Surface Method for Vibration Analysis in Peripheral Milling of Solid Wood

Uwe Heisel, Harald Krondorfer

Institute for Machine Tools, University of Stuttgart, Germany

Abstract:

Deficient surface quality of planed solid wood workpieces is often the result of vibrations that cause periodic changes of the relative position between the workpiece and the tool. An exact knowledge of the frequencies and amplitudes of these vibrations is necessary to take specific measures to improve the surface quality. This paper deals with the application of a new method for identification of vibrations in woodworking. It will be shown how to draw conclusions about in-process vibrations from a workpiece surface which is machined with a specially prepared tool. A modified procedure for scanning the surface texture with a contact stylus instrument and numerical methods for analyzing the measured profiles allow the transfer of the surface method from homogeneous materials, for which it was developed, to inhomogeneous materials like wood. Finally, experimental results are discussed to show possibilities and limitations of the surface method.

Introduction:

Milling processes are, because of their wide range of applications, the most commonly used machining processes in woodworking. The attainable surface quality depends on the wear state of the tool and the properties of the material as well as on the woodworking process. Vibrations during machining result in general in a modified surface texture. Many models have been proposed to describe the milling process and the origination of the machined surface /1, 2, 8/. These models were mostlly developed for metalworking although they can also be used to describe planing of solid wood. An overview of the modeling and simulation of a machining process is given by Smith and Tlusty /8/. Elbestawi, Ismail and others describe the surface generation in milling, considering tool wear as well as vibrations /3, 7/.

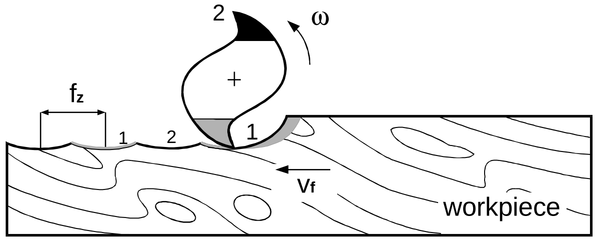
For the specific dynamic optimisation of a milling process, information about the vibrations which reduce the surface quality is imperative. A method which allows this information to be obtained directly from the machined surface was proposed in /4, 5/. This report discusses its application to woodworking machines using the example of a moulder.

Measuring the surface characteristics in solid wood using stylus contact methods often proves problematic /9/. However, using suitable measurement conditions a contact stylus profilometer can be used /6/. Surface simulations as well as experiments confirm the accuracy of the method.

Vibrations and surface quality

In peripheral plane milling the superposition of the rotational cutting motion and the translational feed movement results in cycloidal grooves on the workpiece surface, figure 1. The distance between two grooves (groove width) and their regular pattern are both important factors in the surface quality of a planed workpiece. An irregular pattern of grooves would be found unpleasant, particularly after varnishing or staining, and would lead to costly grinding operations becoming necessary. The groove width is determined by two process parameters, the feed rate and the rotational frequency of the cutter. Causes for an irregular groove pattern are vibrations during cutting as well as unequal tooth radiuses. Vibrations result in periodic changes in the relative position of the tool and workpiece and, depending on their frequency and phase, create grooves on the workpiece with irregular widths and depths.

vibration-free cutting:



relative motion imposed:

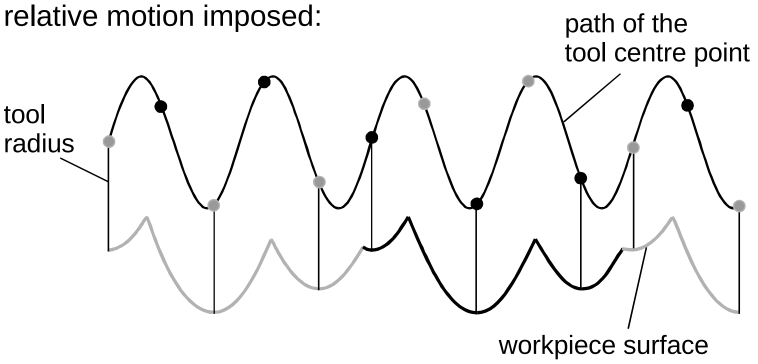


Figure 1: Origination of the surface profile in peripheral plane milling

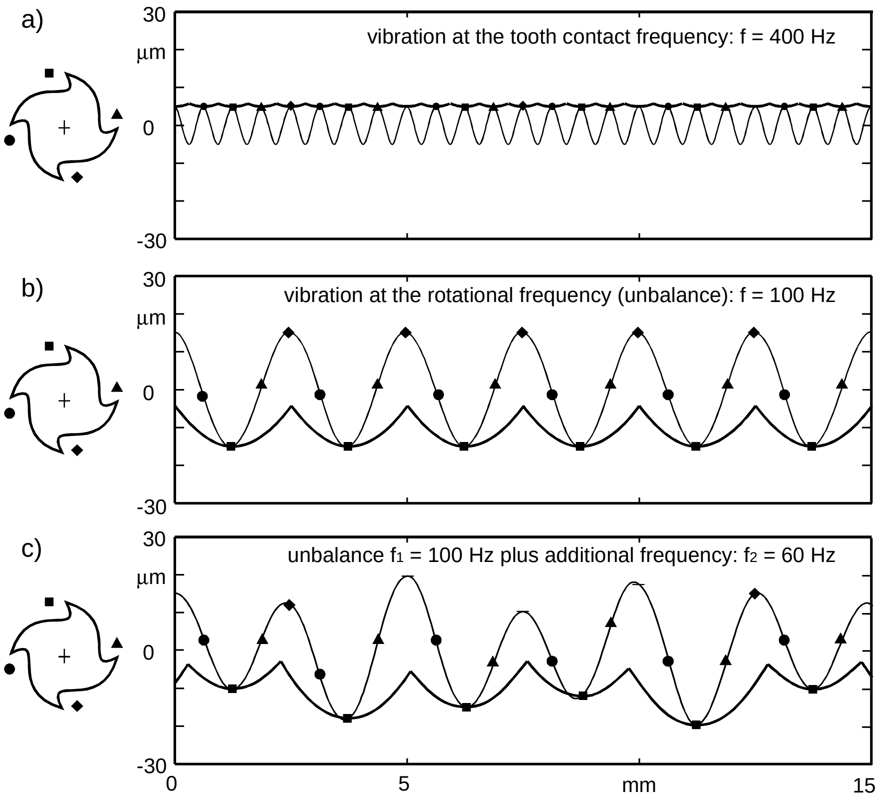


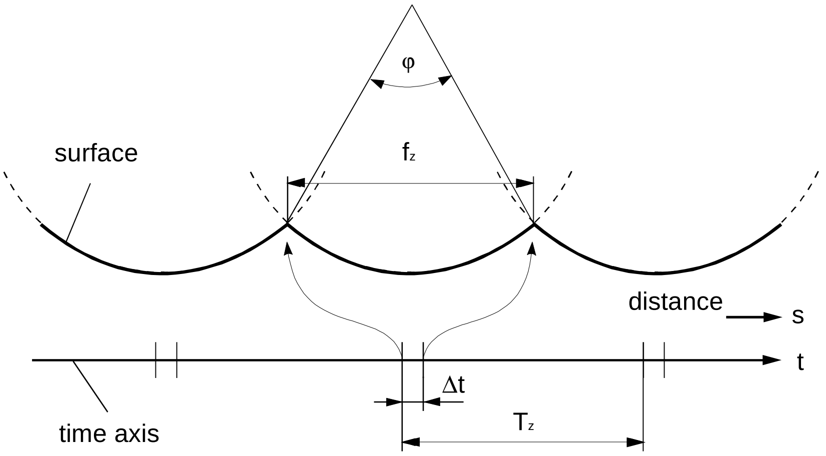
Figure 2: Irregular groove pattern due to vibrations

n = 6000 min^{-1},
v_f = 15m/min,
D = 140 mm

Simulations allow a prediction of the resulting surface profiles for various frequencies and phases of imposed relative movement. In figure 2, the relative motion between the centre point of the tool and the workpiece is marked with a thin line. The resulting workpiece surface is drawn thickly. The symbols represent the time points at wich the corresponding tooth leaves a knife mark on the surface. Vibrations at the frequency of the cutting teeth and its harmonics do not cause an irregular groove pattern but instead result in a quasi-static change in cutting depth, figure 2a. In woodworking machines the amplitude of the unbalance vibrations is usually so large that only one tooth is actually involved in cutting ("one knife finish"). In this case vibrations at the rotational frequency and its harmonics cause only a quasi-static variation in workpiece dimension and not an irregular groove pattern, figure 2b. Unequal cutting tooth radiuses have the same effect as an unbalance. Beyond a particular amount of runout only one tooth marks the workpiece surface. Grooves with unequal lengths and depths result from vibrations with a frequency different from the rotational frequency and its harmonics, figure 2c. The amplitudes of these interfering vibrations are normally small compared with the unbalance amplitude. This often leads to their significance for the surface quality being misjudged and incorrect optimisation goals being sought. An optimisation of the process dynamics must as a priority seek to remove the causes of these quality-reducing vibrations.

Surface method for vibration analysis

The time Δt to cut one groove in the workpiece surface is very small compared with the time T_z which passes between two successive tooth contacts, figure 3. High-frequency components of the vibration (> 5 times the rotational frequency) are normally of very small amplitude and can therefore be ruled out as a cause of reduced surface quality. During the short creation time Δt of a groove the relative position of the tool and workpiece barely changes. Thus one can talk of discrete creation time points t_N for the individual grooves.



$$\left.\begin{array}{l} \dfrac{\varphi}{2\cdot\pi} \approx \dfrac{f_z}{\pi\cdot D} \\[2ex] \Delta t \dfrac{}{T_z = z} \dfrac{\varphi}{2 \blacktriangleleft \square} \end{array}\right\} \quad \Delta t = \frac{f_z \blacktriangleleft T_z \blacktriangleleft z}{\pi\cdot D} = \frac{V_f}{V_c}\cdot T_z$$

Figure 3:
Estimation of the creation time for one groove

Vibrations during cutting influence therefore only the levels of the grooves and not their shapes. Information regarding the instantaneous relative position of the tool and workpiece can be taken from the level of the relevant groove's base. Assuming that the feed velocity v_f is small compared with the cutting speed v_c, the cycloid shape of the groove can be approximated by a circle segment of radius D/2. Using this simplification, the groove depth W_t , which would occur in vibration-free cutting, can be calculated :

$$W_t = \frac{1}{2} D\left(1-\sqrt{1-\frac{f_z^{\,2}}{D^2}}\right). \tag{1}$$

Vibrations during machining cause deeper penetration into the surface for some teeth. An already created groove can thus be partly or wholly removed by the following tooth. However, this does not mean that some teeth cut no material. For this the vibration amplitude would have to be larger than the cutting depth a_e , which is practically never the case. A so-called one knife finish results when because of unequal tooth paths or unbalance only one tooth leaves knife marks on the workpiece surface and so all grooves are due to a single cutting edge. The resulting groove depth can be calculated from equation (1) where the feed per tooth f_z is replaced by the feed per revolution.

In planing usually either a one knife finish occurs or a combined profile in which only a few of the existing cutting edges leave knife marks on the workpiece surface. Missing grooves mean a loss of information about the relative position of the tool and workpiece. To be able to obtain time domain information about the movement of the tool relative to the workpiece, it is necessary to ensure that during each revolution of the tool every single knife leaves behind exactly one groove in the workpiece. In order to achieve this a specially prepared tool, the so-called coded tool, is used, figure 4. Some areas of the cutting edges of this tool are ground back a small amount. Particular parts, the so-called coding teeth, are not ground back and thus trace a path of slightly larger radius than those on the rest of the cutter. The coding teeth are staggered in the axial direction to ensure that each coding tooth contacts the workpiece surface exactly once per revolution.

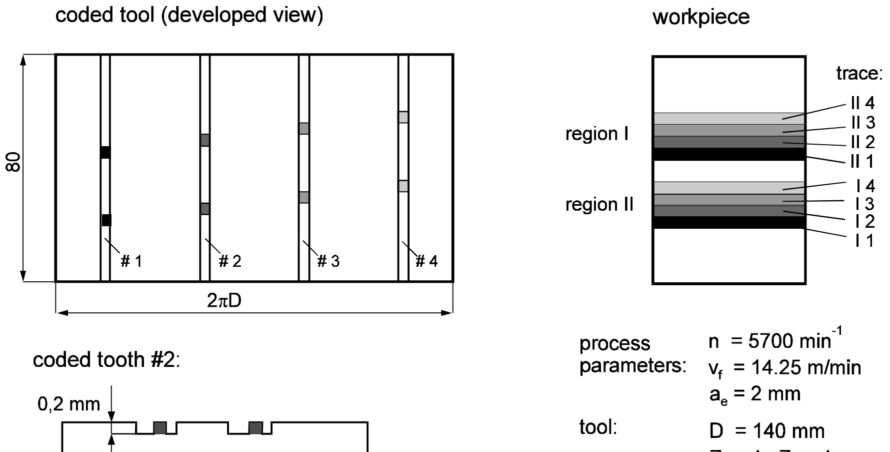


Figure 4:
Coded tool and resulting workpiece surface

The amount by which the teeth are recessed depends on the amplitude of the expected vibrations. It should not be chosen to be too large, because the ground back teeth must also play a part in the cutting process. Grinding them back too far would mean that the coding teeth would do a disproportionately large amount of the cutting and thus wear out quickly. Beside this there is the danger of torn grain which would mean that the grooves would not show accurately enough if at all.

Each coding tooth leaves behind its own trace on the workpiece. These traces are scanned with a contact stylus profilometer and the points at the bottoms of the grooves in each trace are determined, figure 5. These trough points represent the instantaneous relative position of the workpiece and tool at the time the groove was cut. The points from all the traces are then ordered together according to the times at which they were cut, and a time domain representation of the motion between the workpiece and tool is obtained. The order in which the points are placed togther depends on the arrangement of the coding teeth on the tool. Assuming a constant rotational speed and equally-spaced coding teeth on the circumference of the tool the intervals between successive points in the time domain signal are all equal. This is an important property for the next step, a Fast Fourier Transform (FFT) of the time domain motion signal. The result of the FFT is the frequency spectrum of the motion which contains the required information regarding the frequency, amplitude and phase of the vibration, figure 5.

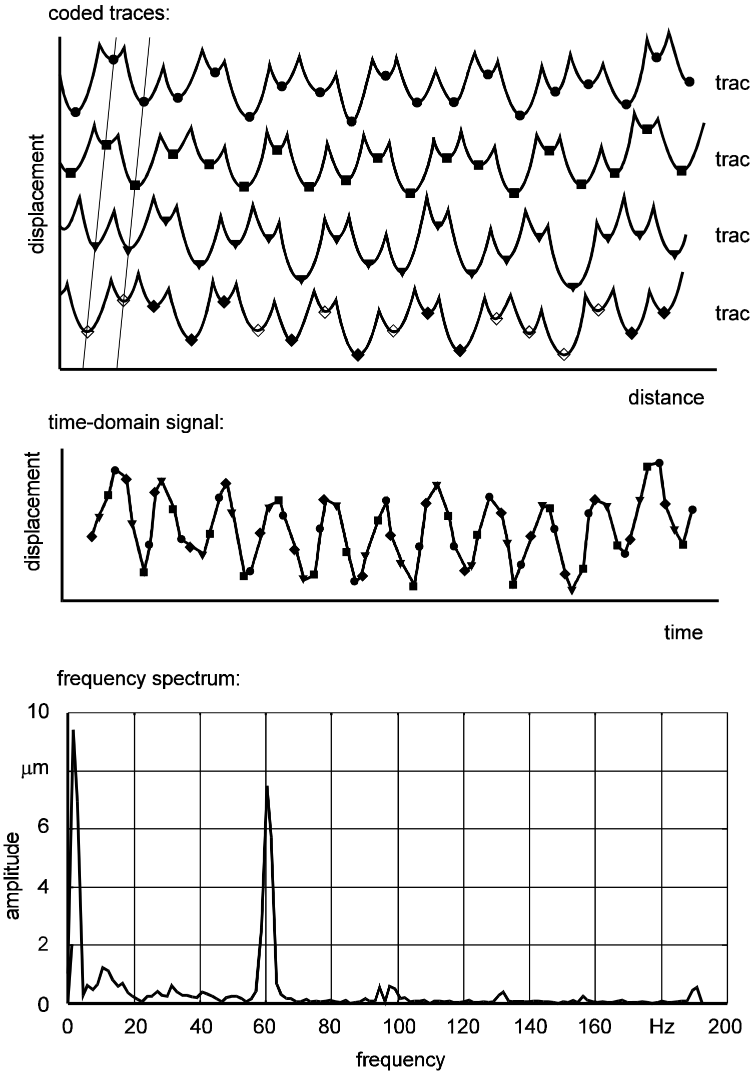


Figure 5:
Time domain signal generated from groove trough points and corresponding frequency spectrum

If a one knife finish is obtained, vibrations at the rotational frequency and its harmonics do not result in an irregular groove pattern but merely in a quasi-static variation in dimension of the workpiece. They thus do not impair the surface quality, compare figure 2. Measuring vibrations with conventional methods (accelerometers) normally results in frequency spectra in which this unbalance and its harmonics dominate because of their large amplitudes. The vibration components which are responsible for poor surface quality are therefore easily overlooked in the frequency spectrum. The surface measuring method offers the possibility of comparatively simply filtering the unbalance and its harmonics out of the spectrum.

According to the amplitude of the unbalance and the amount of difference in tooth radiuses, the traces on the workpiece lie at different levels, figure 6a. The levels of the recorded traces are equalized by subtraction of each trace's mean value, figure 6b. Because of this level compensation the influence of the unbalance and its harmonics is eliminated before the time domain signal is generated. In the frequency spectrum the unbalance vibration and its harmonics thus no longer appear.

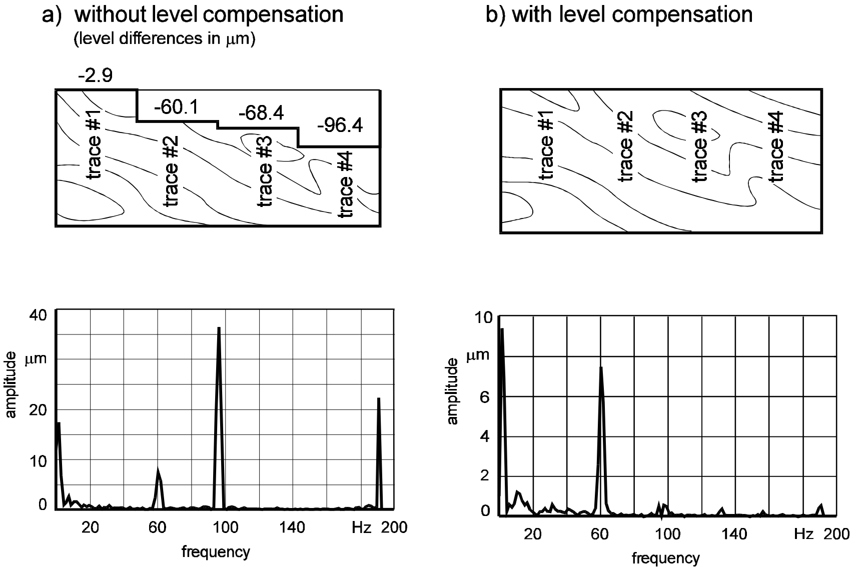


Figure 6: Workpiece cross-sections and frequency spectra withand without level compensation

Limitations of the method

The surface method is limited to peripheral plane milling processes. Other limitations are determined by the tool's rotational frequency and the feed rate, the traverse length of the profilometer and the geometry of the tool (its diameter and number of coding teeth).

The maximum frequency which can be identified depends on the rotational frequency as well as the number of coding teeth z_c. According to Shannon's theorem for the sampling of periodic signals the maximum identifiable frequency f_{max} is less than half the sampling frequency f_{sample}. The sampling frequency is determined by the rotational frequency and the number of contacts per rotation of the tool (the number of coding teeth z_c):

$$f_{\max} < \frac{1}{2} \cdot f_{sample} = \frac{1}{2} \cdot n \cdot z_c . \tag{2}$$

The frequency resolution Δf is equal to f_{max} divided by half the blocksize N (the number of points in the time domain signal). The blocksize N depends in turn on the tool's feed per revolution f, the number of coding teeth z_c and the traverse length l of the profilometer:

$$N = \frac{l \cdot z_c}{f} . \tag{3}$$

For the frequency resolution Δf results then

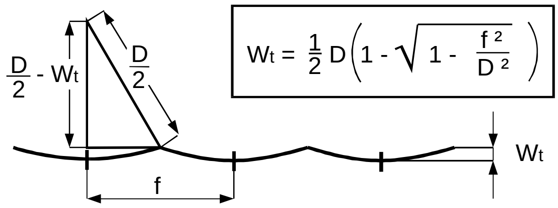
$$\Delta f = \frac{2 \cdot f_{\max}}{N} = \frac{v_f}{l} \qquad . \tag{4}$$

The amplitude limit A_{max} for the surface method is determined by the diameter D of the tool, the feed per revolution f and the ratio η between the vibration frequency and the rotational frequency of the tool:

$$A_{\max} \leq \frac{D}{4 \cdot \sqrt{\sin^2(\eta\pi)}} \cdot \left(1 - \sqrt{1 - \frac{4f^2}{D^2}}\right), \quad \text{with} \qquad \eta = \frac{f_S}{f_T} . \tag{5}$$

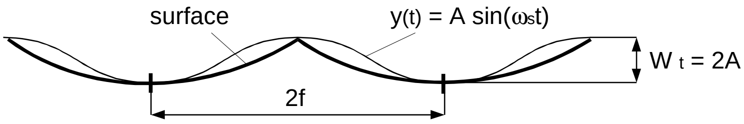
Figure 7a shows the profile of one trace as created by machining without vibrations. The cycloid-shaped grooves are assumed for simplicity to be circle segments. Equation (1) for calculating the groove depth w_t is derived then from simple consideration of geometry. Vibrations during the machining cause a number of the knife marks created to be very deep whilst others are very short and shallow. Figure 7b shows as an example the worst case of a vibration at half the rotational frequency of the tool ($\eta = 0.5$).Once the amplitude limit A_{max} is exceeded, these short grooves are completely removed. The coding tooth leaves a groove on the surface only every second revolution. Frequency ratios $\eta \neq 0.5 + i$; i = 1, 2, ... result in slightly larger amplitude limits. The poles of equation (5) lie at the harmonics of the rotational frequency. In those cases, all coding teeth contact the workpiece exactly once per revolution independently of the amplitude. However, the vibration leads to different mean levels in the traces. If the amplitude limit is exceeded, information about the relative movement between tool and workpiece is lost.

a) vibration-free cutting: regular groove spacing



$$W_t = \frac{1}{2} D\left(1 - \sqrt{1 - \frac{f^2}{D^2}}\right)$$

b) maximum amplitude: one groove disappears due to vibration



ω_s: Frequency of imposed vibration
T: Rotation time of the tool $\omega = 1/T$: Rotational frequency

$$y(T/2) = A \sin\left(\pi \frac{\omega_s}{\omega}\right) = \tfrac{1}{2} W_t$$

$$\boxed{\Rightarrow A = \frac{D}{4\sqrt{\sin^2(\pi\omega_s/\omega)}} \left(1 - \sqrt{1 - (2f/D)^2}\right)}$$

Figure 7: Determination of the amplitude limit

Scanning the profile of wood surfaces with a contact stylus profilometer is problematic because the material is inhomogeneous. Clearly shaped grooves are required in order to determine their trough points with sufficient accuracy. The amplitude limit A_{max} is therefore reduced to smaller values.

Application to solid wood surfaces

Contact stylus techniques are widespread for the measurement of metal and wood surface profiles /8/. A stylus is drawn over the surface at a constant speed and its height changes relative to a reference level (reference surface measurement technique according to DIN 4772) is recorded. A two-dimensional profile of the workpiece surface is obtained as a result.

For the application of the surface method to solid wood workpieces problems in scanning the traces with the profilometer can occur as well as in finding the bottoms of the grooves. The grooves originating from the kinematics of the machining process are overlaid by a surface roughness. This depends on the properties of the material, the cutting angles of the tool and the chosen process parameters as well as the wear condition of the tool. This roughness manifests itself in fuzzy and torn grain. The dimensions of exposed fibres and pores in the surface can under certain circumstances be several times larger than the groove depth.

Generally spherical stylus tips of radius 2.5 µm to 5 µm are used for surface measurements with a profilometer. Stylus tips with that kind of small radius also register the smallest of pores. Moreover, the stylus force in modern profilometers is extremely small (about 1 mN). In general this is definitely desirable for roughness measurements, on one hand to avoid penetration of the stylus into the surface and on the other to register the material-specific roughness. Small fibres can also cause a deflection of the stylus. The influence of fibres and pores makes the measurement of the coded grooves practically impossible under standard scanning conditions.

The influence of pores on the measurement result can be minimised or even avoided by using a modified stylus tip geometry. However, with spherical tips of large radius short grooves are no longer registered. Wedge-shaped tips with a comparatively large dimension perpendicular to the measurement direction (b = 0.8 mm or 1.6 mm) and a small radius in the measurement direction (r = 2.5 µm) offer some help. Because of its large width the stylus will glide over pores, but because of its small radius short grooves will also be detected. An increased contact force can prevent individual fibers deflecting the stylus. Both measures - increased contact force and the use of a wedge-shaped stylus tip - operate like a mechanical filter which suppresses the interfering influence of the material's roughness.

The effectiveness of this filter can be confirmed by comparative measurements with a homogeneous plastic material (acrylonitrile-butadiene-styrene copolymer - ABS). To do this a test workpiece was machined which was made of wood with an inlaid plastic strip. Because both materials were machined at the same time the surface profile measured in the plastic can serve as a reference. In figure 8 the profile scanned from the wood surface is compared with the appropriate reference profile (in the ABS). If a standard stylus and a contact force of 1 mN is used, no similarity is recognisable between the two profiles, figure 8a. Using a larger contact force and a wedge-shaped stylus a good similarity is achieved, figure 8b.

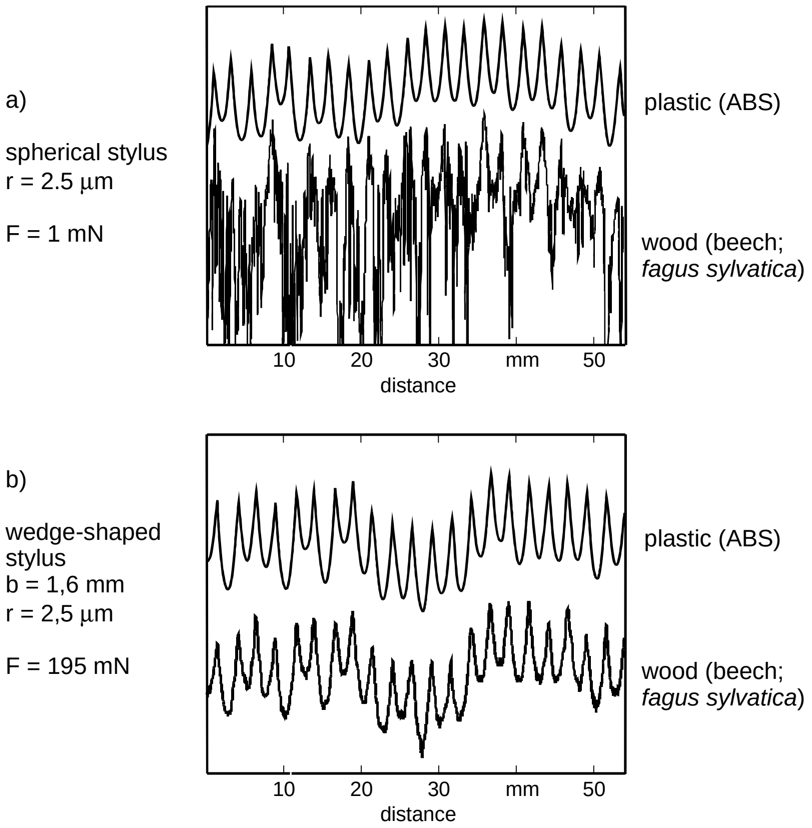


Figure 8:
Surface profiles scanned under different scanning conditions

Despite the increased contact force the profiles measured from wood surfaces are, especially in the regions of the bottoms of the grooves, not completely smooth. Finding the trough points of the grooves is thus made more difficult by these freak values in the measured profile. The application of numerical methods is of help in determining the positions of the trough points. Each groove is approximated by a segment of a circle of the tool radius. The centre point of this circle is moved in iterative steps until the curvature and the actual measured points correspond as well as possible. An optimum correspondance is assumed to be found when the RMS error is minimum. The trough point of the groove is then assumed to lie directly underneath this calculated centre of curvature.

Experimental Investigations

The experiments in the application of the surface measuring process to woodworking described here were performed on the horizontal spindle of a moulder. In order to be able to assess the influence of the inhomogeneous properties of the wood, once more test workpieces with inlaid plastic strips were machined. The coded tool, figure 4, was set up in such a way that coding region I cut the wood whilst coding region II cut the plastic. During machining a vibration of known frequency and amplitude was introduced from an electrodynamic shaker via a ball bearing mounted at the free end of the spindle. Figure 9 shows a sketch of the experimental setup. The vibration amplitude was adjusted before machining and controlled using an accelerometer positioned on the tool in coding region I (wood). In addition the amplitude was measured using a non-contact distance sensor. This sensor was directed on a ground and hydrostatically centred bush on the end of the spindle and allowed the vibration amplitude to be checked during machining as well. Because of the mode of the introduced vibration (a bending vibration perpendicular to the workpiece surface) the largest amplitude occurs at the spindle end and the smallest in coding region II (plastic). The geometry of the setup allows the amplitude ratio between the wood and plastic areas to be determined.

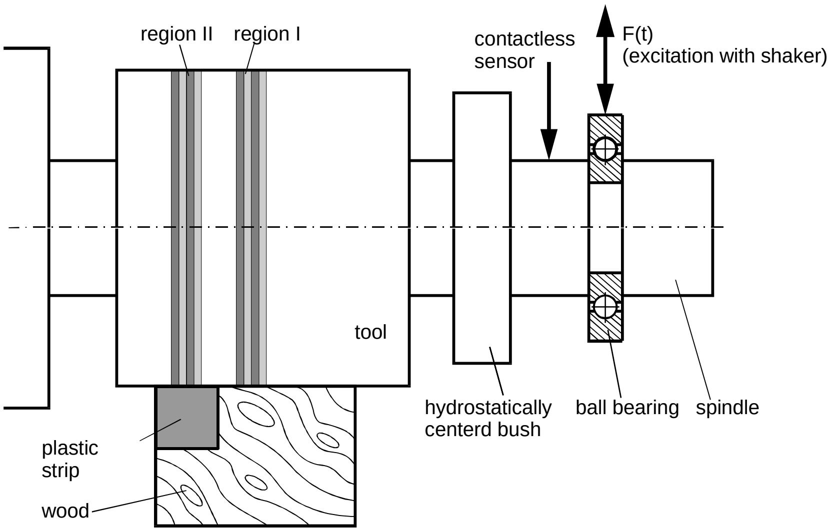


Figure 9:
Experimental setup

The frequency of the vibration introduced was 60 Hz in all experiments. The amplitude was increased step by step. It was set to 2.5 µm, 5.0 µm, 7.5 µm and 10.0 µm in coding region I. The surfaces of the machined workpieces were scanned with the profilometer and analysed.

By considering the chosen process parameters and the known introduced vibration the resulting surface profiles can be simulated. Figure 10 compares a coded trace measured in wood with the simulation result. The simulation and the measured profile show good similarity in the arrangement of the trough points as well as the groove depth and length.

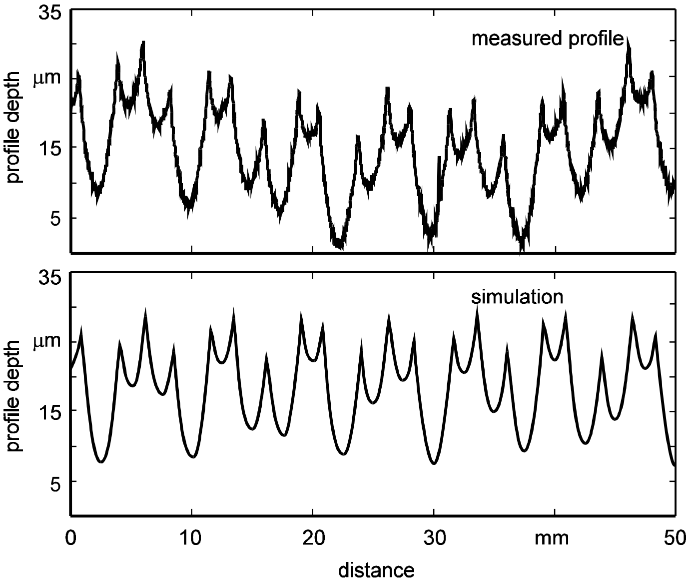


Figure 10:
Measured and simulated surface profiles of a coded trace

The results obtained from the surface analysis are the frequency spectra shown in figure 11. The height of the peaks at the introduced frequency of 60 Hz corresponds to the amplitude introduced in each case. A mean level compensation was performed in the analysis of the traces, so the spectra contain no vibration components at the rotational frequency (95 Hz).

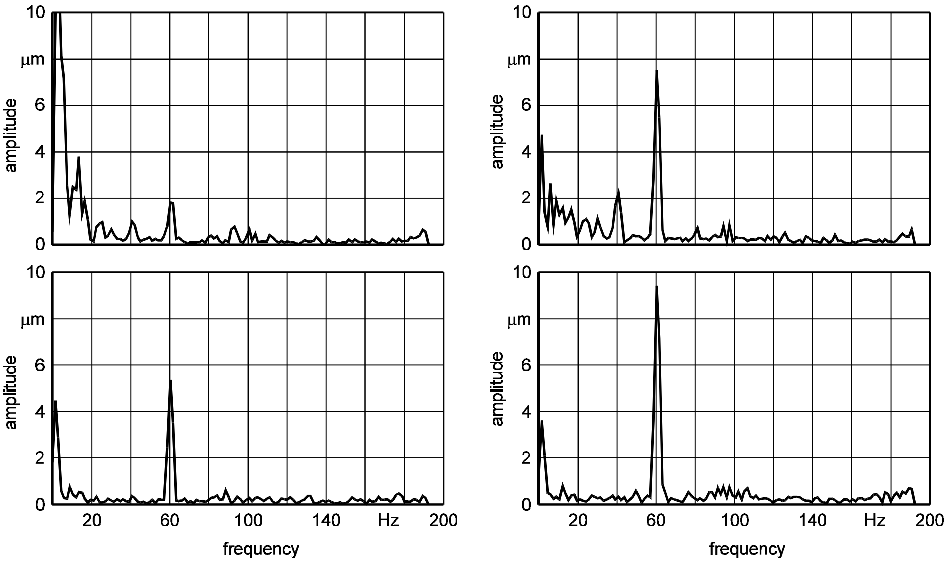


Figure 11:
Results of the vibration analysis using the surface method

vibration amplitudes in mm: f = 60 Hz			
region I (wood)		region II (plastic)	
introduced	identified	introduced	identified
2.5	1.8	2.05	1.72
5.0	5.36	4.10	4.45
7.5	7.51	6.15	6.76
10.0	9.43	8.20	7.49

Table 1:
Introduced and identified vibration amplitudes

The maximum discrepancy between the amplitude introduced and that identified from the surface is smaller than 1 µm. A comparison between the results for the plastic and the wood gives, as expected, smaller amplitudes in the plastic region, table 1. The amplitude difference between the plastic and wood regions corresponds to the amplitude difference resulting from the mode of vibration.

Conclusion

The experiments confirm that the surface method for vibration analysis is applicable to solid wood surfaces. Within the limitations discussed, the frequencies and amplitudes of relative movements between tool and workpiece can be detemined with good accuracy. Under some restrictions the mode of the vibration can also be found by comparing amplitudes in two adjacent coding regions. For example, in the described machining on the horizontal spindle of a moulder the introduced vibration mode (bending of the spindle) led to larger amplitudes in coding region I, nearer the end of the spindle.

The surface method for vibration analysis offers essentially three advantages. Firstly, relative movements between workpiece and tool can be measured at the cutting point, which conventionally is possible only with extremely complex measurement technology if at all. Secondly, the time required for machining a workpiece with a coded tool is extremly small compared with other test methods. The machine only needs to be taken out of the production process for the short time this machining takes. While the actual surface measurements and vibration analysis are done, the machine can be used for normal production. Thirdly, the surface method allows a vibration analysis to be made at a distance. Only a workpiece machined with the coded tool and the chosen process parameters are necessary to do this. Because of this, this technique is suited to regular checks of the state of a machine. At regular intervals similar test workpieces can be machined and the resulting vibrations documented. The surface method is thus an important supplement to existing techniques for investigating the dynamic behaviour of machines.

References

/1/ Altintas, Y.; Montgomery, D.; Budak, E.: Dynamic Peripheral Milling of flexible Structures. ASME J. of Eng. for Ind. Vol. 114 (1992), pp. 137-145.

/2/ Ehmann, K. F.; Hong, M. S.: A Generalized Model of the Surface Generation Process in Metal Cutting. Annals of the CIRP, Vol. 1/43 (1994), pp. 483-486.

/3/ Elbestawi, M. A.; Ismail, F.; Yuen, K. M.: Surface Topography Characterization in Finish Milling. Int. J. Mach. Tools Manufact., Vol. 2/34 (1994), pp. 245-255.

/4/ Heisel, U.: Vibrations and Surface Generation in Slab Milling. Annals of the CIRP Vol. 1/43 (1994), pp. 337-340.

/5/ Heisel, U.; Fischer, A.: Von der Oberfläche zur Maschinenbeurteilung beim Umfangsplanfräsen. HOB - Die Holzbearbeitung, Vol. 39 (1992), Nr. 6, pp. 30-34.

/6/ Heisel, U.; Krondorfer, H.: Meßtechnik für Massivholzoberflächen. HOB - Die Holzbearbeitung, Vol. 42 (1995), Nr. 5, pp. 205-207.

/7/ Ismail, F.; Elbestawi, M. A.; Du, R.; Urbasik, K.: Generation of Milled Surfaces Including Tool Dynamics and Wear. ASME J. of Eng. for Ind., Vol. 115 (1993), pp. 245-252.

/8/ Smith, S.; Tlusty, J.: An Overview of Modeling and Simulation of the Milling Process. ASME J. of Eng. for Ind., Vol. 113 (1991), pp. 169-175.

/9/ Yoo, S. M.; Dornfeld, D. A.; Lemaster, R. L.: Analysis and Modeling of Laser Measurement System Performance for Wood Surface. ASME J. of Eng. for Ind., Vol. 112 (1990), pp. 69-77.