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METHOD FOR SAFE EXPERIMENTAL TESTING OF MACHINE TOOL USABLE SPINDLE POWER

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Abstract

The regenerative chatter during milling is a consequence of the machine tool dynamic compliance and the specific setting of the cutting process. The basic request on the machine structure is to enable a stable cut with dominant portion of the installed spindle power. In order to improve the dynamic properties of newly-designed machine tools, the machine tool structures are optimized using various advanced simulation methods and are made of various advanced materials. The final design should be tested experimentally. The test of usable spindle power provides important feedback on the machine tool design. The testing of large machine tools is time consuming due to the significantly varying machine dynamic compliance dependent on the working space. Due to the installed high power and large diameter tools used, the occurrence of chatter might be dangerous with a high risk of machine tool damage. The article presents a method for the safe and time-effective experimental testing of the machine tool usable spindle power. The method is based on the experimental identification of the cutting force coefficients and the experimental identification of machine tool behavior with the support of extrapolation models based on identified experimental data. The dynamic compliance is measured within a rough network of measurement points in the machine working space. The measured dynamic compliance results are characterized by a model based on modal identification data. Only a few cutting tests are done for the cutting force coefficient identification. Finally, a map of the usable spindle power is calculated. This approach makes it possible to calculate the results with respect to the real machining process and the current machine tool conditions across the whole working space in an acceptable time. The approach is demonstrated on a real case study.

Keywords:
Machine tools; Dynamic compliance; Chatter; Milling stability; Spindle usable power

1 INTRODUCTION

Chatter is undesirable effect of interaction between the machining process and machine tool dynamic properties. The resulting self-excited vibration can damage the workpiece, the tool or even the machine tool. The main mechanism of the chatter occurrence based on the regenerative principle was described by Tlusty and Polacek [Tlusty1957] and Tobias and Fiswick [Tobias1958]. The stability limit calculation for face milling is based on the real part of dynamic compliance determined at the end of the tool, engagement conditions, number of tool teeth and specific cutting force. This basic theory has been later improved in partial knowledge by various authors, see the review [Altintas2004] and recent summary [Altintas2020] and [Zhu2020].

The dynamic compliance characterizes the tool and machine tool dynamic behavior. This compliance can be obtained by experimental measurement, simulation or a combination of measured data and simulated tool geometry [Schmitz 2000, Schmitz2001, Park2003].

The specific cutting force characterizes the workpiece material and the real cutting-edge geometry. The Kienzle model [Kienzle1952] or mechanistic model [Altintas2012] can be used for the specific cutting force description. The specific cutting force is influenced by various parameters, e.g., the average instantaneous uncut chip thickness, cutting speed, tool wear [Kolar2015], applied cooling emulsion, etc. Due to this reason, operational methods for the in-process identification of the cutting force coefficient are used. Dunwoody [Dunwoody2005] proposed the identification of the tangential cutting force coefficient using spindle motor power. Aggarval [Aggarval2013] proposed an improved model based on detailed analyses of power losses during machining. Janota [Janota2019] demonstrated an operational method for the identification of the specific cutting force during milling based on the ratio of the active spindle power and removed material volume. Hänel [Hänel2019] used this in-process approach for the creation of a digital process twin for process optimization.

The dominant volume of published work is focused on chatter prevention and suppression for improving machining productivity expressed by the metal removal rate [cm^3/min]. However, the identification of the stable cut limit is also important for an evaluation of the machine tool design quality.

The machine tool structures are made of various materials and are optimized using various advanced simulation methods [Möhring2015]. The final design is tested in virtual space, e.g., with a predictive calculation of the metal removal rate. The basic request on the machine structure is to enable a stable cut with a dominant portion of the installed spindle power. Such experimental testing of the usable spindle power is one of basic tests of machine tools. However, this test is not standardized therefore the machined materials, used tools and cutting condition range are not unified even within a single company. Wagner [Wagner2012] presented an approach for the systematic improvement of the machine tool properties based on a combination of machine tool structure optimization and machine tool performance testing using a standardized machining process. The approach is demonstrated on medium-sized machines using an end mill with a diameter of 24 mm.

This paper follows the idea of [Wagner2012], but the implementation is done on a large-size boring machine. There are some drawbacks related to the large size of the machine: The dynamic compliance of the machine depends on the kinematic position and machining at more working space positions is time demanding. Specific cutting force coefficients may vary depending on the engagement conditions and the tool tip state. Due to the installed high power and large diameter tools used, the chatter occurrence might be dangerous due to the high risk of machine tool damage.

This article presents a method for the safe experimental testing of machine tool usable spindle power. The method is based on the experimental identification of the process and machine tool behavior with support of simulation using a model identified from experimental data. The dynamic compliance is measured within a rough network of measurement points in the machine working space. Only a few cutting tests are done for the cutting force coefficient identification. Finally, the usable spindle power is calculated using a model based on the experimental data identification. This approach makes it possible to calculate the results with respect to the real machining process and the current machine tool conditions across the whole working space in an acceptable time. The paper is organized as follows: The method is described in section 2. A demonstration of use is presented in section 3. The advantages and limits of the method are discussed in section 4.

2 METHOD DESCRIPTION

The test of machine tool usable spindle power is done using a specific process setting. In general, the tool type, cutting parameters and engagement parameters are defined with respect to the expected typical machine tool operation. The usable spindle power is determined during the test. There are two possible results: a) the maximum of the installed spindle power is reached, i.e., the usable spindle power is 100% of the installed spindle power; or b) a stable cut limit is reached, i.e., the usable spindle power is less than 100% of the installed spindle power.

The method for safe experimental testing is presented as a flow chart in Fig. 1. The test conditions are defined at the beginning: network of measurement points, cutting tool and cutting conditions. The network of the measurement points can be two-dimensional or three-dimensional: it depends how the dynamic compliance of the machine tool is changing with the kinematic position of all movable axes.

The experiment consists of two tasks. First, the dynamic compliance at the end of the tool is measured at a rough network of the measurement points (marked in orange). Then, machining tests are conducted on a few points of the network (marked in blue) for identification of the stable cut limits. The spindle power is recorded concurrently during every machining run.

The experimental data are processed: the dynamic compliance model is built using the modal identification of the measured FRFs [SchmitzSmith2009]. The cutting force coefficient K_C is calculated using the recorded spindle power signal and volume of removed material [Janota2019].

The dynamic compliance model, identified cutting force coefficient and tool engagement information are used for the calculation of the stable cut limit [SchmitzSmith2009], [Altintas2012]. This result is validated with the experimental data at a few points of machining (blue points).

The dynamic compliance model makes it possible to calculate the dynamic compliance on the refined mesh of calculation points. The stable cutting depth across this refined mesh is calculated. Subsequently, the spindle power consumption for stable machining in the whole working space is calculated using the calculated limit of the axial cutting depth. As the last step, the machine tool performance is evaluated within the working space.

The method is demonstrated on the case study in the following section.

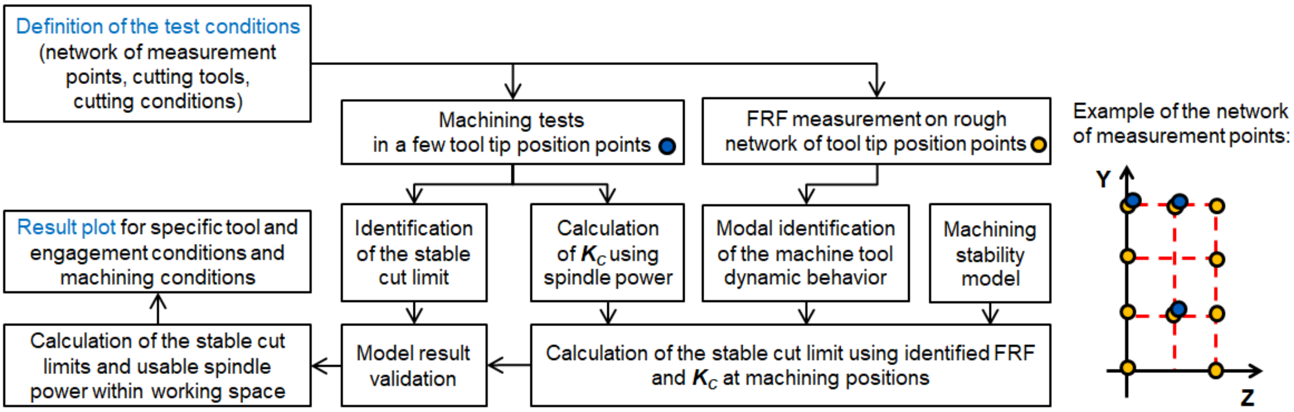

Fig. 1: Flow chart of the proposed method.

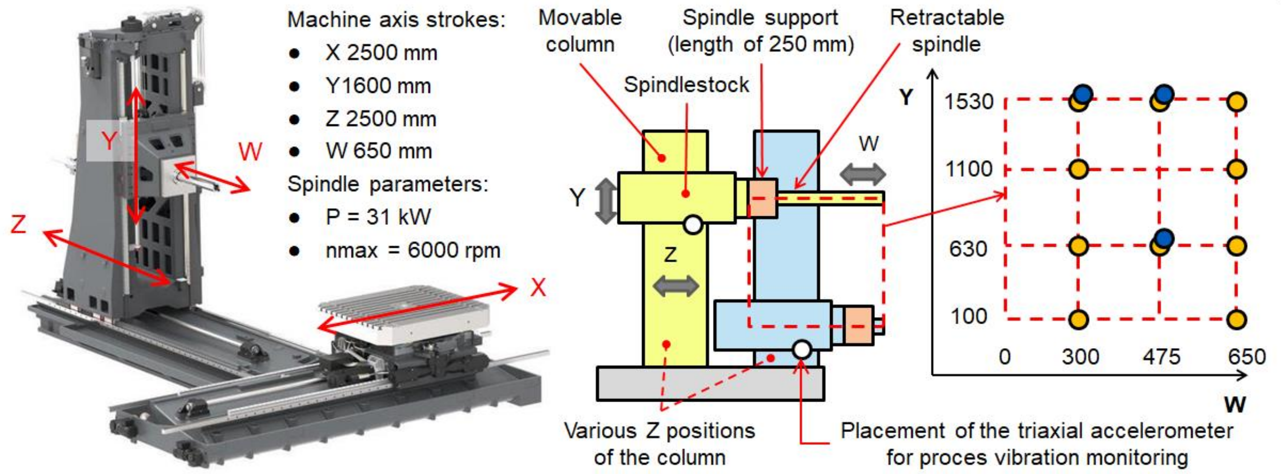

Fig. 2: Structure of the tested horizontal boring machine (left), schematic 2D picture of the machine tool (middle) and network of measurement points for various Y axis and W axis positions (right).

3 DEMONSTRATION CASE STUDY

3.1 Main experiment parameters

A horizontal boring machine with a table diameter of 1250 mm and retractable spindle with a diameter of 112 mm was used for the method demonstration. The machine has a spindle with power of 31 kW. The machine structure and strokes of the movable axes are presented in Fig. 2.

The workpiece was blocks of C45 carbon steel clamped in the vertical position on the fixturing frames (Fig. 3). The two-dimensional network of the measurement points was proposed for the Y axis (the vertical position of the spindle stock on the column) and W axis positions (the retractable spindle position). The column position on the bed (Z axis) and table position on the bed (X axis) does not influence the dynamic compliance at the end of the tool.

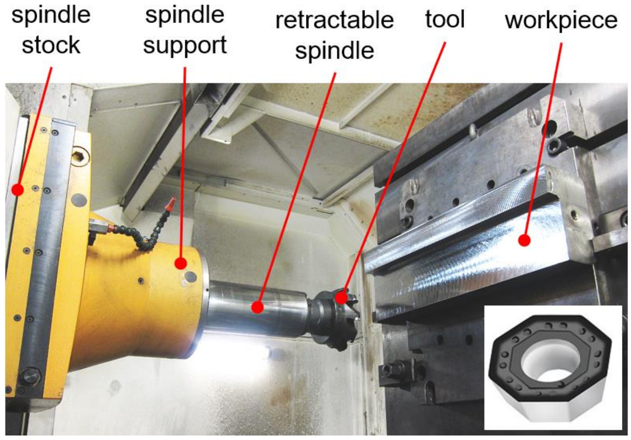

Fig. 3: The experiment setup. Detail of the retractable spindle, the machined block of material and detail of the octagonal cutting plate (by Walter) is presented.

A face mill cutter with a diameter of 160 mm and 9 teeth was used. The octagonal Walter cutting plates ODHT0605ZZN-F57 WSP45S (see Fig. 3) were installed on the cutter. The total weight of the cutter was 9.8 kg. Such a tool is a typical tool for face milling operations done by horizontal boring machines.

A cutting speed of 181 m/min (spindle speed of 360 rpm) and feed per tooth of 0.35 mm (feed of 1130 mm/min) was used for down milling with a radial depth of the cut of 110 mm (69% of the tool diameter).

Machining tests, as well as FRF measurements, were done on the network of measurement points for various spindle extraction positions (machine axis W) and various spindle stock vertical positions (machine axis Y), see Fig. 2. The spindle support with a length of 250 mm was installed on the spindle stock. Thus, the lowest W axis position was set at 300 mm.

3.2 Modal identification of dynamic compliance

The dynamic compliance was first measured using a tap test on the tool for a combination of the Y axis and W axis positions. The excitation of the system was done using a modal hammer PCB 086D20. The dynamic response was measured using a Bruel&Kjaer 4524 B triaxial accelerometer, see Fig. 4.

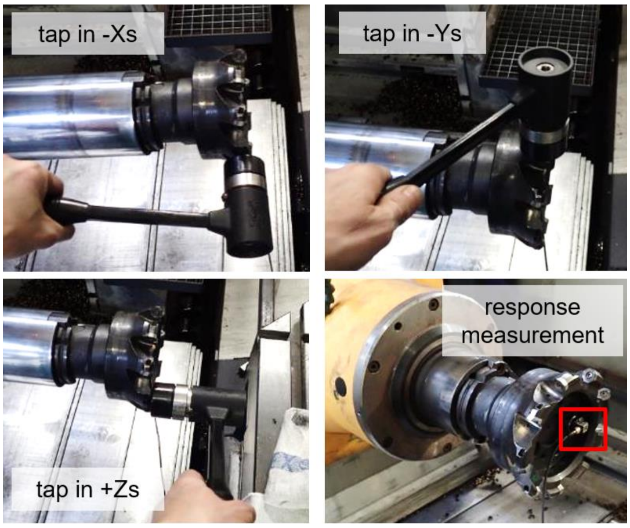

Fig. 4: Schema of FRF measurement on the tool.

Some selected dynamic compliance in the X and Y directions measured on various tool center point positions are presented in Fig. 5 for illustration. There is one dominant compliance on the presented figures. It seems to be a joint mode of two modes on close frequencies.

For the tested machine tool, the dynamic compliance is strongly sensitive on the retraction of the spindle (W axis position). The vertical position of the spindle stock on the column (Y axis) has a small influence on the compliance. There is a higher compliance of about 20-30% in the X (horizontal) direction compared to the Y (vertical) direction.

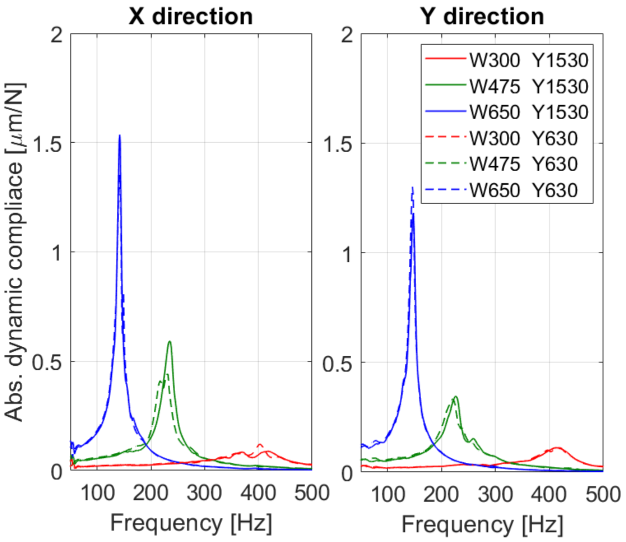

Fig. 5: Measured dynamic compliance characteristics.

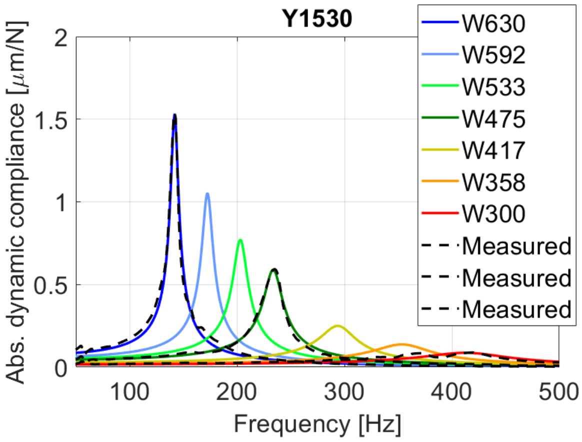

Fig. 6: Comparison of the measured FRF (black dashed lines) and computed FRF (color full lines) using model based on modal identification approach. FRF is computed for more W axis positions using this model.

The system can be modeled as a one-mass system with modal parameters dependent on the tool center point position in the Y and W axes. The modal identification was done using the peak picking technique [SchmitzSmith2009]. The values of the Eigen frequencies Ω, relative damping ζ_q, modal mass m_q and modal stiffness k_q were computed for every YW position where the measurements were done. An interpolation technique within the table of data identified from the measurements was used for the determination of modal parameters at new YW positions. Using these interpolated parameters, it is possible to reconstruct the FRF on the tool for every point within the defined Y and W axis strokes. The agreement of the model and the measured data are presented in Fig. 6.

3.3 Machining tests

The machining tests were done using the face mill and cutting conditions mentioned in section 3.1. There were three machine tool postures with various Y and W axis positions, see the blue points in Fig. 2.

A down milling setup was used. The radial depth of cut a_e was 110 mm for all experiments. A varying axial depth of cut a_p was used. The experiments started for a safely-low value of a_p. If the machining operation was stable, the depth of cut was increased by about 1 mm for the subsequent cut until the process became unstable for the defined depth of the cut.

Tab. 1: Machining experiment results. Three cases are marked for detailed identification in Fig. 7

Depth of cut ap [mm]	TCP position:		
	W300 Y1528	W475 Y1528	W475 Y630
4,5	chatter (M08)		
4	marginally stable (M07)		
3	stable (M06)		chatter
2	stable	chatter	stable
1		stable	stable

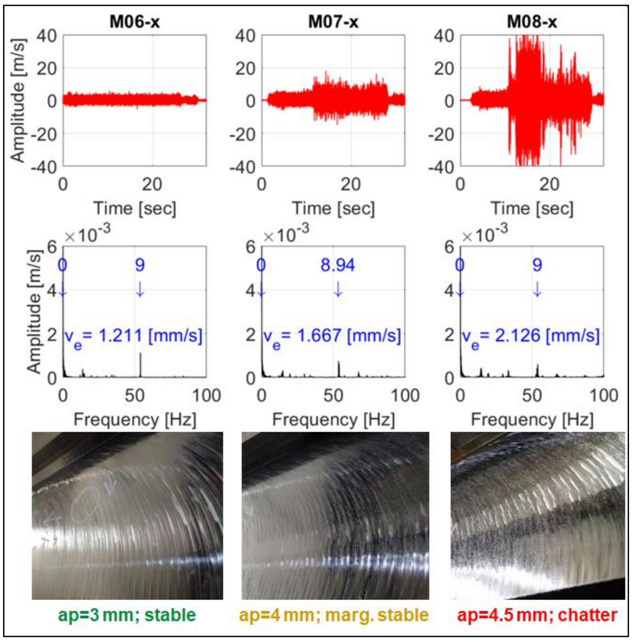

Fig. 7: Selected machining examples: vibration time records, vibration spectra and detail of the machined surface.

Vibrations were monitored using a Bruel&Kjaer 4524 B triaxial accelerometer placed on the lower side of the spindle stock, see the white point in Fig. 2. The stability of the cut evaluation was based on the vibration spectra and check of the surface marks. All the results of the experiments are summarized in Tab. 1. The measured vibration records, their spectra and surface marks for selected machining examples are presented in Fig. 7. In this case, the dominant peak in the spectra seems to be the harmonic frequency of the revolution frequency. The chatter occurrence in case M08 was identified through the high vibration velocity and clear chatter marks on the surface.

3.4 Cutting force coefficient identification

The spindle power was recorded during every machining run. The specific cutting force coefficient was calculated using the process power and the metal removal rate [Janota2019]:

$$K_C = \frac{\overline{P_{machining}} - \overline{P_{idle}}}{a_p \cdot a_e \cdot v_f} \tag{1}$$

The machining power was evaluated within the defined time window. Some selected examples of the recorded data and the processing time window marked by the blue color are presented in Fig. 8. The time of 10 sec was used for the cutting force coefficient identification.

The spindle power signal was monitored using the internal oscilloscope of the Sinumeric 840D sl control system. The monitoring frequency was 125 Hz (time period of 8 msec).

The spectra of the power signal are also presented in Fig. 8. As can be seen, there is a dominant peak at a revolution non-harmonic frequency in the power spectra for the M07 measurement (marginally stable) and M08 measurement (chatter occurred). It was probably caused by torsional vibrations of the face mill with a relatively large diameter of 160 mm that loaded the spindle drive. This shows that, for some special cases of large tools, the chatter occurrence can also be observed in the spindle power spectra recorded by the control system with relatively low frequency.

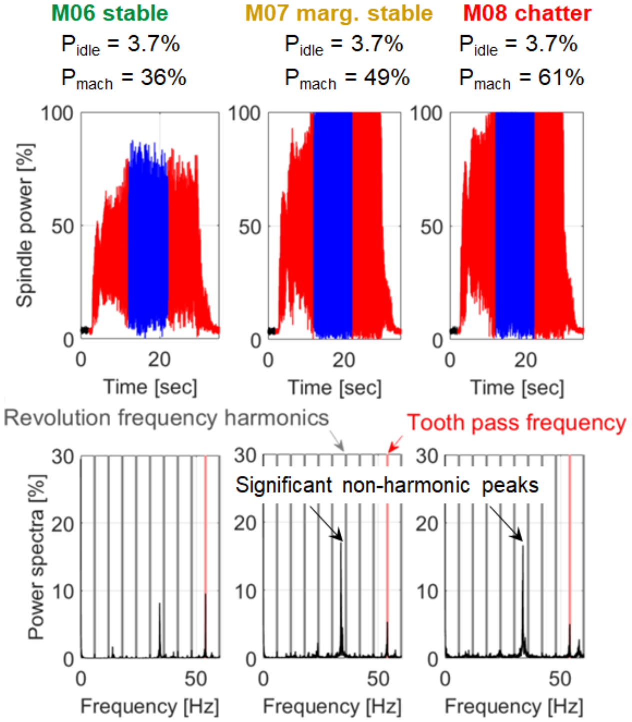

Fig. 8: Selected machining examples: spindle power time records and power spectra. In the time record, the black curve means the spindle idle run, the red curve means the process power and the blue curve means the signal time window used for the cutting force coefficient calculation.

Tab. 2: The calculated tangential cutting force coefficients K_C based on the experiment data.

Depth of cut ap [mm]	TCP position: W300 Y1528	W475 Y1528	W475 Y630
4.5	1980 MPa (M08)		
4	1843 MPa (M07)		
3	1792 MPa (M06)		N/A
2	1778 MPa	N/A	1681 MPa
1		1930 MPa	1742 MPa

The tangential cutting coefficient K_C calculated using (1) is summarized in Tab. 2. The relevant value cannot be calculated for two chatter cases due to the very short machining time caused by an immediate heavy vibration occurrence. As can be seen, the value of the cutting force coefficient K_C depends on the axial depth of the cut. It is expectable because there is an influence of the inclined cutting edge of the octagonal plates for the lower axial depth of cut. The K_C average value calculated from the stable machining cases is 1785±82 MPa. It means 10% uncertainty in the K_C estimation, which is acceptable.

3.5 Cutting stability model

Due to the dynamic system behavior characterized with one significant compliant mode, the basic frequency-domain model [Tlusty1957, SchmitzSmith2009] was used for the calculation of the limit axial depth of the cut:

$$a_{p,lim} = \frac{-1}{2\cdot K_S\cdot \min(Re[FRF_{orient}])\cdot N_t^{*}} \qquad (2)$$

where K_S is the cutting force coefficient and N_t^* is the average number of teeth in the cut. The K_S value is calculated as:

$$K_S = \frac{K_C}{\sin(\beta)} \qquad (3)$$

where β is the angle between the direction of the active force and radial force. If the usual empiric ratio of the tangential and radial cutting force components of 2:1 is assumed, the value of the β angle is 63°. Using this estimation, the K_S value of 2003 MPa can be calculated for the machining process cases described in the previous section.

Fig. 9 compares the results of the machining tests and the calculated limit (2) of the axial depth of the cut. The measured dynamic compliance (see section 3.2) and the cutting force coefficient K_S identified from the machining process (see section 3.4) has been used in this case. As can be seen, the calculated limit of the axial depth of the cut is for all three TCP positions between the experimentally identified values for stable and chatter machining. It demonstrates that the in-process calculation of the cutting force coefficient (1) and (3) gives quite useful results.

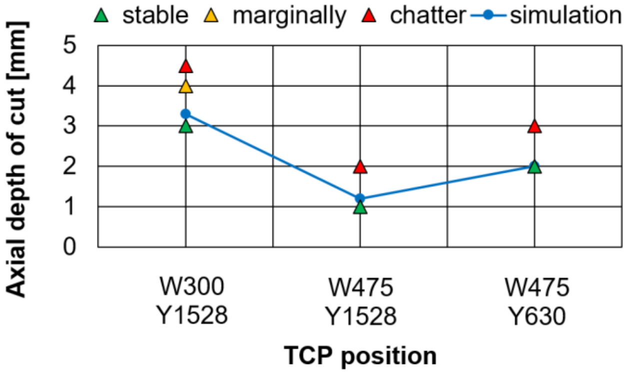

Fig. 9: Comparison of calculated limit from axial depth of cut with the machining test results for three TCP positions.

3.6 Calculation of the usable spindle power

Using the identified model of the dynamic compliance and the identified cutting force coefficient, it is possible to calculate the maximum axial depth of the cut for stable cutting for the given radial depth of the cut and the defined tool (2), see Fig. 10. The model of the dynamic compliance made it possible to also calculate the compliance out of the measured YW positions.

Thus, the cutting power needed for machining can be computed as:

$$P_{machining,calc} = v_C \cdot \sum_{1}^{N_t} F_{Ci} =$$

$$= v_C \cdot f_t \cdot a_{p,lim} \cdot K_C \cdot \sum_{1}^{N_t} \sin(\varphi_i) \qquad (4)$$

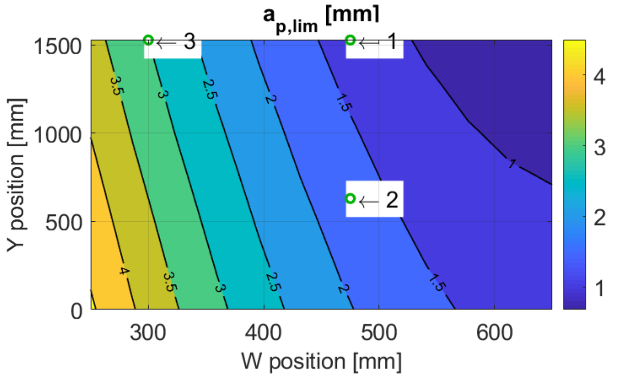

Fig. 10: Map of the calculated maximum axial depth of the cut for the given face mill, the defined engagement conditions and the workpiece material. The experimentally identified stable depth of the cuts are marked (see Tab. 1).

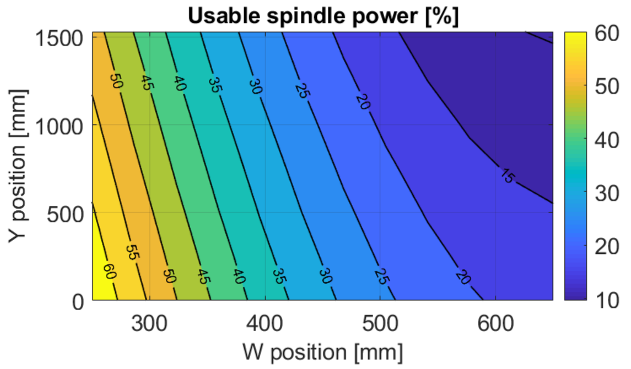

Fig. 11: Map of the relative usable spindle power for the given face mill, the defined engagement conditions and the workpiece material. Significant sensitivity the retractable spindle position W is visible.

where f_t is the feed per tooth, N_t the number of the teeth in the cut and φ_i is the angular position of every tooth in the cut.

The relative usable spindle power can be calculated using the known machining power (4) and the power losses measured during the idle run:

$$\eta_{stable\ machining} = \frac{P_{machining,calc}+\overline{P_{idle}}}{P_{max}} \qquad (5)$$

where P_{max} is the installed power on the spindle for S1 mode.

The relative usable spindle power was calculated for the defined range of Y and W axes positions, see the map in Fig. 11. The strong sensitivity on the spindle retraction W and lower sensitivity on the spindle stock vertical position is visible, which is quite normal for the discussed type of horizontal boring machine with a retractable spindle.

4 DISCUSSION

The main advantage of the presented method is saving time during performance tests, especially of large machine tools, and increasing the operational safety of the experimental process by eliminating the need of chatter. The dynamic compliance is measured on a broad network of the tool positions in the machine tool working space. The cutting tests are conducted in just a few points to identify the cutting force coefficients and the reference stability limit. The modal identification technique is used for the creation of the machine dynamic behavior model. Using this model, the map of the stable depth of the cut can be computed within the machine tool working space.

The approach is based on experimental methods. There are two main motivation points for the selection of this approach: a) the real state of the machine tool is measured (especially, real values of the damping ratio); b) it is a universal approach that does not need any simulation model of the machine tool. The cutting force coefficient is identified using a spindle power record, thus the real cutting-edge geometry state and material properties of the specific workpiece are taken into account.

On the other side, there are also some drawbacks to the method. The main issue is that the measured dynamic compliance is valid just for that one specific tool. More tool types require a repeat of the measurements.

The calculation of the stability limit is valid for specific cutting conditions, engagement parameters and machined material. However, the method is not recommended for a process optimization, but for testing the usable spindle power as a validation process of the machine tool design. Thus, some standardized test conditions (workpiece materials, cutting tools, cutting conditions) within the company are recommended.

A simplified empiric rule of the tangential/radial cutting force components is used. This influences the calculation of the oriented FRF and cutting coefficient K_S by sin(β) value. Due to the goniometric function used in the calculations, the influence on the final result is quite small.

The experimentally-identified cutting force coefficient K_C using the spindle power monitoring method might be a more important source of calculation inaccuracies. First, the described method uses the simplified assumption that power losses during machining are the same as power losses during the spindle idle run. This might not be the truth [Dunwoody2005]. The estimation error is about 10% of the loss power. Secondly, K_C identified using this method depends on the axial depth of the cut due to the cutting plate radius. To minimize this error, a higher axial depth of the cut are recommended for tests. Also, a calculation of the average value from more tests is helpful. In this case, the K_C average value calculated from the stable machining cases was identified at 1785±82 MPa, which is reasonable for a cutting plate with a very positive cutting geometry.

With respect to all the aforementioned simplifications and uncertainties, the accuracy of the method for the calculation of the stable axial depth of the cut is estimated to be about ±20%. This is acceptable for such an operational method.

The method was demonstrated on an example of a horizontal boring machine. As can be seen in Fig. 11, the retractable spindle is the main limit of high-power machining. However, the usable spindle power of 50-65% for Y250 is a good result.

5 MACHINE TOOL OPERATOR SUPPORT

The presented method is easy to use also as a handy tool for the machine tool operator. The results can be implemented easily in the machine tool control system as an independent application to visualize the axial cutting depth limits with respect to the tool center point position for a specific cutting operation.

An example of implementation in the TOS Control machine management system by TOS Varnsdorf is shown in Fig. 12. This management system is a unified interface for the implementation of various applications in the Siemens Sinumerik 840D sl and Heidenhain TNC640 control systems. This interface is currently implemented in all new machine tools produced by TOS VARNSDORF a.s. The management system represents the basic user interface of the machine tool displayed on the operator panel, which also includes the standard user interface of the control system. The application for the axial cutting depth limit visualization is created in the C# programming language using the .NET Framework and is accessible from the main menu of the management system.

In order to be more general, the dynamic behavior model should also be identified as dependent on the tool weight. This is planned as the further implementation steps. The application on the control system is a concurrent interface for the collection of the process data for various cutting tools and cutting plates.

Identification of the stable depth of cut is for machine tool operator the most basic approach to reach the stable process. There are more useful methods available as was summarized e.g. by Munoa [Munoa2016]

6 SUMMARY

The paper presents an operational method for the safe experimental testing of machine tool usable spindle power during cutting performance tests. The method is mainly based on experimental measurements. The dynamic compliance is measured on the network of points across the machine tool working space. Using these data, the dynamic behavior model is identified using the regression of modal identified parameters. Only a few test cuts are needed for the identification of the tangential cutting force coefficient. Combining the model of dynamic compliance at the tool and the identified cutting force coefficient, it is possible to calculate a map of the relative usable spindle power for the specific tool and workpiece material. This result makes it possible to evaluate the ability of the tested machine tool for high-performance machining. Due to simplifications in the cutting force coefficient identification and adoption of the regression of the modal identified parameters, the accuracy of the method for the calculation of the stable axial depth of the cut is estimated to be about ±20%.

The implementation of the method is demonstrated on the example of the horizontal boring machine. The method is primarily dedicated for the support of the cutting performance tests on the large machine tools in order to save time and decrease the risk of machine tool damage during the occurrence of chatter. The aforementioned prediction accuracy of ±20% is acceptable for this purpose. Within some limited conditions, the results can also be used to process the planning support done by the machine tool operator.

7 ACKNOWLEDGMENTS

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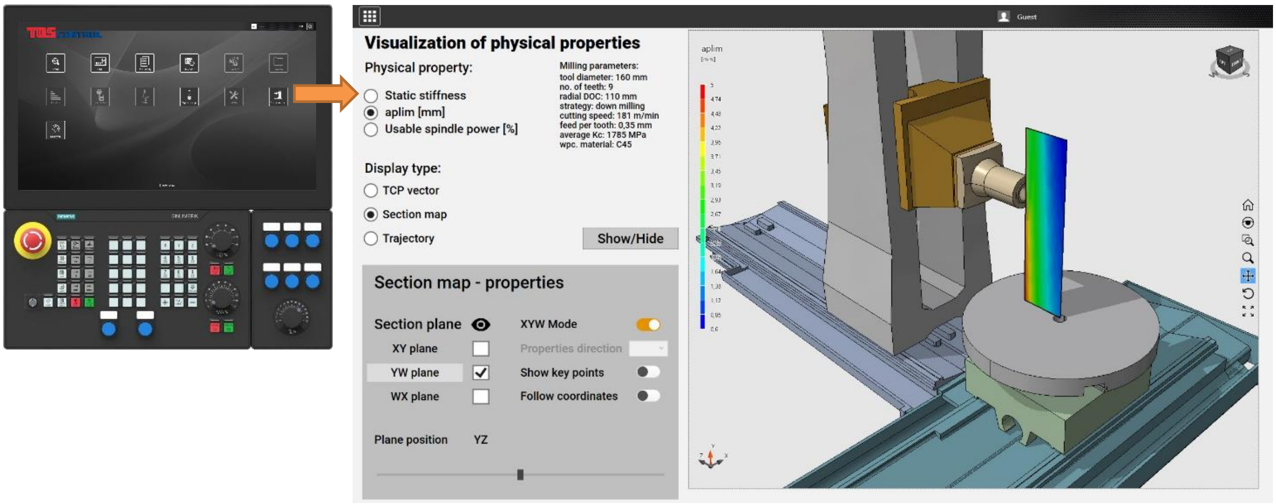

Visualization of physical properties

Physical property:
○ Static stiffness
● aplim [mm]
○ Usable spindle power [%]

Milling parameters:
tool diameter: 160 mm
no. of teeth: 9
radial DOC: 110 mm
strategy: down milling
cutting speed: 181 m/min
feed per tooth: 0,35 mm
average Kc: 1785 MPa
wpc. material: C45

Display type:
○ TCP vector
● Section map
○ Trajectory

Section map - properties

Section plane
XY plane ☐
YW plane ☑
WX plane ☐
XYW Mode: on
Properties direction
Show key points: off
Follow coordinates: off
Plane position YZ

Fig. 12: Example of the HMI machine for visualization of the stable cut limits integrated in the machine tool management system TOS Control.

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