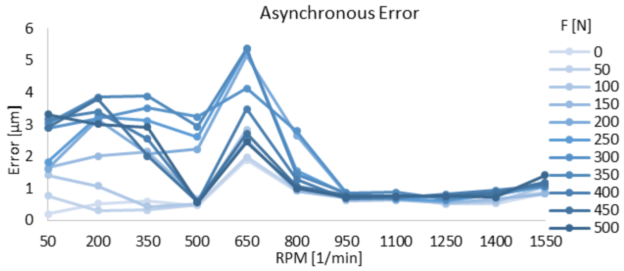

Figure 5. Dependency of asynchronous error on spindle speed and load

The results demonstrate a relatively high dispersion of values for speeds under 950 rpm independently of the acting load. On the other hand, the lowest asynchronous error motion showed the run with no load. For speeds higher than 950 rpm, the identified curves became stabilized with a moderate increase.

The peak at 650 rpm corresponds to the resonance frequency and is presented in all data regardless the acting load. Clear evidence of dependency of asynchronous error on the spindle speed or acting load was not confirmed. Nevertheless, to be certain to disprove this relationship, more sample tests should be appropriate.

Synchronous error motions are errors that result in workpiece waviness. Dispersion of identified synchronous motions is improved considerably compared to the previous asynchronous motions (Figure 6.). Dependency of error motions on spindle speed is evident. If there were no resonance peak at 650 rpm, it would be almost linear. On the other hand, the acting force had no obvious impact. Unloaded spindle had the lowest number of synchronous error motions.

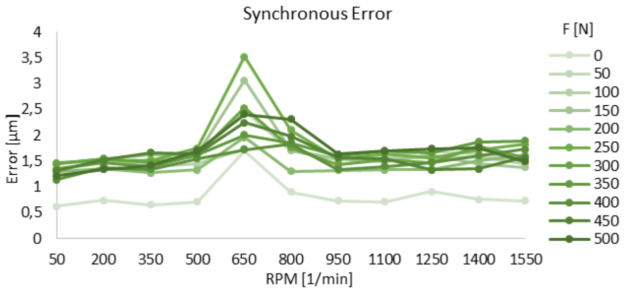

Figure 6 Dependency of synchronous error on spindle speed and load

A total error motion is an overall identified deviation in spindle revolution (Figure 7). Basically, it embraces both previous error motions. Due to a substantial contribution of asynchronous error, the data cannot offer any new information.

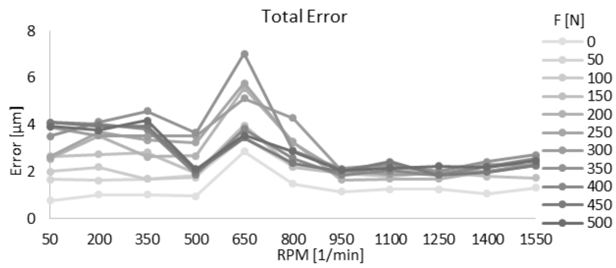

Figure 7 Graph of resulting total error based on spindle speed and load

5 CONCLUSIONS

The introduction describes the significance of measurement and identification of geometry errors of the spindle. These errors do not refer only to the quality of the spindle, but can also be used for diagnosis and estimation of production accuracy. Commonly used assessment of spindle run without load does not correspond to actual conditions, and therefore it is important to measure the spindle run under load.

To simulate the load, a novel method was applied that effectively simulates the load initiated by the machining force. This method is easily applicable to different types of machines and can be used for various operating conditions. Scanning of spindle run was carried out by sensors in two orthogonal directions X and Y. In addition, according to the configuration of sensors, the axial error and tilt can also be recorded.

The test of the unit was performed on the three-axis machine tool under the conditions that correspond to the real machining.

The results of asynchronous error showed a large variance of up to 950 rpm. The results did not show the dependency of errors on load size or speed. The influence of these parameters is probably, due to the rigidity of the spindle, negligible. Synchronous errors increased almost linearly with speed. Dependency on the load has not been proven.

The very method of error evaluation could affect the results - notably the calculation setting – a sampling frequency of scanning and how many revolutions are necessary for calculations. Setting of these parameters depends on speed. In further work it would be useful to analyze the setting.

A change of the load force detected during the test was negligible; however, to completely exclude its influence, another experiment would be desirable.

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