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PROCESSING WITH PARALLEL KINEMATICS – AN EXPERIMENTAL ANALYSIS

This article summarizes experimental analyses for the determination of process parameters that can be achieved in an industrial machine tool with parallel kinematics. Focus is on the examination of the machining results' dependency on position and direction. Therefore milling experiments are conducted, testing different positions and directions within the workspace. Surface quality, process forces, acceleration as well as vibration characteristics of the working platform are assessed. Based on measured frequency responses the stability limits are determined at different locations within the workspace. By these examinations it can be confirmed that the dependency of static and dynamic machine properties on position and direction has an influence on machining results. Best results are achieved in central positions of the machine used for most of respective operations. Furthermore it's represented that the machining results are comparable to conventional serial machines though parallel kinematics show a stronger dependency on direction.

1. INTRODUCTION

In the last years there have been done a lot of research and development work in the area of machine tools with parallel, hybrid and redundant kinematic structures. Most important advantages of parallel kinematic structures, especially structures like hexapods or pentapods are the low masses that have to be moved or the high degree of common components. Further the accuracy requirements for the basic platform or machine frame can be limited because of the generally recommended static calibration. In practice this is supported by solutions for self-calibration [2][7], too. This simplifies application in real manufacturing environments. Beside the functional and economic benefits there are also some properties of machine tools with parallel kinematics that make design or operating more difficult in comparison with serial machine tools. Mentionable problems are the noticeable dependence of the potential process parameters on the machining position and the machining direction in the workspace and the fact that structures with lean struts are more susceptible to vibrations [6]. Properties such as static and dynamic

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elasticity are often used to analyze machine tools. Ultimately, they do not supply any statements on their reachable process qualities. In the following the machining behavior of an industrial applied parallel structure will be evaluated by milling tests and experimental analysis. First the analyzed machine tool and the concept of the experiments is introduced. After that the results of milling small circles are described. The analyzed values are the surface roughness of the machined workpiece, the process forces which occurs during milling and the averaged maximum accelerations of the working platform. At the end some position-dependent process stability limits will be presented which were calculated form measured frequency responses. A short discussion covering serial machine tools will close the works.

2. ANALYZED MACHINE TOOL

Due to their way of functioning, some parallel kinematic machine properties depend on the machining position and machining direction to a greater extent than serial machines. Especially, this is true for static and dynamic elasticity and vibration properties. In the same way, the potential machining quality and the reachable process limits depend to a greater extent on the machining position and direction. To identify these dependencies, experimental studies were done on a machine tool with parallel kinematics. The experimental studies were realised on the pentapod machine tool METROM P 800 (workspace 800 × 800 × 500 mm³, Fig. 1). The kinematics includes five length-variably lead screw struts which are connected to the basis platform via cardan joints. Four of the five struts are able to transmit forces in axial direction only. One strut is also loaded with bending moments. The kinematics enables the main spindle to have a pivoting angle of more than 90 degrees in two directions. This makes the machine tool suitable for five-axis milling. Further the machine tool includes a rotary table.

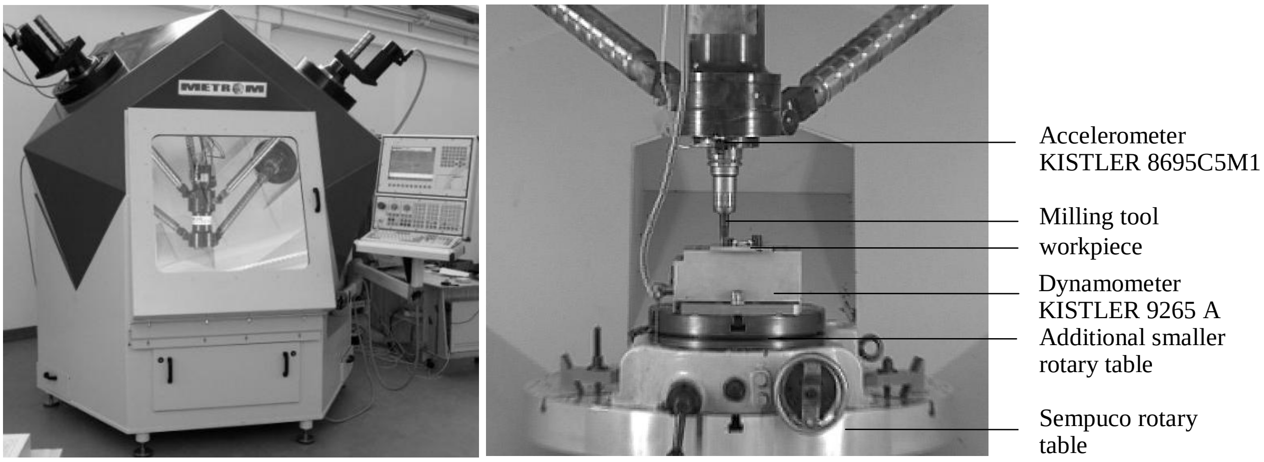


Fig. 1. Experimental equipment METROM P 800

3. EXPERIMENTAL CONCEPT

To quantify the dependencies of machining position and direction to reachable process parameters, in a first step the surface quality of the workpiece after milling will be evaluated at different positions. In a second step the process stability limits will be calculated from experimental frequency responses. To indicate the position and direction dependencies of surface quality simultaneously milling of small circular paths was considered as the best procedure. For it a second smaller circular table was installed on the main rotary table, see Fig. 1. The position of the circular path to be milled can be used to analyze position dependency if the circular path diameters are acceptably small. Likewise, the continuous direction changes when milling circular paths made it possible to detect the effects of the direction of machining. Milling test were carried out by machining circular paths with a diameter of 70 Millimeters in three positions in the workspace (Fig. 2 and Tab. 1). The selection of positions based on experimental analysis of static stiffness (Tab. 2). As can be seen the static stiffness is depending on tool position as well as machining direction.

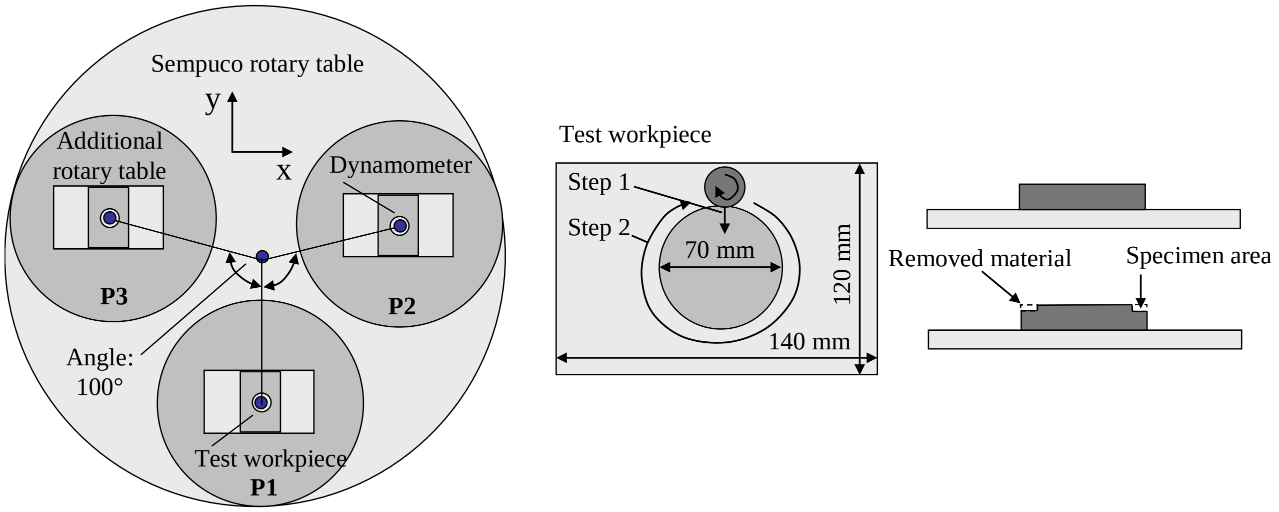


Fig. 2. Experimental concept

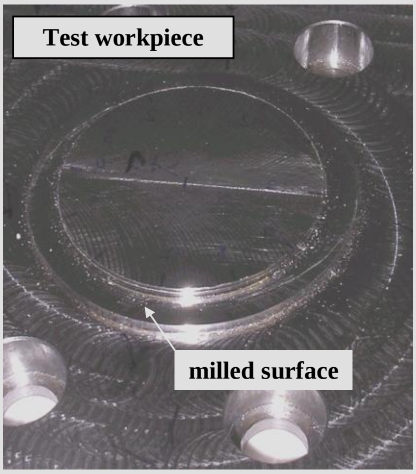
Table 1. Positions of milling tests

Position	X [mm]	Y [mm]	Z [mm]
1	0	-180	200
2	-170	55	200
3	170	55	200

Table 2. Measured stiffness at test positions

Position	c_x [N/µm]	c_y [N/µm]	c_z [N/µm]
1	34,7	37,4	61,3
2	60,6	31,2	35,0
3	28,7	47,2	65,5

Further for evaluating process forces a dynamometer KISTLER 9265 A was installed between the additional rotary table and the workpiece (Fig. 1 and 2). The get knowledge about significant vibrations a tri-axial accelerometer KISTLER 8965 C5M1 was mounted at the front of the working platform (Fig. 1). Relevant technological constraints can be seen in figure 3. For milling tests a new end mill with a cutting diameter of 16 mm and one cutting insert was used. The part material is steel C45 which was machined with a cutting velocity v_c of 380 m/min. During milling, all technological constraints have been kept constantly. Only the machining position and feed direction have been changed. In Fig. 3 (left) the test workpiece and the milled circular surface are shown.



Working space (area)	800 mm x 800 mm
Workpiece Material Area Heigth	 Steel C 45 (1.1191) 254 mm x 254 mm 100 mm
Cutting tool **Cutting insert**	End mill ∅ 16 mm Sandvik R390-012A16-11l P25
Cutting parameters Cutting velocity v_c Feed/tooth f_z Cutting depth a_p Infeed a_e **Feed direction**	 380 m/min 0,08 mm 1 mm 7 mm Circular milling X/Y-plane

Fig. 3. Test workpiece and technological constraints

4. RESULTS OF MILLING TESTS

4.1. SURFACE ROUGHNESS

The surface roughness and the evenness of the milled surfaces in the X-Y-plane were quantified. Therefore every of the three milled circular areas was divided into twelve single areas what is standardized in DIN EN ISO 4287. For every single area the surface roughness parameters *Rz* and *Ra* were evaluated with HOMMEL TESTER T8000. With an infinite stiffness of mechanical structure the workpiece surface is defined by the milling grooves. With the used parameters the minimally reachable dimension of the grooves is round about 1 μm. In Fig. 4 the evaluation strategy for surface roughness and the background for calculating the minimal milling groves are shown.

As can be seen in Fig. 5 at position P1 the roughness *Rz* is round about 150 percent of the minimal milling groove. At position P3 *Rz* increases up to 340 percent. Nearly the same position dependencies can be noticed for Ra. Considering direction dependencies, differences between various machining directions vary by more then the factor two. Minimum direction dependency occurs at P1. A greater directional dependency has to be

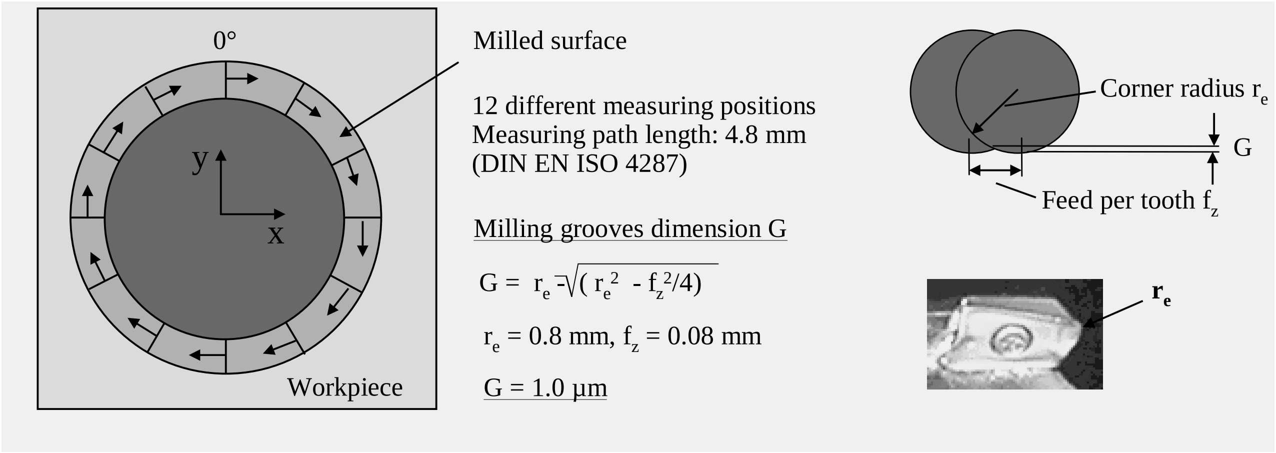


Fig. 4. Evaluation strategy for surface roughness and minimal theoretical groove dimension

noticed on the positions P2 and P3 on the edges of the workspace. At feed directions 60° and 300° both roughness values are nearly position-independent. Summarized the central position P1 is characterized by the best behavior which corresponds with the position- and direction dependent static stiffness of the machine tool.

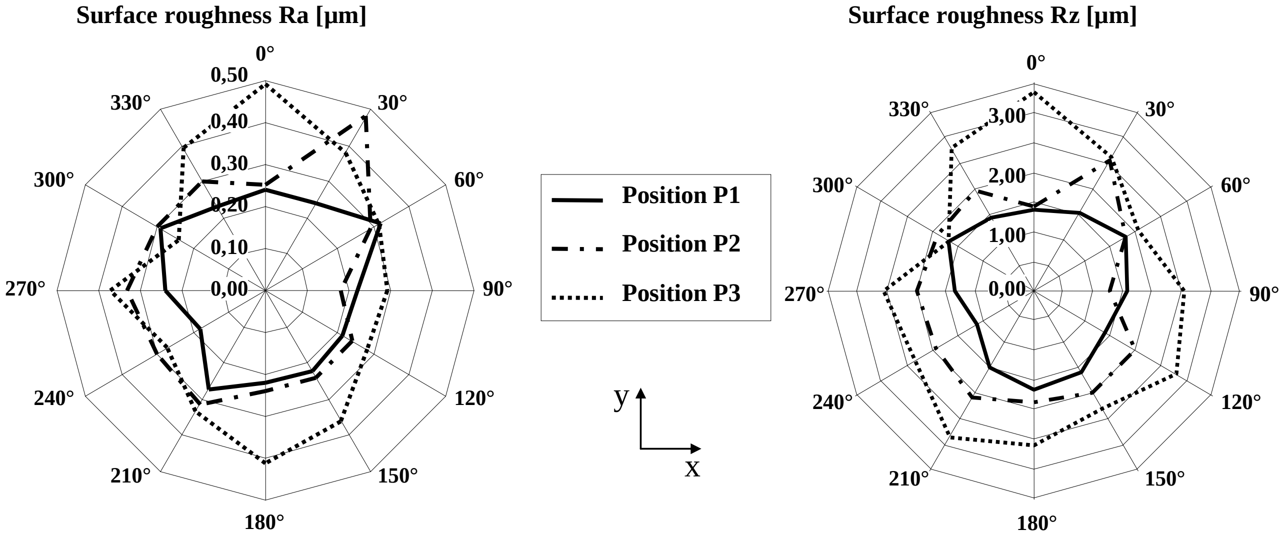


Fig. 5. Position- and feed direction dependent surface roughness parameters R_a and R_z

Furthermore, the results of three machining positions were compared with those of the similar-sized conventional five-axis milling machine DIGMA 850 HSC. As can be seen, the parallel kinematic machine METROM P 800 has a quality comparable to the conventional machine at the central position P1. But higher values of direction dependency of reachable surface qualities have to be recognized in comparison with the serial machine tool.

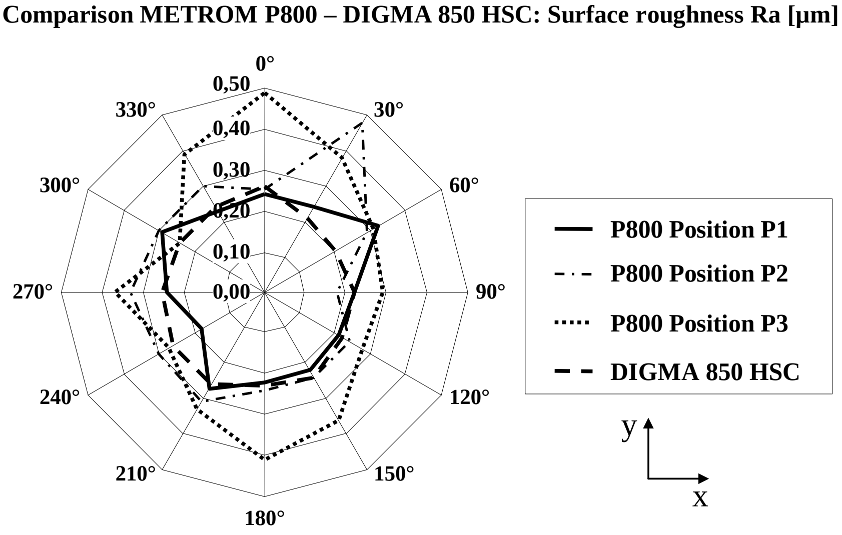


Fig. 6. Comparison of surface roughness *Ra* between METROM P800 and DIGMA 850 HSC

4.2. FORCES AND ACCELERATIONS

During milling, 250 values of global force components F_x, F_y, F_z using 3D-dynymometer (KISTLER 9265 A) were measured. The vector sum of the three average maximum force components are shown in Fig. 7 for the three positions. In addition to this

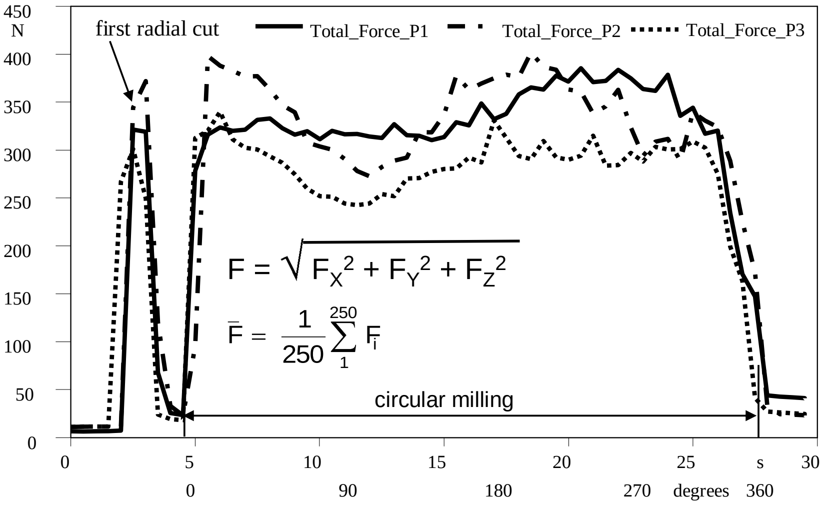


Fig. 7. Comparison of moving averaged total force *F* at three milling positions P1, P2, P3

the global force values were transformed into radial, normal and axial process force components. In Fig. 8 the position- and direction dependent axial process force component is shown. As can delivered from the measured axial acceleration (tri-axial accelerometer KISTLER 8695C5M1) the peaks at the beginning and in the middle of the circular milling test results from stronger vibrations of the working platform. In Fig. 8 the average of the maximum axial acceleration is shown. Comparing force peaks as well as acceleration peaks with the measured surface roughness values it can be reasoned that not only the direction-dependent static stiffness behavior is relevant for roughness variation but also higher direction-dependent vibration sensitivity of the kinematics. But as can be seen in Fig. 9 the absolute values of direction dependency of dynamic behavior are position-dependent but the qualitative characteristics is nearly the same.

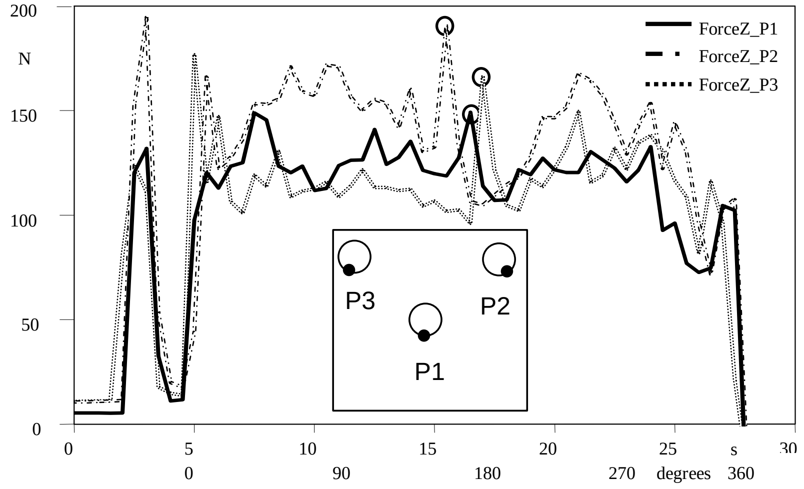


Fig. 8. Comparison of moving averaged axial force F_z at three milling positions P1, P2 and P3

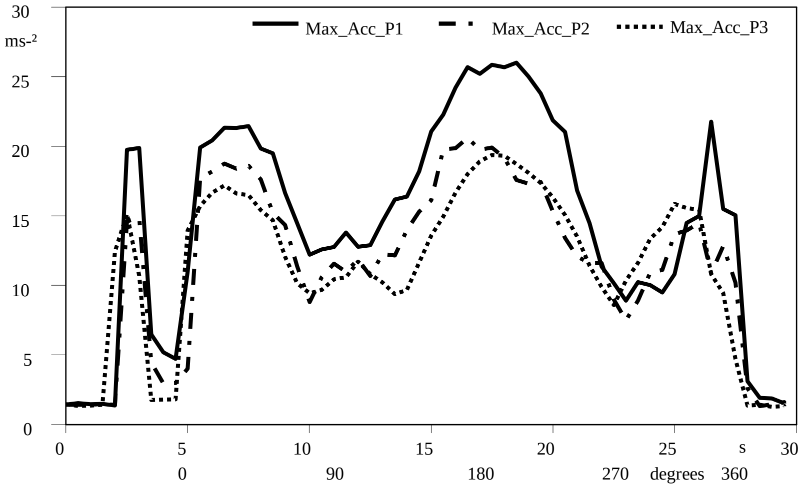
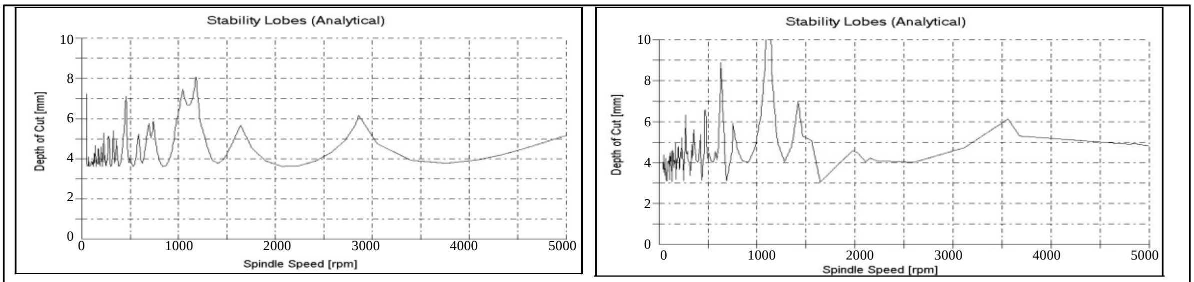


Fig. 9. Comparison of moving averaged axial acceleration a_z at three milling positions P1, P2 and P3

4.3. PROCESS STABILITY

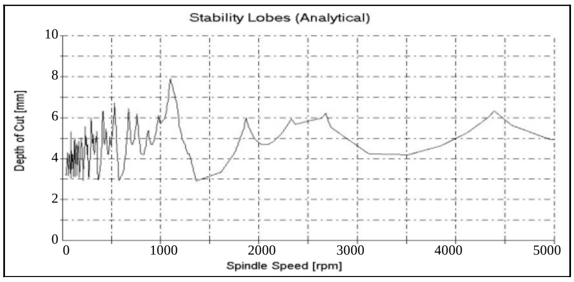
It will require a significant amount of time to experimentally determine the minimal depth of cut. However, to still be able to assess the position dependency of the limit of stability, it will be calculated based upon the frequency response properties taken from experimental analyses. This is also the reason why the frequency responses are measured on the tool in the center of three positions P1-P3. Furthermore, the response properties on the workpiece side were neglected because this factor is only of lesser importance.

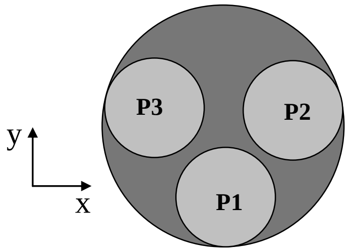
The CUTPRO software package (Manufacturing Automation Laboratories, Inc.) was used to calculate the minimal depth of cut while the metal-cutting and stability models that the software based on were published in [1][4][5]. The process parameters applied were mostly taken from the milling tests (refer to Fig. 3) with the difference of changing the number of cutting inserts from 1 (milling tests) to 2 (simulation stability lobes) and the width of the infeed a_e that is now 8 mm, half of the milling diameter. Finally, the feed direction was Y. Fig. 10 illustrates the three stability lobes calculated based upon the measured frequency response. As expected, this shows a pattern similar to the surface roughnesses measured. The difference of the position-dependent minimal depth of cut ranges between P1 and P2/P3, i.e. approximately 25%.



Position P1
Minimal Depth of Cut: 3,7 mm

Position P2
Minimal Depth of Cut: 3,0 mm





Position P3
Minimal Depth of Cut: 2,9 mm

Fig. 10. Stability lobes (analytical) based on experimental frequency response functions (feed: Y)

5. CONCLUSIONS

Experiments bear out the thesis that the position- and direction-dependency of the properties of pentapods also have an impact of the obtainable working qualities and process parameters. At the same time, these studies confirm that conclusions on the attainable process parameters can be directly drawn from the basic properties of the machine tool (such as stiffness and dynamic behavior). That means that the process limits behave approximately proportional to the machine properties. Thirdly, this article showed that the absolute processing parameters in serial machines are comparable to PKM designs. It can be stated that the best behavior can be obtained in the central areas of the machine. In other words, PKM differ from serial machines whose process limits are also position- and direction-dependent. Indeed, the best results are scored with serial machines in one corner of the AR while the poorest results are scored in the opposite corner (refer to Fig. 11).

If we are pursuing the visionary agenda of working on the limits of the process in the entire workspace, the availability of a model would be beneficial for process planning in particular with parallel kinematics. It would make sense to expand the mechanical model to process parameters to make quantitative statements.

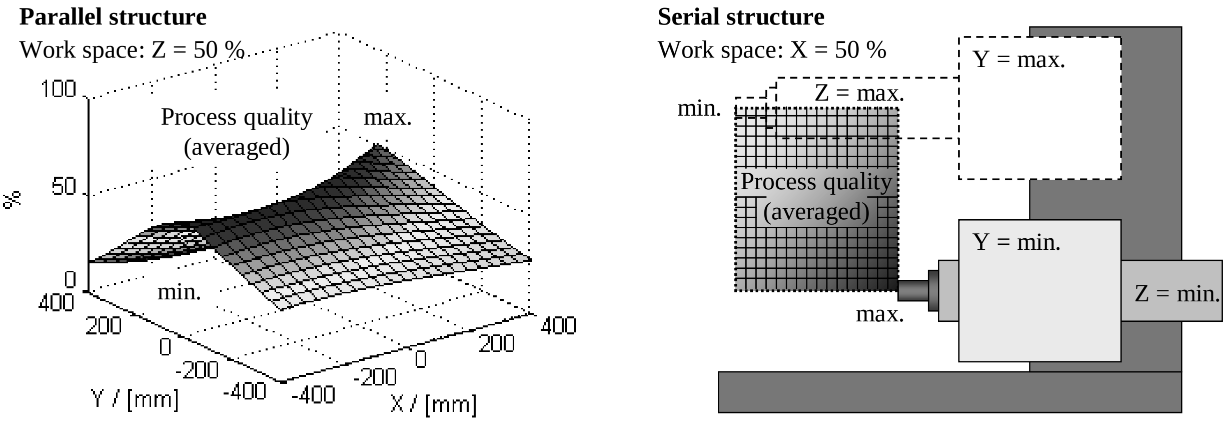


Fig. 11. Qualitative characteristics of the position dependency of processing behavior of parallel and serial machine tool structures

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