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Laser scanned patterns of machined surfaces

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Abstract

In this contribution, machined surfaces are analyzed corresponding to the dynamic aspects of cutting operation. Productivity is limited due to harmful vibrations that deteriorate the quality of the machined surface. The related surface pattern carries the history of the resultant relative vibrations, thus the dynamical properties of the machining system could be extracted. To describe the surface of a machined workpiece, a laser displacement sensor is applied for scanning purposes. The measurement procedure of the surface scanning is described, its applicability and limitations are also discussed. In turning processes, the static displacement error and the arising chatter frequency are analyzed along a shaft by means of the measured diameter offset and gradient of the chatter marks, respectively.

Keywords: Machining; Chatter; Laser scan; Surface analysis;

1. Introduction

In the manufacturing industry, productivity is a key factor besides quality, efficiency and sustainability. However, productivity cannot be increased arbitrarily due to undesired vibration that may arise during the cutting process. This harmful vibration is the so-called chatter which leads to unacceptable surface quality or even to possible damage in the machine-tool-structure. Therefore, it is an essential task of mechanical engineers to predict the dynamic behaviour of a machining process in order to achieve high material removal rate, thus to increase the production rate in manufacturing while also avoiding chatter.

In turning operation, the most commonly accepted explanation of the self excited vibration is the surface regenerative effect which can be described as a time delayed system where the position of the cutting edge in the previous revolution affects the chip evolution (see the detailed mechanical models in [1,2]). Several studies on the corresponding chatter vibrations are summarized in [3].

The so-called stability chart [4] presents the chatter-free (stable) domains of technological parameters which are usually illustrated in the plane of the spindle speed and the depth of cut.

The experimental construction of these maps is usually based on chatter detection techniques [5], which often do not require stability lobe calculations (see, for instance, [6,7]). Some of them investigate the resultant spectrum of the sensors (typically industrial microphone and/or accelerometer) in frequency domain [8,9] or the sampled time signal is analysed in time domain [10,11]. In some cases, the applied techniques cannot define well stability properties, which are usually referred to as marginally stable, the final human qualitative decision based on surface patterns is needed [12].

During cutting, relative vibrations are copied onto the surface and leave surface patterns (chatter marks) there. The spectral properties of the machining process can be obtained by means of analysing the spectrum of the surface marks after the cutting operation. This can give an insight into the stability of the machining operation, for instance, this can help detecting chatter frequency in case of stability loss.

In this paper, we introduce a method which is capable to reconstruct dynamic properties from machined surface patterns by means of scanning and analysing the chatter marks.

The structure of the paper is as follows. First, the applied laser scanning method is described in details in order to reconstruct the surface errors in case of cylindrical parts (see Section 2). Then, the mathematical analysis of the reconstructed surface is described, namely how to trace the static deformation error and how to detect the frequency of the self excited vibration. This section gives an analytical formula for the identification of the chatter frequency. Then, experimental results are presented through a real case study (see Section 3).

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Table 1. Main paremeters of the used Laser Differentiation Displacement Sensor.

Type	KEYENCE IL-030
Analogue voltage output U	±5 V
Measurement range	±5 mm
Sensitivity	1 mm/V
Sampling frequency	3000 Hz
Nominal accuracy/repeatability[1]	1 μm
Spot dimensions (at reference distance)	200×750 μm
Operation principle	triangulation

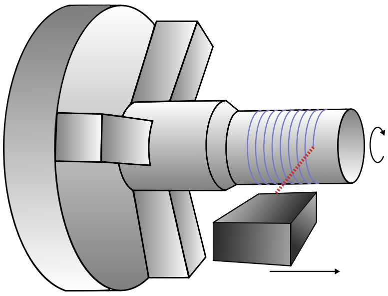

Fig. 1. Scanning method of peripheral object

2. Laser scanning method

In order to achieve reconstruction of dynamic properties from surface marks, it is needed to digitize these patterns. For this purpose, an industrial laser differentiation displacement sensor was applied, which can measure the surface deviation from the ideal geometry. This difference between the pre-set (idealised/nominal) geometrical dimensions and the measured surface patterns carries information about the vibration induced surface errors. In order to check the 2D surface of structures, the laser sensor's path is controlled by NC machine and processed further in MATLAB environment (see Section 2.1-2.2). The parameters of the applied sensor can be found in Table 1.

In case of cylindrical workpieces, the surface scanning method consists rotating of the movement of the workpiece and the feed movement of the laser sensor, which creates helical laser path (see left panel in Fig. 1). We set the rotating speed and the feed velocity according to the sampling frequency of the laser displacement sensor in order to keep uniform grid along the circumference and the length of the workpiece.

For scanning flat surfaces (e.g.: milled parts), as an appropriate choice, the laser sensor is moved along a zig-zag path which covers the area of interest. The distance between the straight paths are set for few hundreds of microns in order to get uniformly distributed grid along the scanned area.

According to the accuracy of the sensor, it can be a suitable option to reconstruct the surface pattern and waviness, which are sufficient for the purpose of this study. On the other hand, one limitation of the sensor is that the laser spot is not an ideal point, it is elliptical with extension about 200×750 μm. In this way, the sensor measures the average position of the rough surface belonging to this area. Since this effect can be considered as a moving average along the path, this is not a proper method to measure the surface roughness accurately, other technique could be more appropriate for this purpose.

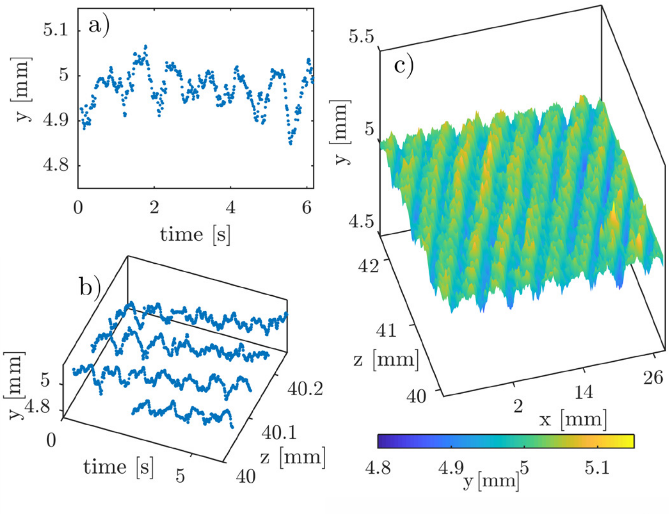

Fig. 2. a) Measured time history of the laser sensor; b) splitted signal for each revolution in order to get the point cloud in cylindrical coordinate system; c) reconstructed surface with the help of delaunay triangulation.

2.1. Processing of measurement data

Since the sensor measures time signal only (see Fig. 2a), the measured data have to be preprocessed in order to reconstruct and analyse the surface. In case of cylindrical parts, it is needed to split the recorded time signal under each revolution, that is, to transform it into a cylindrical coordinate system (see Fig. 2b). Then, 2D unfolded surface profile can be obtained with the help of delaunay triangulation, which is a proper tool to create 2D surfaces from a point cloud [13].

2.2. Analysis of the reconstructed surface

In order to extract spectral properties, firstly, the measured time history signal is transformed into real time representation with the following condition:

$$t_{\mathrm{real}} = \frac{v_{\mathrm{l}}}{v_{\mathrm{c}}} t, \tag{1}$$

where t_{real} is the time "coordinate" during the real machining process, t is the time during the scanning operation; v_{l} and v_{c} are the speed of the laser sensor and the cutting insert along the shaft's circumference, respectively.

From the reconstructed surface, the static deformation error can be obtained, which is the deviation between the pre-set geometry and the machined surface; this is caused by the deformation due to the cutting force in case of stable turning operation. Corresponding experimental results are presented in the next section.

In case of highly flexible workpiece (e.g.: slender shaft, tubular parts), large static deformations take place, which can lead to an offset error in the diameter. This error can be significant and must be included in the modelling, since it modifies

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[1] measured as an average of 0.128 s duration measurement with 1000 Hz sampling frequency

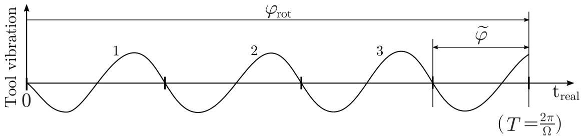

Fig. 3. Schematic representation of tool position under one revolution in case of chatter vibration at ω_c frequency at the third lobe.

the resultant diameter and changes the chip width for the next immersion [14].

The main application of the machined surface analysis can be found in unstable operation. In case of self excited vibration in turning, a chatter frequency ω_c is emerging which causes wavy surface along the shaft's circumference. In a typical turning process, the so-called lobe number n [15] is large, that is the chatter frequency is much larger than the spindle frequency Ω, which creates multiple waves on the surface under one revolution ($n = \mathrm{floor}(\omega_c/\Omega)$, see Fig. 3). The chatter frequency usually differs from any of the natural frequencies of the workpiece-tool holder-machine structure or the spindle speed. Therefore, the so-called regenerative phase shift $\widetilde{\varphi}$ appears revolution by revolution between the waves left on the surface during two subsequent turns (see Fig. 3). This additional vibration can be recognised from the slopes α of the scanned surface patterns (see Fig. 6a). The tangents of the slope is determined as $\tan\alpha = \widetilde{\varphi}R/h$, where h is the feed per revolution and R is the radius of the shaft.

Based on the surface reconstruction, these two parameters $(n, \widetilde{\varphi})$ can be extracted directly, from which the chatter frequency can be explicitly derived.

First, consider the total regenerative phase of chatter vibration under one revolution:

$$\varphi_{\mathrm{rot}} = \omega_c T = \omega_c \frac{2\pi}{\Omega}. \tag{2}$$

The regenerative phase shift can be calculated as

$$\widetilde{\varphi} = \frac{\mathrm{mod}(\omega_c, \Omega)}{\Omega} 2\pi, \tag{3}$$

where the modulo operation mod(., .) finds the remainder after division which can be expressed as:

$$\mathrm{mod}(\omega_c, \Omega) = \omega_c - \Omega\,\mathrm{floor}\left(\frac{\omega_c}{\Omega}\right). \tag{4}$$

Rearranging the above equation, the frequency of the self-excited vibration can be expressed as follows:

$$\omega_c = \Omega\left(\frac{h}{D\pi}\tan\alpha + n\right). \tag{5}$$

The above described measurement technique is applied in a case study in the following section.

Table 2. Applied workpiece and technological parameters.

Initial diameter D	42 mm	Material	34CrNiMo6
Total length L	363 mm	Density	7800 kg/m^3
Cutting length l	308 mm	Elasticity	220 GPa
Chip thickness h	0.2 mm	Rake angle	26.5°
Spindle Speed Ω	3500 rpm	Clearance angle	45°

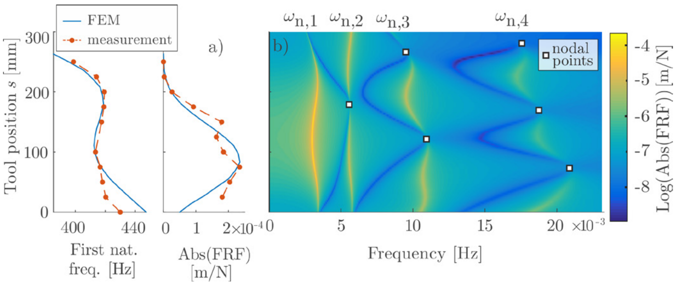

Fig. 4. a) Measured and calculated values of the first natural frequency and the corresponding peak values of the receptance functions; b) Tool position dependent Frequency Response Function together the nodal points [16]

3. Case study

Several cutting tests were performed in a Doosan Puma 2500Y CNC lathe with a Sandvic SNMM 12 04 12-PR 4215 insert in PAFANA hR 111.26 2525 tool holder on a 34CrNiMo6 workpiece. The technological parameters are presented together with geometry and material properties in Table 2. Note that the workpiece was a thin long shaft fixed at both ends, therefore its dynamic properties were changing as a function of the tool position.

In case of such a flexible workpiece, its dynamics can significantly change during the cutting operation in two different ways.

One corresponds to the motion of the cutting tool, which is taken into account by means of the mode shapes, represented by the varying Frequency Response Function (FRF) amplitude along the tool path in Fig. 4b. The other effect of the changing dynamic properties relate to the effect of the material removal process. It leads to varying workpiece geometry and correspondingly varying dynamical parameters, such as natural frequency, damping and stiffness. Figure 4a presents the first natural frequencies and the corresponding peak values of the direct receptance functions at a given tool position after the material segment was removed. It can be seen, that the first natural frequency changes a lot along the tool path. Therefore, in case of stability loss, the frequency of the self excited vibration will change accordingly.

For the static displacement error, the static stiffness variation is relevant only. This variation can be seen in the coloured 3D FRF plot at 0 frequency (see Fig. 4b), also presented in Fig. 5a. It is clearly visible that the middle area of the shaft is significantly softer.

Figure 5b shows the measured resultant diameter along the length of the shaft after a turning process. Note that the static displacement error is the half of the deviation between the measured diameter (blue continuous curve) and the nominal one (black dashed line). The static displacement and the compliance show very good correlation as expected in case of constant cutting force. There are regions denoted by shaded areas

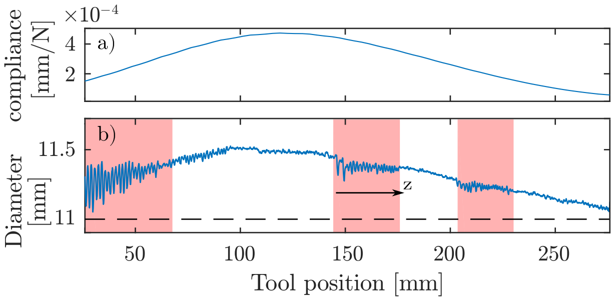

Fig. 5. Compliance along the shaft (a) and the corresponding resultant diameter (b) of the proposed laser scanning method (denoted by blue line curve) caused by static deformations compared with ideal geometry (black denoted by dashed line) for roughing operation for chip width $w = 1.5$ mm and initial diameter $D_0 = 14$ mm. In the shaded area significant surface roughness can be found which is created by chatter vibration.

(e.g.: 0-68; 146-175 and 204-230 mm) where the chatter marks strongly influence the diameter measurement leading to larger variation in the diameter measurement.

These marked areas can be selected for further analysis according to Eq. (5). Figure 6 traces the variation of the tangent of the slope α along the length of the shaft in the range between 146-175 mm. The calculated chatter frequency continuously increasing which can have various explanations. The first can be the changing relative difference between the natural frequency and the spindle frequency caused by varying dynamical properties along the shaft as shown in Fig. 4b. An other explanation can be the nonlinear and non-smooth effects of the cutting force characteristics [17] and the chip formation process [18].

4. Conclusion

In the present study, a scanning method is proposed, which is capable to reconstruct a machined surface and spectral properties of a machining operation in an off-line way. The provided analytical form for the extracted chatter frequency can help to quantitatively validate the theoretical prediction of the chatter models. The proposed method identifies the surface error and the arising self excited vibration frequency in case of stability loss, and it can also be applied even for a more complex workpiece shape.

With this scanning method, the geometrical error could be measured after every cut if the laser sensor is properly mounted on the turret of the machine tool. An additional possible application of the static error measurement may be the prediction of the cutting force if the stiffness of the workpiece-tool holder-machine structure is known (e.g.: measured by modal analysis, computed by corresponding Finite Element Model).

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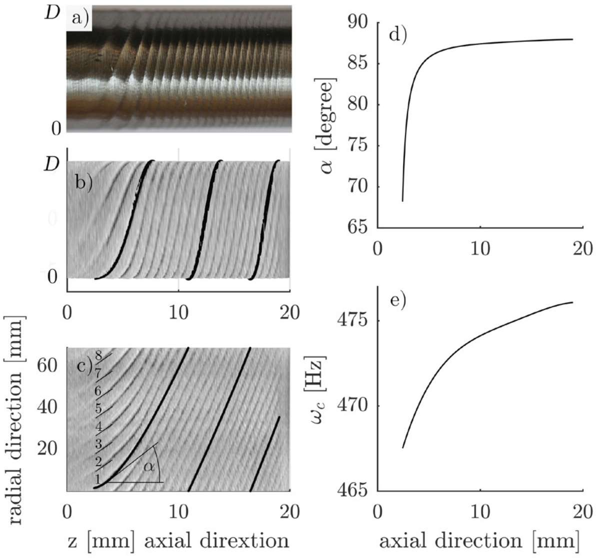

Fig. 6. Chatter marks on the workpiece around near lobe # 8 for parameters: $D_0 = 14$ mm, $w = 1.5$ mm; photo of the surface a); laser scanned surface profile together with the detected tangent of the slopes (black lines): spatial b), unfolded c); detected tangent of the slope d) and reconstructed chatter frequency e) in case of varying dynamics.

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