Confirmation of Chatter Prediction Reliability

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Abstract

The paper describes sensitivity of the simple turning model – which corresponds with the basic theory of self-excited vibration – on considered milling features. The paper also shows the course and the results of experimental confirmation of the complex milling model, which is used for predicting cutting process stability.

Key words

Self-excited vibration, chatter, milling

1. Introduction

Self-excited vibration (chatter) presents one of the limits of machining productivity. It could occur in any machining operation. At a certain removal rate, the tool or work piece starts to vibrate violently, the noise increases and there is a significant deterioration of surface roughness. The stable cutting suddenly becomes unstable. Machining under chatter conditions is impossible in relation to surface roughness and life expectancy of a tool or machine tool. A dramatic change from stable to unstable cutting is connected with an increase in the axial depth of cut above the limit value.

The fundamentals of the theory of self-excited vibration and application to milling process are described in [1], [2] and [3]. The findings were extensively applied in [4]. The theory allows us to draw the stability diagram, which divides stable cutting conditions area from unstable ones. The diagram shows dependency of axial depth of cut on spindle speed. In the diagram, there are regions (gaps) where the depth of cut could be higher than elsewhere. The diagram provides essential information utilizable in machine tool design or in setting optimal cutting conditions.

The original theory was designed for turning. Milling application requires a number of simplified assumptions. Milling features are significantly different from turning: interrupted cut, changes in chip thickness during cutting, changes in the direction of cutting force during the cut and also differences between up and down milling. There are other differences such as more than one tooth in cut. One of the working objectives was to determine the effect of the simplifications on the stability limit. This approach helps to find a reason for the difference between the stability calculation and the experimental results.

2. Model Sensitivity – Modifications of Simple Turning Simulation Model

Simple Turning Simulation Model (STSM, *fig. 1*, [2]) is based on the original theory (on regenerative principle). It works in a time domain. The results obtained by the simulation were closely matched by those obtained by classical calculation (*fig. 2*). Modifications of Simple Turning Simulation Model show effect of individual differences between milling and turning process on the cutting process stability. Model inputs (e.g. shape of nominal depth of cut) will be modified. Some constants (e.g. directional factor and orientation of cutting force, specific cutting force) will be defined as functions. Modifications will be applied separately to show their effects.

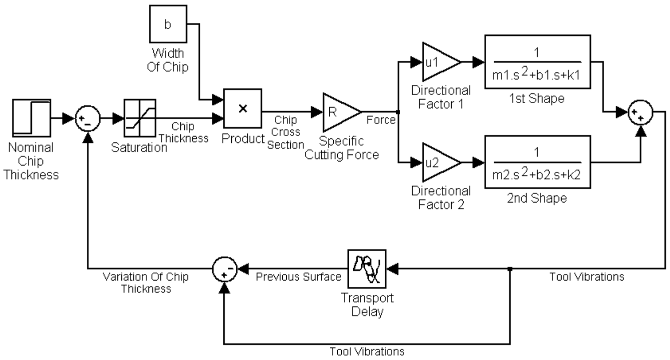

Fig. 1: Turning Model Scheme

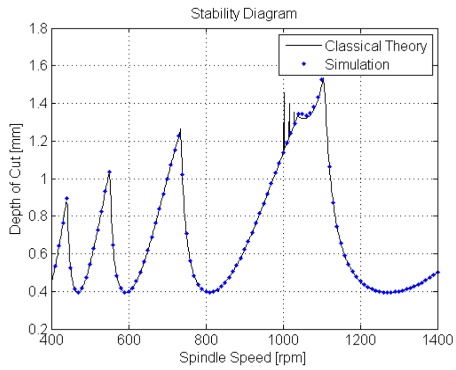

Fig. 2: Results Comparison

2.1 Interrupted Cutting

In contrast to turning process, during milling, the tooth of cutter is in the cut only for part time. There is an interrupted cut. The length of cut is determined by radial depth of cut and feed per tooth. When no tooth is in the cut, cutting force does not excite the system. Damping is still acting though its magnitude may change in relation to the tool leaving the cut. Interrupted cut changes the proportion of supplied and consumed energy in the system. This should affect the stability of the system.

Strategy: Nominal value of the cut or zero value will be sent to input of STSM. Zero value provides no excitation of the system. The system will be damped continuously. Three simulations will be described: tooth in the cut for a whole, half and quarter of work piece revolution (*fig. 3*). Simulation can be compared with turning solid or flute shaft.

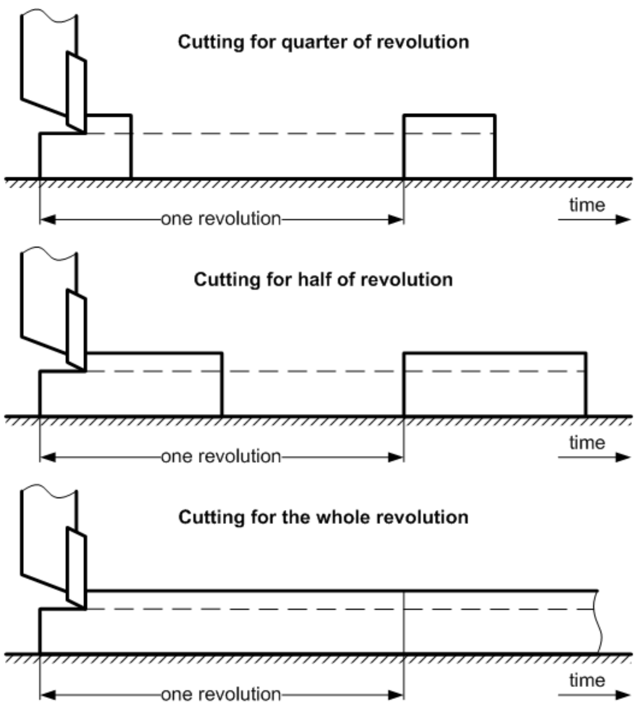

Fig. 3: Shape of Nominal Depth of Cut

Results of simulations are shown in *fig. 4*. It appears that the greatest stability was reached when the system was excited for a quarter of revolution. Continuously force-excited system reached the lowest stability. The growth of stability is dependent on the reduction of exciting time. Lobes (gaps) arrangement is unchanged. There is only a vertical shift of the whole diagram.

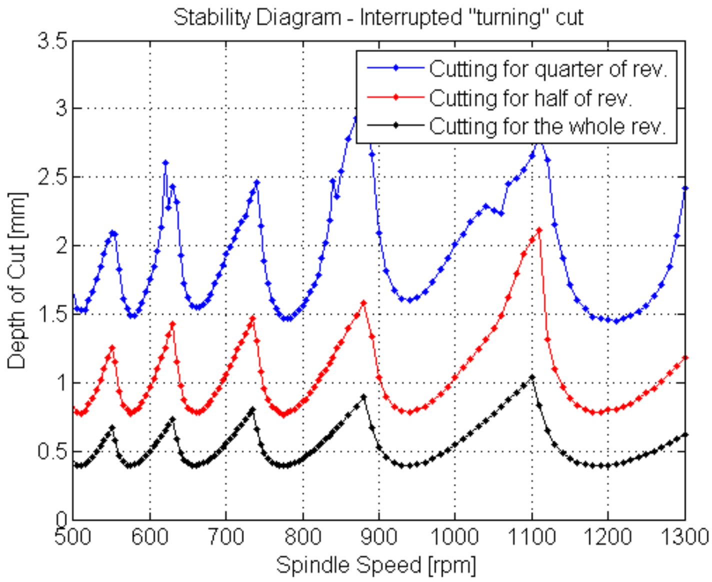

Fig. 4: Comparison Between Stability Diagrams for Interrupted Cut

2.2 Triangular Chip Section

Nominal depth of cut during milling is not constant. It varies in relation to the orientation of the cutter, the value of the radial depth of cut, the value of the tooth shift and also in relation to up milling or down milling. Force shocks are caused by tooth insertion and leaving the cut. The value of shock is determined by the above mentioned factors as well as by the number of teeth which are in the cut simultaneously. It is the value of shock that could change the proportion of supplied and consumed energy in the system, which would have an impact on the stability of the system.

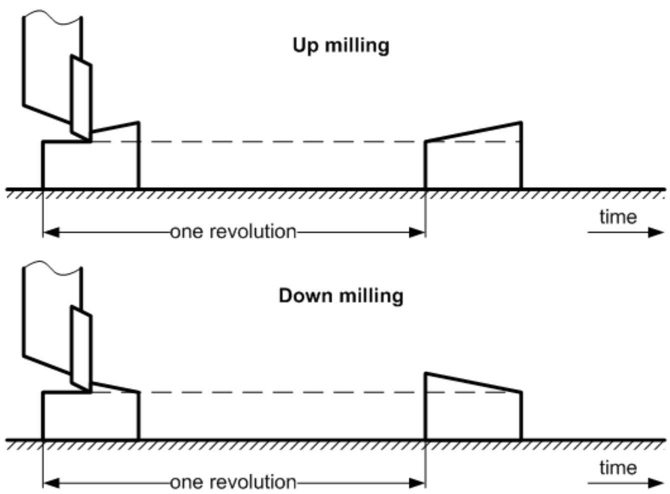

Fig. 5: Shape of Nominal Depth of Cut

Strategy: Nominal value of the cut will be sent to input of STSM. The nominal value will change from zero to maximum in the first quarter of revolution, which corresponds to up milling. Or it will change from maximum to zero, which corresponds to down milling. In the remaining three quarters of revolution, the nominal value of the cut will be zero (*fig. 5*). The simulation can be compared with milling utilizing a one-tooth cutter when the radial depth of the cut equals the semi-diameter of the tool.

The results of simulations for turning, up milling and down milling cut are shown in *fig. 6*. The length of cut is the same in all cases. "Turning" cut reaches the lowest stability (*fig. 7*). "Up milling" cut reaches a slightly higher stability. "Down milling" cut reaches the highest stability. It is necessary to remember that no change in orientation of the cutting force i.e. no change in directional factors has been considered during these simulations. Why then is there a difference between "up milling" cut and "down milling" cut? *Fig. 8* and *fig. 9* indicate this. Here, we can observe the course of the nominal and real depth of the chip and the course of tool vibrations. During "down milling" cut, there are greater shocks. This causes greater vibrations of the tool during the cut. The tool leaves the cut more easily when the depth of the chip is smaller. This is easier in the case of "down milling" cut than in the case of "up milling" cut. When the tool leaves the cut, it results in a reduction of force-excitation time. This has the same effect as shortening the length of the cut i.e. a growth of stability. From the stability point of view, the difference between up and down milling is not significant. Only the difference in the values of vibrations is significant. Again, there is only a vertical shift of the diagram. The arrangement of lobes remains unchanged.

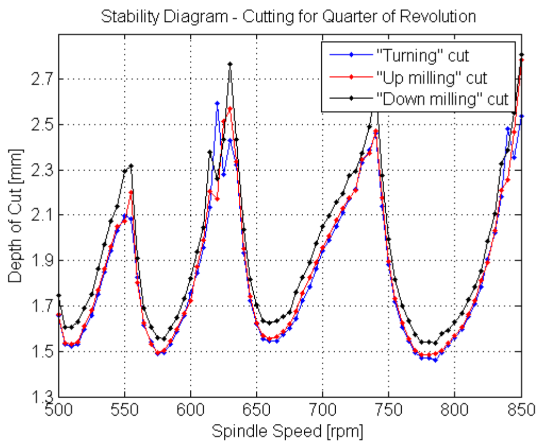

Fig. 6: Comparison of Different Types of Cut

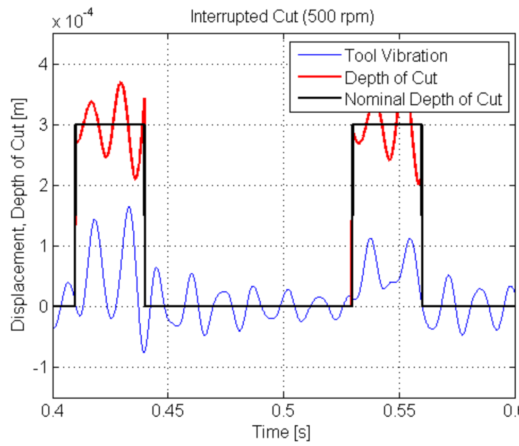

Fig. 7: "Turning" Cut

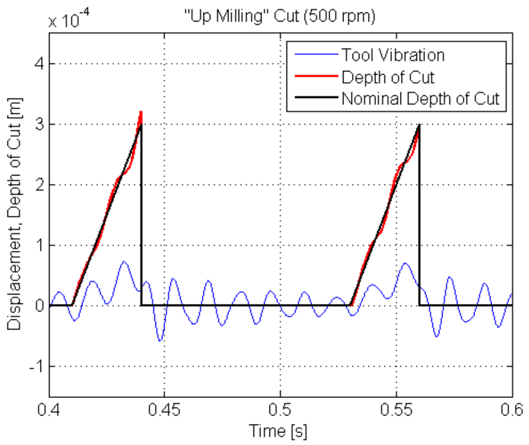

Fig. 8: "Up milling" Cut

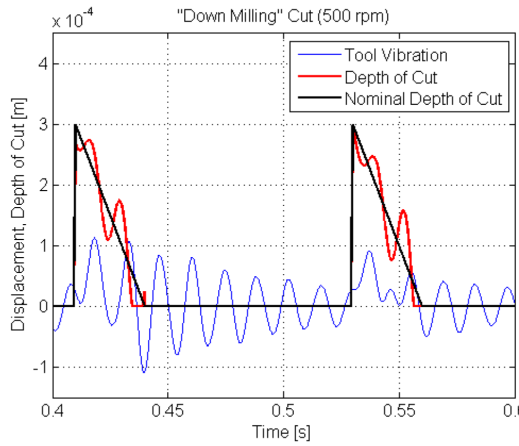

Fig. 9: "Down milling" Cut

2.3 Effect of Chip Thickness

Many sources [6] state that there is a dependence of specific cutting force K_C on the main chip thickness h_m. Nominal value K_C is given for the chip thickness of 0.2mm. It is known that in lower values of chip thickness, the tool gets into the cut with difficulty due to plastic deformations of material. *Fig. 10* shows specific cutting force in relation to the main chip thickness. If we applied the same dependence on instant chip thickness, the change of this value during the cut could alter the proportion of supplied and consumed energy in the system. This would have an impact on the stability of the system. In addition, the maximal value of chip thickness, which is related to the value of feed per tooth, would also have an impact.

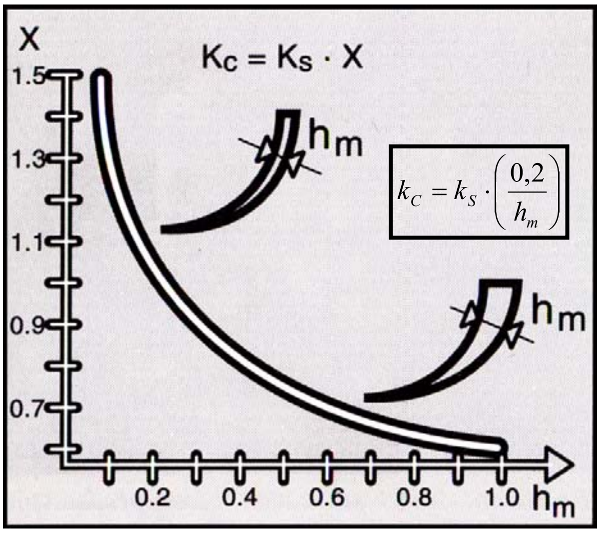

Fig. 10: Dependency of the Specific Cutting Force

Strategy: Constant specific cutting force R in STSM will be substituted with empirical function K_C shown in *fig. 10*. Specific cutting force will be computed in relation to instant chip thickness. Other modifications accord to the strategy in the previous chapter.

Simulations for up and down milling were calculated with constant nominal value of K_C, with variable value of K_C, feed per tooth which was 0.1 and 0.3 mm/tooth. Results are presented in *fig. 11* and *fig. 12*. It is clear that a decrease of specific cutting force, due to the value of maximal chip thickness, increase stability. The maximal chip thickness corresponds

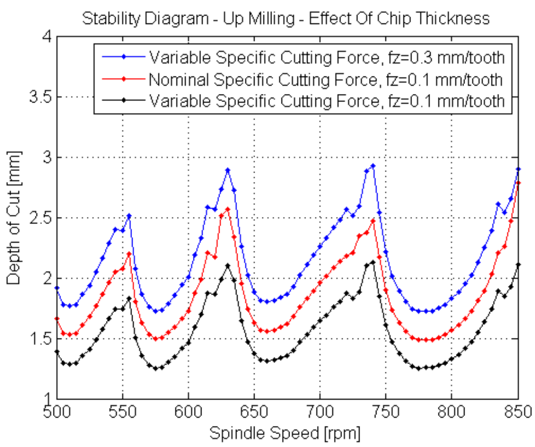

Fig. 11: Comparison between stability diagrams for up milling cut

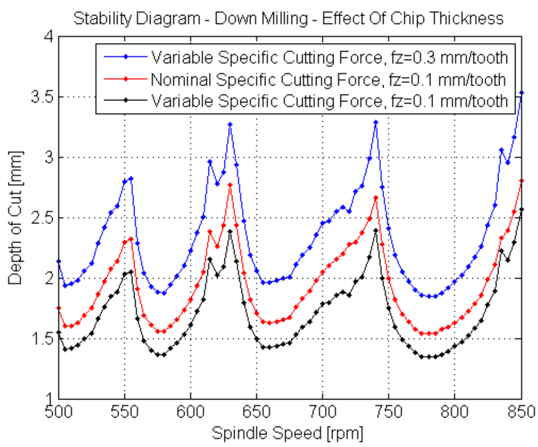

Fig. 12: Comparison between stability diagrams for down milling cut

to feed per tooth. An increase in value of $\boldsymbol{K_C}$ produces lower stability. Results can be compared with result of the simulation with constant value of $\boldsymbol{K_C}$ (independent of the chip thickness). Again, the difference between up and down milling is not significant. Similarly to all the previous cases, there is only a vertical shift of the diagram. The arrangement of lobes remains unchanged.

2.4 Changing Direction of Cutting Force

As well as changing chip thickness (triangular chip), there is also a change in the force direction during the cut in the milling. The problem has been considered in the original theory and a solution has been found in incorporating average values (in half way through the depth of cut) into the calculation. This solution has been accepted despite the fact that the change in the direction of cutting force means a change of directional factors. These factors have a great effect on the resulting stability. Let us remember that directional factors divide exciting cutting force between two main modal shapes of the system. The change of factors during the cut results in a change in the proportion of the supplied and consumed energy in the system. This would have an effect on the stability of the system.

Strategy: Input of STSM will be modified according to the strategy in the chapter "Triangular Chip Section". In addition, constant directional factors will be substituted with functions dependent on the instant orientation of the cutter. The change in directional factors with varying orientation of cutting force during up and down milling will be considered.

The result of the simulation with constant and variable directional factors during up and down milling is shown in the two following figures. When compared, a great impact of the change of directional factors on stability is evident. This change is caused by the method of milling (up or down milling). There was not only a vertical offset of particular curves but also a change in the lobes (gaps) arrangement. This is not surprising and corresponds with the original theory. The use of variable directional factors brings interesting results. In case of up milling (*fig. 13*), it seems that there was a constant offset of stability diagram similarly to all the previous cases. In case of down milling (*fig. 14*), it is evident, that the offset is not constant. In some ranges of spindle speed, there is an increase in stability and in other ranges there is a decrease. If we take a detail look at the graph, we can discover a slight horizontal offset which is not constant either.

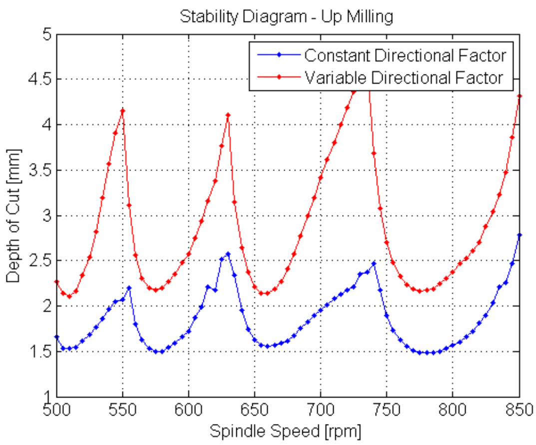

Fig. 13: Comparison Between Stability Diagrams for Up Milling

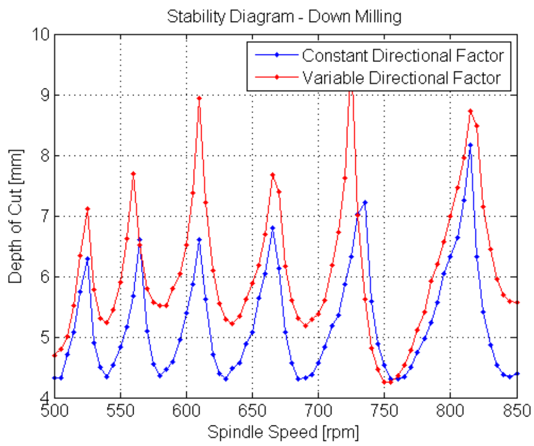

Fig. 14: Comparison Between Stability Diagrams for Down Milling

No previous modifications of the model had a similar impact. Previous modifications resulted only in an approximately constant vertical offset of the stability diagram. The use of variable directional factors caused an inconstant horizontal and vertical shift of the diagram points. This shift is a common problem in experimental confirmation of the results of the original theory. The problem has been as yet assigned to the difference in the measured dynamic compliance and the real operating compliance of a machine during machining.

3. Experimental Confirmation

This chapter describes experimental confirmation of Complex Milling Simulation Modes (CMSM, [5]). This model works in a time domain as well as STSM, but utilizes a different method for regenerative principle modeling. CMSM consider milling features (interrupted cut, variable chip thickness, variable directional factors) tested in previous chapters except variable specific cutting force. Moreover, it considers more than one tooth in cut.

The machining tests were performed on experimental machine tool LM2. During the experiment, two-edged tools were used. In the first case, a common tool was used. In the second case, we used a tool with special geometry which corresponds to the designed model. The machined material was dural.

The tests had the following course. First of all, the dynamic compliance of tool – machine tool system was measured by the MetalMAX device. Wedge-shape surface was pre-machined on a workpiece. Then, the slots were machined into the workpiece. During machining, the noise was recorded for chatter identification and for finding a chatter frequency. Wedge-shaped workpiece produces a gradual increase in axial depth of cut. So chatter arose in a certain moment. The occurrence of chatter is visible on both the machined surface and the noise record. Each slot was machined with a different spindle speed (feed per tooth was constant), so chatter rose at a different moment by a different depth of cut. So the stability diagram was created in an experimental way. The repeatability of measurement of the stability limit was tested too.

3.1 Common Tool Geometry Test

During this test, the end-mill head for changeable tips was used. Tips have common geometry with a small helix angle. Tool diameter was 12mm. The machined material was dural 2024-T351. Measured dynamic compliance and fitted curve is shown in *fig. 15*.

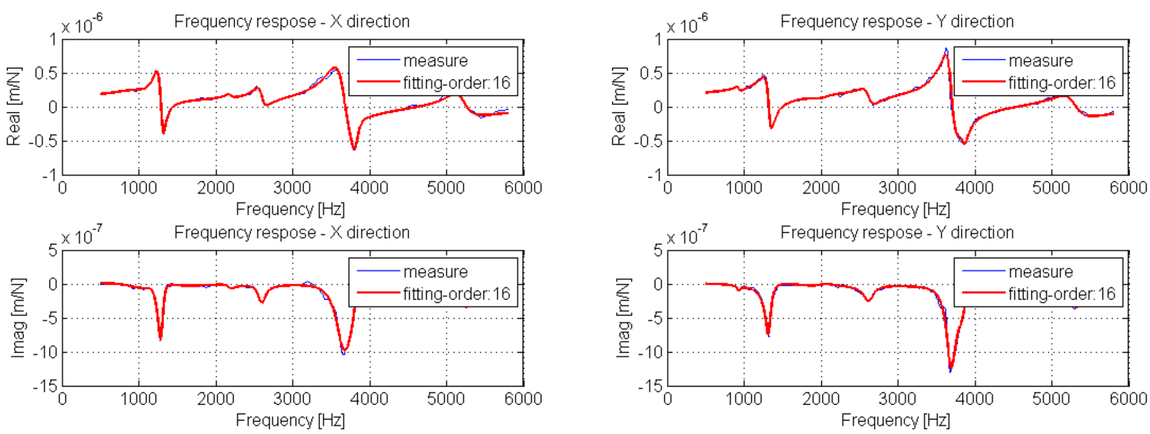

Fig. 15: Measurement of Dynamic Compliance and Fitted Curves

Spindle speed was changed in the range from 8,000 to 9,825 rpm. Feed per tooth was 0.05mm. Four series were measured successively. Results are shown in *fig. 16*. Stability limits for 8,400 and 8,800 rpm were measured twice. The results point to repeatability. The spread of the values may be caused by dependency of stability limit on the duration of spindle running. *Fig. 17* shows the results of the machining test, the results of MetalMAX calculation and the results of simulation. In comparison with the experimental results, the lobes in the stability diagrams were shifted in a horizontal and a vertical direction.

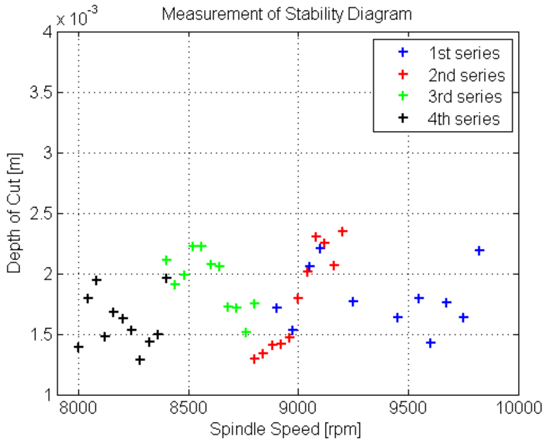

Fig. 16: Machining Test Results

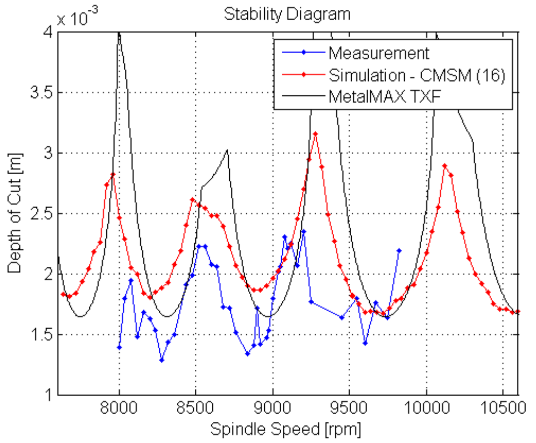

Fig. 17: Results Comparison

3.2 Special Tool Geometry Test

During this test, the solid carbide end-mill without a helix was used. Tool geometry was very simple. Tool diameter was 10mm. The machined material was dural 7075-T651. Measured dynamic compliance and fitted curve is shown in *fig. 18*.

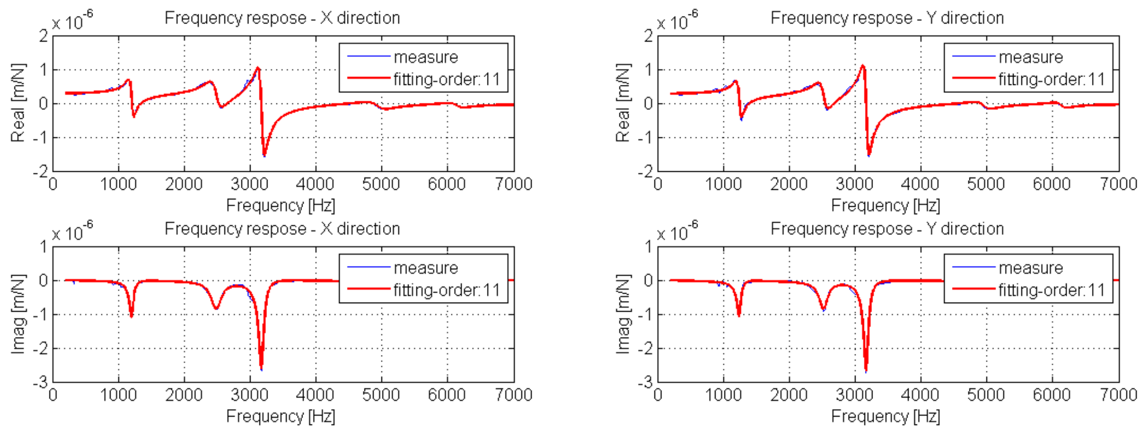

Fig. 18: Measurement of Dynamic Compliance and Fitted Curves

Spindle speed was changed in the range from 10,700 to 17,050 rpm. Feed per tooth was 0.05mm. Four series were measured successively. The results (*fig. 19*) were affected by impaired disposal of chips. This problem was caused by using the tool without a helix. In the fourth series, when the cutting process was lubricated by aerosol, the problem was eliminated. At the bottom of lobes, when the axial depth of cut was lower and cutting process was not affected, the repeatability was higher. *Fig. 20* shows the results of the machining test, the results of MetalMAX calculation and the results of simulation. In comparison with previous case the differences between results are smaller, but a horizontal and a vertical shift of lobes in the stability diagrams still exist.

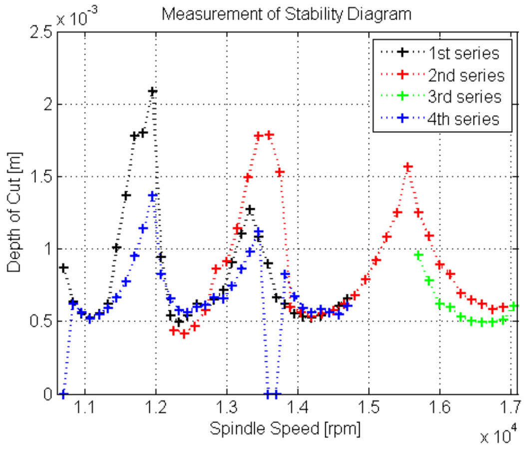

Fig. 19: Machining Test Results

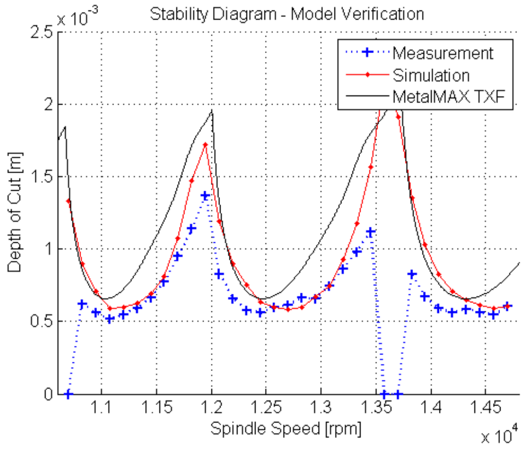

Fig. 20: Results Comparison

4. Conclusions

The chosen approach towards modification of STSM enabled better understanding of milling process. In the paper was shown, that all explored phenomena appeared to have a small or big impact on the cutting process stability. The information can be summarized as follows: Interrupted cut decreases the time of force excitation of the system and increases its stability. The shape of triangular chip does not affect the stability as much as it affects the magnitude of vibrations. Functional dependence of specific cutting force (as was defined) influences the stability in relation to feed per tooth. Variable directional factors have a great effect on the resulting shape of the stability diagram as they alter lobes (gaps) positions.

Tests show that reliability of chatter prediction is not satisfactory using MetalMAX calculation (frequency domain) or simulation in time domain. A higher reliability of chatter prediction was proved during the tests with the simple tool without a helix. A vertical shift can be caused by inaccurate determination of specific cutting force. For its specification, it is necessary to perform measurement of cutting forces. The cause of the horizontal shift may dwell in the changes in the course of the dynamic compliance during spindle running. Unfortunately, we are not able to measure the operating dynamic compliance. It is necessary to verify the effect of friction and process damping. The simulation in a time domain allows this.

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