Online detection of the onset and occurrence of machine tool chatter in the milling process

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Abstract: Machine tool chatter is a limiting factor for the performance and efficiency of the milling process. In this paper, a method is presented to online detect chatter before it has fully developed. Such early online chatter detection allows us to interfere in the process such that the occurrence of chatter and marks on the workpiece are avoided. The method can be applied using various sensors, however, the use of accelerometers is preferred for practical reasons. The proposed detection method is evidenced by experimental tests. **Keywords:** Chatter, Experimentation, Detection, Machining

1. INTRODUCTION

One of the main goals in high-speed machining is to maximise the material removal rate while maintaining a high quality level of the workpiece. The material removal rate is often limited by the occurrence of chatter. This results in a heavy vibration of the tool. Furthermore, the tool and machine wear out rapidly and a high level of noise is produced. Therefore, it is important to detect chatter in an early stage. If chatter can be detected in an early stage, there is time to take measures against it, such as changing the machining conditions.

Extensive research has been performed on detection of chatter. A commonly used sensor for chatter detection is a microphone, see e.g. [Schmitz et al., 2002]. In [Delio et al., 1992], it is stated that the microphone has the best properties to detect chatter. Furthermore it has been suggested to use force sensors, [Landers and Ulsoy, 1998; Gradišek et al., 2002], accelerometers [Choi and Shin, 2003] and monitor the spindle drive current [Soliman and Ismail, 1997].

Apart from the different sensors used, a large variety of different signal processing methods has been suggested. Some examples include performing Fast Fourier Transforms (FFT) of the measured signal and finding the highest peak [Smith and Delio, 1992; Liao and Young, 1996; Liang et al., 2004]. In [Choi and Shin, 2003], the use of wavelets is suggested whereas the coherence in the resulting spectrum of two orthogonal accelerations is used as an indicator for chatter in [Li et al., 1997].

However, a drawback of these methods lies in the fact that with these methods chatter can only be detected in high speed milling if it is already in an (almost) fully developed

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Figure 1; Block diagram of the milling process.

stage. Either the method used needs heavy chatter in order to detect it, or the method itself takes so much computational time that chatter has become fully grown before chatter is detected. In that case, the workpiece is already damaged. Therefore, it is necessary to detect the onset of chatter in such an early stage that no chatter marks are yet made on the workpiece. This requires on the one hand, a clear measurement signal that includes features of chatter in an early stage and, on the other hand, a fast detection algorithm.

This paper describes such a method. Furthermore, the detection method has been tested in various experiments using a wide range of sensors. This includes displacement, acceleration and force sensors and a microphone. It was found that the method can be applied using several of the above measurement signals in order to accurately detect the onset of chatter in an early stage. Furthermore, the method can also be used to identify whether or not a cut is exhibiting chatter.

The outline of the paper is as follows. In section 2, a short background of the milling process and chatter is presented. In section 3, the detection method is described. In section 4, the detection method is applied on milling simulations and, in section 5, the experimental results are presented. Finally, in section 6, conclusions are drawn.

2. THE MILLING PROCESS

In figure 1, a block diagram of the milling process is shown. The static chip thickness h_{stat} is a result of the predefined motion of the tool with respect to the workpiece. This chip thickness results via the cutting process (block Cutting) in a force <u>F</u> that acts on the tool. Interaction of this force with the spindle and tool dynamics (block Machine) results in a dynamic displacement of the tool <u>v</u> which is superimposed on the predefined tool motion. The block Delay is due to the regenerative effect (see e.g. [Tlusty and Polacek, 1963; Faassen et al., 2003]). Via trigonometric relations, the tool motion results in a dynamic chip thickness h_{dyn} , which is added to the static chip thickness.

In the milling process, the static chip thickness is periodic. The movement of the cutter \underline{v} can therefore be described by a movement \underline{v}_p , which is periodic with period time $T = \tau = \frac{1}{f_t} = \frac{60}{z\Omega}$. Here, τ is the delay as mentioned in the block Delay, z is the number of teeth on the cutter and Ω the spindle speed in rpm. A perturbation on that periodic movement is denoted by \underline{v}_u . If no chatter occurs, the periodic movement \underline{v}_p is an asymptotically stable solution of the set of delay differential equations describing the milling process and the perturbation \underline{v}_u tends to zero asymptotically. When the periodic solution loses its stability (e.g. with an increasing axial depth-of-cut), in most cases a

secondary Hopf bifurcation occurs and in other cases a periodic doubling bifurcation occurs [Insperger et al., 2003]. This means that the original periodic solution \underline{v}_p becomes unstable and a new periodic motion with a different frequency f_c is superimposed on the original periodic solution. In the remainder of this paper we will call f_c the basic chatter frequency. For a Hopf bifurcation, the frequency of the new motion $f_c = f_h$ is incommensurable to the frequency of the original solution f_t . Hence, this results in a quasi-periodic motion of the tool. For the period doubling bifurcation, the frequency of the new motion $f_c = f_{pd}$ is exactly half the frequency of the original motion. Apart from the frequencies mentioned above, also higher harmonics can occur. Therefore, the following frequencies occur in the vibration signals [Insperger et al., 2003]: the tooth passing excitation frequency, $f_{TPE} = kf_t$, with $k \in \mathbb{Z}^+$, and the damped natural frequency of the tool, $f_d = f_n \sqrt{1 - \zeta^2}$, with f_n the undamped natural frequency of the tool and ζ the dimensionless damping. In an unstable cut, the following frequencies can occur additionally [Insperger et al., 2003]: chatter frequencies due to the secondary Hopf bifurcation:

$$f_H = \pm f_h + k f_t, \text{ with } k \in \mathbb{Z},\tag{1}$$

or chatter frequencies due to the period doubling bifurcation:

$$f_{PD} = f_{pd} + kf_t = (k + \frac{1}{2})f_t, \text{ with } k \in \mathbb{Z}.$$
(2)

When chatter occurs, the amplitudes of the frequencies related to f_H (or in special cases f_{PD}) increase. Since (1) and (2) represent a large set of discrete frequencies, one of these frequencies will generally lie close to a natural frequency of the machine-tool system and will consequently be dominant in the vibration signals. This frequency will be called the dominant chatter frequency in the remainder of this paper. The goal of the detection method is to online detect the rise of one of these chatter frequencies as soon as possible.

3. DETECTION

In an early stage of chatter, the energy at the chatter frequencies will be very small compared to the energy at the tooth passing frequencies. Therefore, it is important to filter the measured signal in such a way that the frequencies f_{TPE} will be eliminated. This is done by demodulation of the signal. This principle will be illuminated for the case of a fictitious measured signal $\xi(t)$ containing two sinusoids at frequencies f_1 and $f_2 < 2f_1$:

$$\xi(t) = 2c_1 \cos(2\pi f_1 t + \phi_1) + 2c_2 \cos(2\pi f_2 t + \phi_2), \tag{3}$$

with $c_{1,2}$ the respective amplitudes and $\phi_{1,2}$ arbitrary phases. In this case, it is assumed that f_1 is known and f_2 is unknown. Multiplication of $\xi(t)$ with $\cos(2\pi f_1 t)$ gives

$$\xi(t)\cos(2\pi f_1 t) = c_1\cos(4\pi f_1 t + \phi_1) + c_2\cos(2\pi (f_2 + f_1)t + \phi_2) + c_1\cos(\phi_1) + c_2\cos(2\pi (f_2 - f_1)t + \phi_2).$$
(4)

Clearly, this modulated signal contains four frequencies, two of which are the original frequencies shifted with f_1 and two are shifted with $-f_1$. The downward shifted frequencies can easily be extracted using a lowpass filter with cut-off frequency f_1 . The spectrum of this demodulated and filtered signal contains two peaks, namely at frequency zero and at



Figure 2; Upper: simulation of the displacement in y direction. Lower: detection signal.

frequency $|f_1 - f_2|$, which we will call f_p . Since f_1 is known and $\cos 2\pi f_p t = \cos -2\pi f_p t$, two possibilities for f_2 exist: $f_2 = f_1 + f_p$ if $f_2 < f_1$ or $f_2 = f_1 - f_p$ if $f_2 > f_1$. Referring to (1), fortunately in the milling process the frequencies at f_H can be built from both equations with $f_1 = f_t$ and $f_2 = f_h$, so it is not necessary to know which of the two cases holds.

When applying this demodulation in milling some extra filtering is necessary. Therefore the following steps are performed: first, a certain harmonic of the tooth pass frequency nf_t , with $n \in \mathbb{N}$ is chosen and a bandpass filter is applied around this frequency, where the size of the passband is f_t . Second, The demodulation is applied as described with $f_1 = nf_t$ and a low-pass filter with cut-off frequency f_t is applied to extract the downward shifted frequencies. Third, the zero frequency component is filtered with a high pass filter with a low cut off frequency (typically 10-15 Hz). Now, only the frequency $f_p = |f_1 - f_2|$ is left in the signal. Finally, the absolute value is computed and a low pass filter with cut-off frequency 100 Hz is applied. The value for this cut-off frequency is empirically determined. In the remainder of this paper, the final resulting signal will be called the detection signal.

4. SIMULATION RESULTS

A simulation of a full immersion cut at 30.000 rpm using the model of section 2 and the detection algorithm is performed, where the axial depth of cut is increased linearly in time in 10 seconds from 1 to 2 mm, which results in chatter to occur during the cut. More details of the model, including the parameters used, can be found in [Faassen et al., 2005][†]. The displacement of the tool normal to the feed direction is used as the signal for chatter detection. The results are shown in figure 2. Using a tight threshold for the amplitude of the detection signal, chatter can be detected at about 6.7 s, whereas it has only become fully grown at about 6.8 s. Thus, in this case the detection method alarms 0.1 s before chatter has fully developed. In 0.1 s, 15 mm of material has been cut in feed direction.

[†] For simplicity, a circular tool path is assumed.

PSfrag replacements



Figure 3; The set-up. 1: Microphone, 2: Accelerometers, 3: Eddy current sensors, 4: Dynamometer, 5: Accelerometers, 6: Tool, 7: Workpiece, 8: Mounting device, 9: Spindle, 10: Toolholder, 11: Bed.

5. EXPERIMENTAL RESULTS

5.1. Set-up

Experiments have been performed to test the detection method in practice. First, experiments have been performed on a Mikron HSM 700 milling machine using a wide range of sensors. A picture of the milling machine is shown in figure 3a and the set-up is schematically depicted in figure 3b. The following sensors have been used: a microphone, accelerometers at the spindle housing in feed (x) and normal (y) direction, eddy current sensors measuring the displacement of the tool in x and y direction, a dynamometer measuring forces in x, y and axial (z) direction and accelerometers mounted on the dynamometer measuring in x, y and z direction. The tool used is a 10 mm diameter JH420 cutter with two teeth and the workpiece material is aluminium.

5.2. Sensor choice

Measurements are performed for a cut where the mill is rotating at 42.000 rpm. The axial depth of cut is 2 mm and the chip load is 0.15 mm/tooth. The radial depth of cut is increased from 4 to 6 mm, which results in the occurrence of chatter during the cut. Due to a small eccentricity not only the tooth passing frequency can be seen from the measured signals, but also the spindle speed itself and its higher harmonics. We will call these frequencies f_{RPM} . This frequency is exactly half the tooth passing frequency since the tool has two teeth. This has as a consequence that a possible period doubling bifurcation will not be detected since these frequencies coincide with the spindle speed and corresponding higher-order spectral components. In figure 4, a power spectral density plot of the acceleration at the spindle bearing in y direction is shown. As can be seen, due to an eccentricity in the spindle-toolholder-tool combination, the basic chatter frequency $f_c = 96$ Hz is also added or subtracted from all f_{RPM} instead of f_{TPE} . Since the dominant chatter frequency lies around the third harmonic of the spindle speed; $f_1 = 3\frac{\Omega}{60}$ Hz. Normally, this information is not known a priori and several demodulation frequencies



Figure 5; Detection using various sensors.

should be chosen, see also section 5.3. In figure 5, the detection signal is presented for several sensors. At t = 0 the tool enters the cut. During the first part of the cut, no chatter occurs, which results in a low value of the detection signal. When chatter begins (around t = 0.6 s), the amplitude of the chatter frequency rises and thus, the value of the detection signal increases rapidly. Just after t = 1 s, the tool leaves the cut. In all signals presented here, the increase of the detection signal at t = 0.6 s can be seen. However, the increase is relatively the largest in the displacement and acceleration signals. During the stable part of the cut, these signals show the lowest noise level. When a threshold would be set just above the maximum value of the signals of the first part, chatter is detected 0.05 s earlier when acceleration of displacement sensors are used compared to force or sound



Figure 6; Detection on the y displacement using the first four harmonics of the spindle speed for demodulation.

measurements. The increase in the sound signal happens in two parts. This is due to the acoustic environment in the milling cage.

A major drawback of using eddy current sensors is the fact that a special mounting device is necessary and that these sensors are quite expensive. Therefore, from a combined detection performance and cost effectiveness point of view, an accelerometer mounded near the lower spindle bearing is preferable.

5.3. Choice of the demodulation frequency

Theoretically, the chatter frequencies appear according to (1). However, due to eccentricity of the tool, the chatter frequencies appear at $\pm f_c + f_{RPM}$, as can be seen in figure 4. For certain frequencies, the amplitude of the chatter frequency is much larger than for others. For instance, in figure 4, the amplitude of the peak at 2200 Hz is $4.5 \cdot 10^5 \text{ m}^2/\text{s}^3$ whereas the amplitude of the peak at 1500 Hz is only $52.1 \text{ m}^2/\text{s}^3$. This phenomenon can also be seen in the detection method. In figure 6, the detection method is applied at four demodulation frequencies, namely the first four harmonics of the spindle speed. From this figure, it can be concluded that demodulation around the second harmonic does not allow us to detect the chatter properly. Instead, it shows only two peaks when the tool enters and leaves the cut. This is due to the fact that the second harmonic of the spindle speed is equal to the tooth passing frequency. The fourth harmonic also gives a peak at the tooth entrance since it is equal to the spindle speed that does not coincide with a higher harmonic of the tooth passing frequency. In this case, the third harmonic of the spindle speed gives the best results.

Unfortunately, it can not be stated a priori which harmonic gives the best information.

Therefore, it is preferred to have the detection method working for different demodulation frequencies in parallel. During the experiments, a DSpace system is used for online detection. Due to the computational efficiency of the algorithm, it was possible to have the detection working online at a sampling frequency of 20 kHz at four different demodulation frequencies on two measurement signals (namely the acceleration and displacement in y direction). Furthermore, the actual spindle speed was directly measured from the machine controller. This is necessary for using the correct demodulation frequency. When measuring only the spindle speed and one additional variable (e.g. an acceleration), the number of parallel demodulation frequencies can even be increased. If the natural frequencies of the machine-tool system are known, it is quite straightforward to choose the demodulation frequencies. Since the dominant chatter frequency lies in the neighbourhood of one of the the natural frequencies should be chosen. If the natural frequencies are the higher harmonics of f_{RPM} that do not coincide with f_{TPE} .

5.4. Comparison of detection method with workpiece

Next, a cut has been made at 33.000 rpm at full immersion where the axial depth of cut increases from 3.0 to 5.0 mm. The first, third, fifth and seventh harmonic of the spindle speed have been chosen as demodulation frequencies. The threshold for the detection is chosen to be 0.05. Using this set-up, this threshold appeared to be a proper choice. Since the slope of the detection signal at the beginning of chatter is quite steep, a higher threshold only results in a slightly later detection. In this case, the third harmonic detects chatter first after 11.7 cm of cut, see figure 7.

In figure 8, the bottom of the cut on the workpiece is depicted on two different zoom levels. It can be seen that the first traces of chatter appear on the workpiece at about 11.5 cm, and the level increases. The chatter marks are clearly visible at 13 cm and a maximum is reached at about 15 cm. Hence, it can be concluded that the results of the detection of figure 7 coincide very well with the path that is left behind by the cutter. Furthermore, it can be seen that chatter is detected in an early stage. Since the algorithm is very fast, it leaves enough time to interfere in the process in order to stop the rise of chatter, as suggested in [Doppenberg et al., 2006].

6. CONCLUSIONS

In this paper, we have proposed an online chatter detection method for high-speed milling that can detect chatter in an early stage. The method is fast enough to work online on a high speed milling machine with spindle speeds even up to 42.000 rpm. Using a single accelerometer on the lower spindle house and measuring the actual spindle speed from the machine controller, it is possible to have the detection algorithm working online at a sampling frequency of 20 kHz and filter the signal with at least four demodulation frequencies simultaneously. The detection algorithm can be used on an online chatter controller as suggested in [Doppenberg et al., 2006].



Figure 7; Chatter detection with 4 different harmonics. Chatter is first detected in the 3rd harmonic after 11.7 cm.



Figure 8; Workpiece with transition from stable cut to cut with chatter. Top: from 5 to 18 cm. Bottom: zoom on transition area.

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