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Chatter frequencies of micromilling processes: Influencing factors and online detection via piezoactuators

Yinuo Shi [a], Frederik Mahr [b], Utz von Wagner [a,*], Eckart Uhlmann [b]

[a] *Department of Applied Mechanics, Chair of Mechatronics and Machine Dynamics, Technische Universität Berlin, Einsteinufer 5-7, 10587 Berlin, Germany*
[b] *Institute for Machine Tools and Factory Management, Technische Universität Berlin, Pascalstraße 8-9, 10587 Berlin, Germany*

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ABSTRACT

The chatter frequencies in micromilling operations are affected by various structural factors and cutting conditions. In this paper the influences of damping properties, clamping conditions, and the shank length of microend mills are investigated by experiments and analytical solutions. As is well-known, it is challenging to experimentally identify the tool tip dynamics of a micromilling system and thus to predict the chatter stability. This paper presents a new measuring method for online chatter detection. Using external excitations via piezoelectric actuators, chatter frequencies can be identified with an axial depth of cut lower than the actual stability boundary.

1. Introduction

Similar to conventional milling, regenerative chatter can also occur in micromilling in spite of more complicated cutting mechanisms [1,2]. The chatter frequencies are associated with one of the dominant modes of the machine tool system if no period doubling instability arises. However, satisfactory explanations for dominant modes of the system and the corresponding chatter frequencies are still insufficient and challenging.

The free cantilever length of the microend mills is one of the most important structural factors and significantly affects the chatter stability. Mascardelli et al. [3] identified chatter frequencies using tools with a cantilever length of 30 mm. They correspond to the first (at 4.31 kHz) and the second (at 30.4 kHz) dominant modes of the system, in which the second one is not able to be measured from the conventional experimental modal analysis (EMA). Using microend mills with a cantilever length of 20 mm, Biermann and Baschin [4] observed a decrease of the chatter frequencies of about 0.7 kHz in five unstable cases in the spindle speed range from 20,000 rpm to 60,000 rpm. Shi et al. [5] measured the chatter frequencies for tools with a cantilever length of 20 mm. The dominant chatter frequencies are located in a wide range from 7 kHz to 7.6 kHz for spindle speeds from 26,000 rpm to 33,000 rpm.

On the other hand, the stability behavior also depends on the different cutting conditions [1]. The minimum chip thickness effect [6–9] arises at the low feed rates and also influences the chatter frequencies. By simulations Jun et al. [10] studied this effect and other effects, such as elastic recovery and process faults, on the vibrations of microend mills. Biermann and Baschin [11] experimentally investigated the effects of cutting edge geometry, cutting edge radius, and feed rates on the micromilling process stability. Considering the process damping effect [12–14], Rahnama et al. [15] identified the increased chatter stability boundary in micromilling processes, especially in the low cutting speed range.

For (semi-)analytical chatter prediction, it is inefficient to apply the classical methods [12,16–22] if all the unique aspects of microcutting forces are involved. As the feed per tooth is larger than the minimum chip thickness, the shearing mechanism is dominant and the force models can be approximated by those in conventional milling [1,3]. In this case the stability boundaries and chatter frequencies can be computed similarly to the macro-scale cutting processes. For full immersion the zeroth order approximation (ZOA) method according to Altintas and Budak [16–18], in which the directional force matrix is approximated by the constant average values, is the most effective one respecting the computation time.

In this paper all milling tests are conducted on a WISSNER Gamma 303 HP 3-axis micromilling machine tool with two spindle systems

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[*] Corresponding author. Tel.: +49 30 314 21169; fax: +49 30 314 21173.
E-mail addresses: yinuo.shi@tu-berlin.de (Y. Shi), utz.vonwagner@tu-berlin.de (U. von Wagner).

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FISCHER PRECISE SC 3062 (10,000–60,000 rpm) and MFN-8150 (60,000–150,000 rpm). Microend mills with different tip diameters are utilized (see Table 1). Their density, Young's modulus, and Poisson's ratio are 14,900 kg m^{-3}, 640 GPa, and 0.22, respectively. Blocks made of two materials (CuZn39Pb1 and CK45) are used as workpiece. The feed per tooth is chosen as 10 μm so that the minimum chip thickness effect can be neglected for analytical chatter prediction. Slotting operations are adopted to avoid the appearance of the period doubling instability and to focus on the mode-dependent chatter frequencies.

In Section 2 the dominant chatter frequencies of both spindle systems and the multiple values despite full immersion are discussed. The effects of process damping, tool clamping condition, and tool geometry, especially the shank length, on the chatter frequencies are shown in Section 3. Section 4 presents the online chatter detection using piezoelectric actuators. This new method is capable of measuring the chatter frequencies in the transition range in which chatter does not yet develop.

2. Mode-dependent chatter frequencies

In the case of secondary Hopf instability [20–22], chatter frequencies are associated with the dominant modes of the system. Usually, the basic chatter frequency f_c dominates in slotting operations and is located in the resonance range. This mode-dependent chatter frequency is easily distinguishable from the spindle frequency and its harmonics. Fig. 1 shows these chatter frequencies for spindle systems SC 3062 and MFN-8150. Slotting operations are performed on brass (CuZn39Pb1) block workpieces using microend mills with $d_t = 1$ mm and a free cantilever length of 20 mm for SC 3062 and 25 mm for MFN-8150. The analytical results are obtained using the ZOA method for each spindle system. Their dominant modes are achieved by the corresponding finite element (FE) models.

For SC 3062 three milling tests are performed at each n_s–a_p-combination in the range from 26,000 rpm to 33,000 rpm. Chatter is identified by the acoustic emission that is acquired using a microphone near the cutting process. The predicted chatter frequencies are based on a dominant natural frequency of 7.209 kHz and a estimated damping ratio of 0.025 from the FE model. This mode results from the first bending form of the microend mill and the flexibility of the spindle–tool holder–tool (STT) interfaces. It is of interest to see that the measured chatter frequencies are located in a wide range from 7 kHz to 8.6 kHz, particularly in the frequency range from 7 kHz to 7.6 kHz. The predicted basic chatter frequencies, which are denoted by the sloped lines below the dashed line, match the measured ones very well. The sloped lines above the dashed line denote the combination of chatter frequencies and match the measured ones in the range of 8 kHz to 8.6 kHz. These multiple frequencies result from the ratio of the dominant natural frequency to the selected spindle speeds. For instance, at 31,000 rpm the combination frequency (8.128 kHz), which is approximately equal to the sum of the dominant chatter frequency (7.088 kHz) and the cutting edge engagement frequency (1.033 kHz), is still located in the resonance range and thus could be detected by the acoustic signals in spite of full immersion. In conventional high speed milling, these combination chatter frequencies are usually found in low radial immersions (due to the highly interrupted machining) but not in full immersion [12,21–23].

Table 1
Geometric data of microend mills used for milling tests.

	Case 1	Case 2	Case 3	Case 4
Nominal tip diameter d_t (mm)	1	0.5	0.4	0.2
Tip length l_t (mm)	4	2	1.6	0.8
Shank diameter d_s (mm)	3	3	3	3
Taper length l_c (mm)	5.7	3.3	3.4	3.9
Shank length l_s (mm)	28.3	34.7	35	35.3

For MFN-8150 eight axial depths of cut from 60 μm to 200 μm are tested for the spindle speeds from 60,000 rpm to 110,000 rpm. In addition to the acoustic emission, the velocity of a shank point on the microend mill is also measured by a laser vibrometer (Polytec OFW 353). For the analytical solutions, the first dominant mode with a frequency 7.728 kHz and a damping ratio 0.025 is applied. Since the high-speed rotation of the spindle leads to a loud noise, the frequencies comprised in the acoustic signals must be carefully analyzed. There are also cases when striking peaks arise even if the tool edge is out of cut. These frequencies are not deduced from the self-excited vibrations. For the spindle speeds from 104,000 rpm to 107,000 rpm, the stability behavior of several points is regarded as uncertain. For these points the frequencies that are distinct from the excitation frequency can be observed but are not dominant. Note that the multiple frequency phenomenon is less conspicuous here. Due to the high spindle speeds, the sum of the basic chatter frequency and the excitation frequency is not located in the resonance range any more.

3. Effects of process damping, tool clamping condition, and tool shank length

3.1. Process damping

Similar to structural damping, process damping dissipates vibration energy. It arises from the contact between the tool flank and the workpiece surface and is inversely proportional to the spindle speed so that the stability boundary is particularly increased at low cutting speeds [12–15]. This effect is investigated on SC 3062. Milling tests are performed on a brass workpiece with a_p from 60 μm to 200 μm.

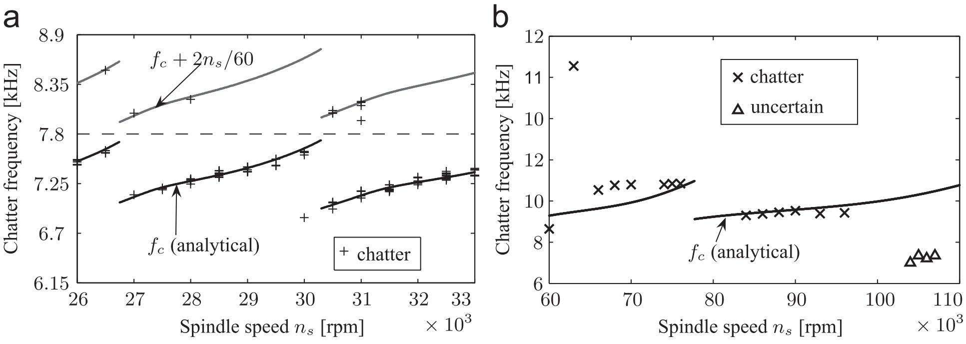

Fig. 1. Mode-dependent chatter frequencies of spindle systems (a) SC 3062 and (b) MFN-8150.