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Optical tip vibration measurement in CNC milling machines

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Abstract
Vibrations of milling tools, especially of slender end mills, are one of the main contributors to shape deviations of machined work pieces in the milling process. For milling machines, the vibration behaviour depends on the spindle speed and end mill properties. Numerical models can help to predict vibrational behaviour and reduce vibrations. This requires measuring the frequency response of the end mill. We propose a system for investigating the frequency response function inside of a milling machine under different rotational speeds. It consists of an automated impact unit generating vibrations with a known force and a novel Mach-Zehnder interferometer based sensor. The sensor enables simultaneous axial distance and lateral velocity measurement at fast rotating surfaces with submicron uncertainty and measurement rates up to 50 kHz. The bidirectional vibration frequencies are estimated by the signal-processing algorithm depending on the geometric relationship of the displacement in two directions.

in-situ, high-speed, bidirectional measurement, tip vibration, interferometry, frequency response

1. Introduction

Vibration measurements of milling tool are very important for the milling process, since the vibrations are the main factors leading to shape deviations of workpieces and, thus, influence the production quality [1,2]. In a milling process, numerical models of the relationship between the vibrations of the machine and milling tool are helpful to predict vibrational behaviour and reduce vibrations. This requires evaluating the frequency response of milling tools based on vibration measurements.

As a conventional measurement approach, accelerometers [3] enable a robust vibration measurement with a wide frequency range. However, the measurements are hard to be applied for working end mills, due to the tactile nature of the sensors. Non-contact techniques such as eddy current sensors [4] and capacitive sensors [5] can be used to measure a rotating object, but are limited in their lateral resolution and easily suffer from interferences of electromagnetic and dirties. Optical, laser Doppler vibrometers [6] offer a higher lateral resolution with several hundred micrometers. However, the measurement accuracy suffers from speckle noise at optically rough surfaces and they are also hard to be used at non-continuous surfaces like the end mill tip.

In this work we propose a novelly bidirectional measurement approach of tool tip vibrations in a CNC milling machine with a high lateral resolution and less speckle noise, by means of a known force and a Mach-Zehnder interferometer based sensor [7,8]. The sensor allows simultaneous axial distance and lateral velocity measurement at fast rotating surfaces, which is introduced in Section 2. The measurement system set up with a impulse hammer force sensor in the milling machine and, the measurement results of the end mill vibration are presented in Section 3.

2. Sensor

The employed laser Doppler distance sensor with phase evaluation (P-LDD sensor) is based on a Mach-Zehnder velocimeter using two interference fringe patterns, illustrated in Fig. 1. The working principle is easily described for single scattering particles passing the measurement volume with the velocity v perpendicular to the fringe systems. The amplitude of the scattered light is then modulated with the Doppler frequency f_{D}. The interference fringe distance d is calibrated to reduce the impact of sensor misaligment. With the calibrated d and v, the Doppler frequency f_{D} results to

$$f_{\mathrm{D}} = v/d. \quad (1)$$

Determining the fringe distance by a calibration and measuring the Doppler frequency thus allow a velocity measurement. In surface metrology, speckles which originate from the surface roughness and move with "v" are treated as scattering particles. Meanwhile, the speckle noise resulting from the superposition of several speckle signals on the photo detectors is the main factor for the distance uncertainty of about 200 nm [8].

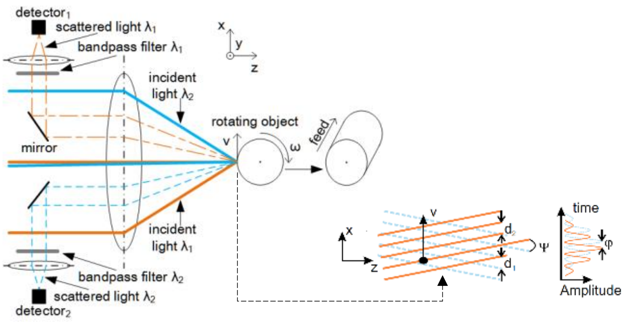


Figure 1. Principle of P-LDD sensor [7,8]: superposition of two interference fringe systems with constant and equal fringe spacing d, which are tilted towards each other by an angle Ψ. The scattered light from each fringe system is detected with a photo detector.

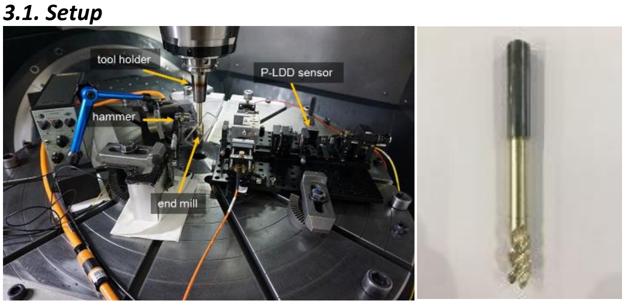
In order to measure the axial position z simultaneously, two mutually tilted interference fringe systems with equal fringe distances and the tilting angle Ψ are superposed. This leads to a position dependent lateral offset between both fringe systems. Thus, z is calculated with the measured phase difference φ between both light signals by

$$z = \varphi \cdot s^{-1} \tag{2}$$

where the s is the slope of the calibration function $\varphi(z)$. The lateral velocity and axial distance oscillate with the vibration of the object. Thereby, the vibratons of end mill tips on both directions can be evaluated simultaneously. Besides, an additional feed forward of the spindle along the rotational axis can achieve a 3-D measurement [7], cf. Fig. 1.

3. In-situ measurement

3.1. Setup



(a) (b)

Figure 2. (a) Measurement system setup with the measured end mill (b).

The measurement system is set up inside of a DMU 80 eVo linear universal machining center shown in Fig. 2(a). A solid carbide end mill (Hoffman Group, Nr. 202253-12, diameter 12 mm, helix angle 45°, 3 teeth) cf. Fig. 2(b), is clamped into the machine and accelerated. An impulse hammer is mounted on one side of the end mill and ensured to pound the end mill shank to create a force for excitating the frequency response of the end mill per measurement. A force sensor is integrated with the hammer transmitting the force signal to a digitizer in a computer which connects a P-LDD sensor and, thus, triggering the measurement. The P-LDD sensor is mounted on the other side of the end mill opposite the hammer. The scattered light signal detected by the sensor is transmitted through multimode fibers to the digitizer. The signal processing and the data evaluation in this work are implemented by using the software MATLAB.

3.2. Measurement

Vibraton measurements on the end mill shank with a continuous surface and on the cutter tip with a non-continuous surface are conducted, respectively, cf. Fig. 3. The rotational speed n_{rot} is increased in 6 steps from 10500 to 18000 r/min. The measurement rate of the P-LDD sensor is set to 50 kHz.

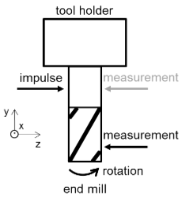
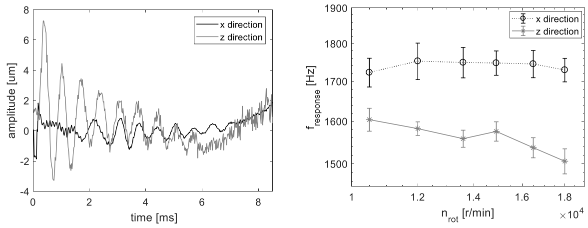


Figure 3. The measurement scheme on the end mill shank and cutter tip.

In Fig. 4(a) the z- and x vibration from a single measurement at n_{rot} = 18000 r/min are depicted. An identified oscillation in the first 6 ms on z direction and 7.3 ms on x direction are excitated by the force. Using the Fast Fourier transform (FFT), the frequency responses on both directions occur at approximately 1500 and 1700 Hz, which are evaluated with Gaussian fitting.

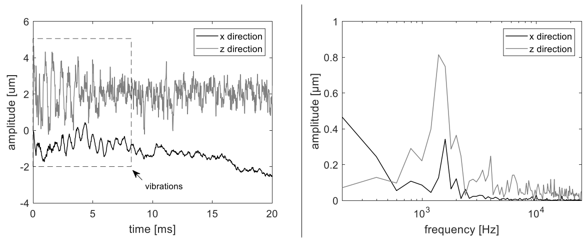


(a) (b)

Figure 4. Displacement depicted vibrations on x and z directions (a), (b) the influence of n_{rot} on frequency responses.

Next, in 6 different rotational frequencies, 20 measurements for each frequency are achieved. Fig. 4(b) shows that the frequency response decreases with the increasing of the rotational frequency, which is comparable with the trend in [9]. The standard deviations and relative measurement uncertainties on z and x directions are 23 Hz & 38 Hz and 1.5% & 2.2%, respectively. Since the x direction is perpendicular to the hammer pounding, this makes the vibration of x direction relatively weak and be more easily impacted by noise.

Due to the large tooth height, only a discontinuous position signal can be obtained from the cutter tip, which does not allow for a frequency analysis using the FFT. To overcome this problem 50 sequential measurements with random angles between the impact direction and the 3 teeth are conducted by random beats of the hammer. Superposing the signals enables reconstructing a continuous vibration signal, cf. Fig. 5(a). The frequency response can be then evaluated by the FFT and is depicted in Fig. 5(b). The discrepancy between shaft and tool tip requires further investigation.



(a) (b)

Figure 5. Displacement depicted vibrations on both directions (a) offer the frequency response spectrum in (b). Note that for a clear show, the displacement on z direction is shifted 2 µm above origin.

4. Conclusion

An interferometric system for vibration analysis of milling tools is presented and applied to measure bi-directional, sub micron vibrations in-situ. The measurements can be employed to validate and calibrate numerical models for machine tool optimizations. The measurements offer an insight to the rotational frequency dependent frequency response of machine tools.

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