REAL-TIME DETECTION AND CONTROL OF MACHINE TOOL CHATTER IN HIGH SPEED MILLING

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Abstract: *This paper presents a method for real-time in-process detection and control of machine tool chatter in high-speed milling including experimental validation. The occurrence of chatter limits the efficiency and accuracy of high-speed milling operations. Usually a working point (spindle-speed and depth-of-cut) that is initially stable (chatter-free) is selected. Here an experimentally validated milling model is presented that can be used for this purpose. Due to changing process conditions (e.g. heating of the spindle or tool wear) the initially chosen stable working point may become unstable. Whereas the chatter control methods proposed in literature are essentially not applicable in real-time, the presented method allows to detect the onset of chatter and automatically adjust the spindle-speed and feed in real-time (i.e. the feed remains nonzero during the entire machining operation) to suppress the occurrence of chatter due to changing process conditions.*

Keywords: Chatter, Detection, Control, Experiments

1 Introduction

High-speed milling (HSM) is an operation widely used in industry. The main benefits of high-speed milling over conventional milling are the high material removal rates with relatively low cutting forces. The performance of high-speed milling is limited by the occurrence of chatter vibrations. Chatter results in an inferior workpiece, the machine and tool will wear out rapidly and a lot of noise is produced.
In this paper, a procedure is proposed to assure a chatter-free machining operation. The procedure is based on a combination of model-based (off-line) chatter prediction and real-time in-process chatter detection and control. In chatter prediction, the stability properties of the milling model are assessed. This results in so-called stability lobes diagrams, in which the boundary between a stable cut (i.e. without chatter) and an unstable cut (i.e. with chatter) is visualised in terms of spindle speed and depth-of-cut. Extensive research has been conducted in the development of models for milling [1, 2, 3]. Based on these stability lobes diagrams the maximum material removal rate can be selected for which the process remains stable. Due to modelling inaccuracies and changing process conditions the determined stability diagrams can differ from actual stability properties of the milling process. These drawbacks can be overcome by using real-time in-process chatter detection and control.
In real-time chatter detection and control, chatter is detected from measurements. When chatter is detected a control strategy adapts the process parameters such that the process remains stable. Several techniques have been proposed in literature to detect chatter from measurements [4, 5]. Due to the relatively high computational time involved, these methods are only applicable for low spindle speeds. For high-speed milling the detection technique must be computationally very efficient since the regenerative effect and therefore the onset of chatter is much faster at high spindle speeds (typically 100ms). Moreover, existing detection

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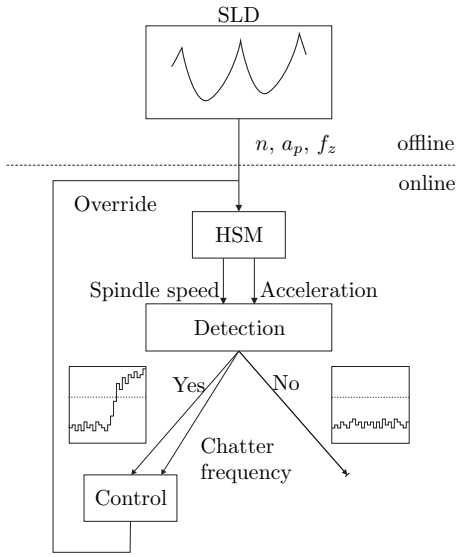


Figure 1: Schematic representation of the procedure for chatter-free machining (Yes/No refers to whether chatter occurs).

methods only detect chatter when it is fully grown which does not allow for a timely chatter control.
The most common way for in-process chatter avoidance is to adjust the process parameters (spindle speed, chip load, depth-of-cut) such that a stable working point is chosen [6, 7]. Hereby the feed is interrupted when chatter is detected and a new spindle speed is set. Then the feed is resumed. This process continues until no chatter occurs. The approach outlined in the current paper ensures that the feed remains nonzero during the entire machining operation (i.e. the milling process is not interrupted). Summarising, this paper presents a comprehensive method for fully automated chatter-free high-speed milling.

2 Procedure for chatter-free machining

In Figure 1 an overview of the procedure for chatter-free machining is depicted. Given a high-speed milling machining environment stability lobes diagrams (SLD) are obtained by assessing the stability properties of the milling model. From these diagrams a machinist determines an initial stable working point (spindle speed n, depth of cut a_p and feed per tooth f_z) that gives a desired material-removal-rate. This working point is set in the NC program. During the machining operation, the spindle speed is kept constant as long as no (onset) of chatter is detected. When (onset) of chatter is detected the spindle speed is adapted by a control algorithm. Next to a change in spindle speed the feed rate is altered such that a constant feed per tooth is ensured. In Section 3, the model-based chatter prediction method is presented. Results of the model are compared with experiments. Section 4 presents the real-time chatter detection and control algorithm underlined with experimental results.

3 Model-based chatter prediction

3.1 Modelling the milling process

Figure 2 shows a schematic overview of the milling process. The thickness of cut per tooth, $h_j(t)$, is a result of the sum of the static thickness of cut $h_{j,stat}(t)$ and dynamic thickness of cut $h_{j,dyn}(t)$. The static thickness of cut is a result of the predefined motion between the tool and the workpiece and is described by $h_{j,stat}(t) = f_z \sin\phi_j(t)$, where f_z is the feed per tooth and $\phi_j(t)$ the rotational angle of tooth j. The dynamic

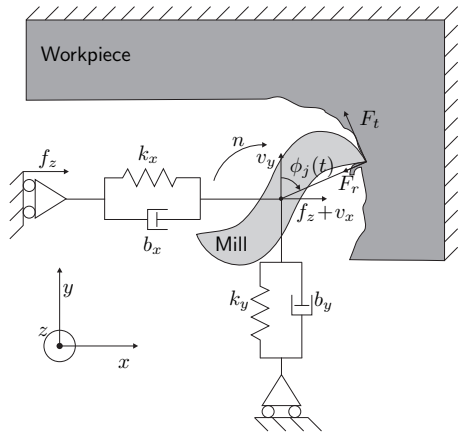


Figure 2: Dynamic model of the milling process.

thickness of cut is a result of the relative movement between subsequent teeth,

$$h_{j,dyn}(t) = \left[\sin\phi_j(t)\ \cos\phi_j(t)\right]\left(\underline{v}(t) - \underline{v}(t-\tau)\right), \tag{1}$$

with $\underline{v}(t)$ the tooltip displacements and τ the time between two subsequent tooth passings, i.e. $\tau = 60/Zn$ with Z the number of teeth and n the spindle speed. The cutting forces $\underline{F}(t)$ acting at the tooltip are modelled by an exponential cutting model:

$$\underline{F}(t) = a_p \sum_{j=0}^{Z-1} g_j(\phi_j(t)) \left(h_j(t)^{x_F} S(t) \begin{bmatrix} K_t \\ K_r \end{bmatrix} \right), \tag{2}$$

where $0 < x_F \leq 1$, $K_t, K_r > 0$ are cutting parameters, a_p is the axial depth of cut, $S(t)$ is rotation matrix describing the transformation from tangential and radial direction to *x*-*y* direction and $g_j(\phi_j(t))$ determines whether a tooth is in or out of cut. The relation between cutting force and thickness of cut is nonlinear. In this way, the effect of the feed rate on the stability boundary is included [3]. The machine dynamics can be modelled as a linear state-space model,

$$\begin{aligned} \dot{\underline{z}}(t) &= A\underline{z}(t) + B\underline{F}(t), \\ \underline{v}(t) &= C\underline{z}(t), \end{aligned} \tag{3}$$

where $\underline{z}(t)$ is the state. The dimension of the machine model depends on the order of the spindle-tool dynamics model. The movement of the tooltip $\underline{v}(t)$ consists of a periodic movement $\underline{v}_p(t)$ with period time $\tau = 1/f_t = 60/nZ$ and f_t the tooth passing frequency and a perturbation on the periodic movement, which is denoted by $\underline{v}_u(t)$, i.e. $\underline{v}(t) = \underline{v}_p(t) + \underline{v}_u(t)$. When no chatter occurs, the periodic motion $\underline{v}_p(t)$ is asymptotically stable and the perturbation $\underline{v}_u(t)$ tends to zero asymptotically. Hence the frequency spectrum of $\underline{v}(t)$ only contains frequencies $f = mf_t$, $m \in \mathbb{Z}^+$. When the periodic solution loses stability, in most cases a secondary Hopf bifurcation occurs and in other cases a period-doubling bifurcation [8]. As a result the periodic motion becomes unstable and a new quasi-periodic motion appears with a different frequency is superimposed on the original periodic motion. When chatter occurs, the energy of the vibration of the frequencies related to the quasi-periodic motion increases. One of these frequencies will generally lie close to the natural frequency of the machine. This frequency will be dominant in the response and will therefore be called the dominant chatter frequency f_c.

3.2 Validation of the model

In this section stability lobes diagrams are computed for a model of the Mikron HSM700 milling machine equipped with a Jabro JH421 end-mill (2 flute cutter with a diameter of 10 mm and length of 57 mm).

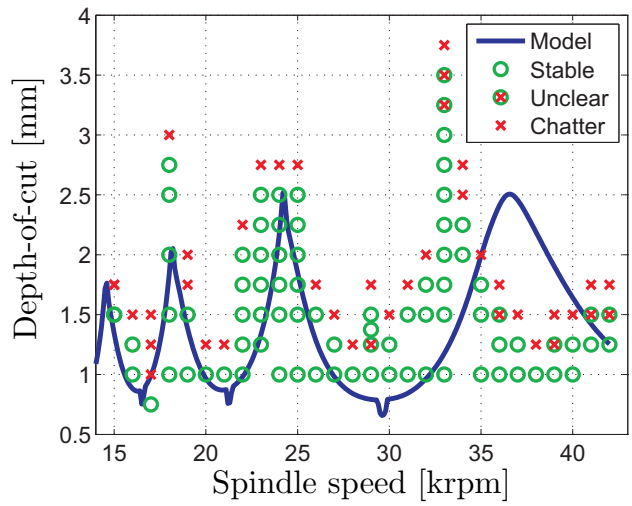


Figure 3: Stability lobes of the Mikron HSM700 using a Jabro JH421L100 tool. Model and experiments.

Stability of the model is assessed using the semi-discretisation method as described in detail in [9]. In order to compute the stability lobes diagram, the parameters of the cutting model and the spindle dynamics need to be identified. The parameters of the cutting model are identified by measuring cutting forces using a dynamometer and fitting the model using a least-square optimisation. The estimated values of the cutting model parameters are $K_t = 271$ N/mm$^{1+x_F}$, $K_r = 33.7$ N/mm$^{1+x_F}$ and $x_F = 0.234$. The spindle dynamics are identified by performing hammer impact experiments. The identified state-space model (3) is obtained by fitting the data using the FDIDENT toolbox [10] for Matlab.
To validate the obtained stability lobes diagram, extensive experiments are performed. Hereto, full-immersion cuts are made in a block of aluminium 7075 for a wide range of spindle speeds and depth-of-cuts. By examining the workpiece quality and the sound during the cut, each cut is marked as exhibiting chatter or not. In Figure 3 the modelled stability lobes diagram together with the experimentally obtained diagram are given. It can be seen that the location of the peaks of the model very well coincide with the experimentally data up to approximately 27000 rpm. For higher spindle speeds the modelled peaks are too wide and lie too far to the right. The discrepancy for higher spindle speeds is likely to be related to the spindle-speed dependency of the spindle dynamics. Even if further model improvements will be achieved in future work, some level of modelling inaccuracies will inherently remain due to the complexity and non-stationarity of the process. Therefore, to be able to confidently exploit such a model-based chatter-free working point in the face of changing process conditions, we propose a real-time in-process chatter detection and control strategy in the next section.

4 Chatter detection and control

In this section, the real-time chatter detection and control strategy [11] will be presented, with experiments discussed in Section 4.3. The purpose of chatter detection is to detect the onset of chatter in an early stage of its growth. Based on the outcome of the detection method a control action (in this case adjusting spindle speed and feed) will be effected to ensure that the process remains stable and chatter is avoided. As already mentioned in the introduction, the detection and control action must be performed in real-time due to the rapid growth of chatter for high spindle speeds. In Figure 4 a schematic overview of the approach is depicted. By measuring process parameters (spindle speed and acceleration) the detection algorithm determines whether chatter occurs and calculates the dominant chatter frequency f_c. The control algorithm then determines new spindle-speed and feed setpoints such that the process remains stable.

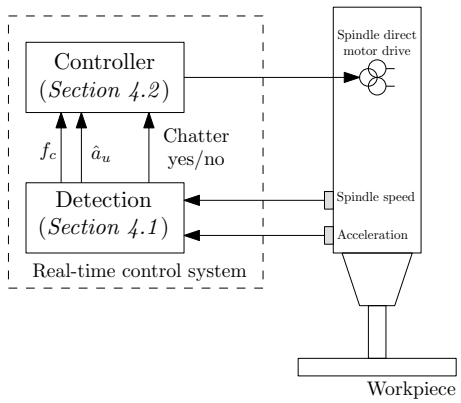


Figure 4: Schematic overview of the real-time chatter detection and control strategy.

4.1 Chatter detection

The need for accurate sensing is essential to detect the onset of chatter. Results of previous research demonstrate that chatter is detected earlier when acceleration sensors are used compared to force or sound sensors [12]. To ensure that no chatter occurs during a cut, the time between the moment of detection and spindle-speed adjustment action must be minimal. Furthermore, knowledge of the chatter frequency is essential to adjust the spindle speed such that chatter is avoided. In the same way as described for the mill displacements in Section 3.1, the accelerations of the tooltip $a(t)$ are composed of a periodic part $a_p(t)$ and perturbation part $a_u(t)$. The measured acceleration can therefore be modelled by a simplified Box-Jenkins model [12]:

$$a(T) = a_p(T) + a_u(T) = B_0(q)u(T) + \frac{1}{D_0(q)}e(T) \tag{4}$$

where $a(T)$ is the measured acceleration in discrete time $T = kT_s$, with $k \in \mathbb{Z}^+$, T_s the sampling time and q the forward shift operator. Furthermore, $e(T)$ is white noise with mean 0 and variance σ^2 . The estimation of the Box-Jenkins model given in (4) is not as straightforward as it seems. However, a rich variety of prediction error methods exist to estimate the model in real-time [11]. The real-time estimation used here is a so-called two-stage estimator. In the first stage, the periodic part $a_p(T)$ is estimated using a FIR estimator given by

$$\hat{a}_p(T) = B(q)u(T), \tag{5}$$

with $a(T)$ again the measured acceleration, $B(q)$ is the estimation of $B_0(q)$ and the input $u(T)$ consist of the cosine/sine series with tooth passing frequencies and higher harmonics as base frequencies. The second stage estimates the perturbation part of the acceleration using AR model given by

$$D(q)(a(T) - \hat{a}_p(T)) = e(T), \tag{6}$$

where $D(q)$ is an estimation of $D_0(q)$. Since chatter frequencies appear in the perturbation signal the roots of the perturbation estimator $D(q)$ contain information of the chatter frequency. When no chatter occurs, the roots of $D(q)$ lie inside the unit-circle close to the origin. When onset of chatter occurs, the roots of $D(q)$ move towards the unit-circle. When the roots cross a circle with an empirically determined radius $r < 1$ [1], chatter is detected. The dominant chatter frequency f_c can then be determined from the dominant root of $D(q)$.

4.2 Chatter control

When the onset of chatter is detected, the controller should adapt the spindle speed and feed such that the milling process remains stable. In most chatter control strategies the new spindle speed is chosen such

[1] r is typically chosen close to, though smaller than, 1 to ensure a timely and robust detection of the onset of chatter

that the dominant chatter frequency coincides with a (higher harmonic) of the new tooth pass excitation frequency [5]. However this does not guarantee that the perturbation signal is minimised. Therefore, the control strategy proposed in this paper is designed such that the perturbation is minimised. The inputs to the controller are the measured spindle speed $n(T)$ at time instant T , the estimated perturbation $\hat{a}_u(T)$ and the dominant chatter frequency $f_c(T)$. The spindle speed setpoint at each sample instant is then determined using a gradient-based approach:

$$n_{set}(T) = n_{init}(1 + c(T)), \tag{7}$$

where,

$$c(T) = c(T-1) - 2\mu\Delta(T)sign(f_o(T)) \tag{8}$$

$$\Delta(T) = \frac{|\hat{a}_u(T)|}{p(T)}, \tag{9}$$

$$p(T) = (1-\lambda)p(T-1) + \lambda\hat{a}_u^2(T), \tag{10}$$

$$f_o(T) = \frac{n(T)}{60} - \frac{f_c(T)}{ZK_{harm}}, \tag{11}$$

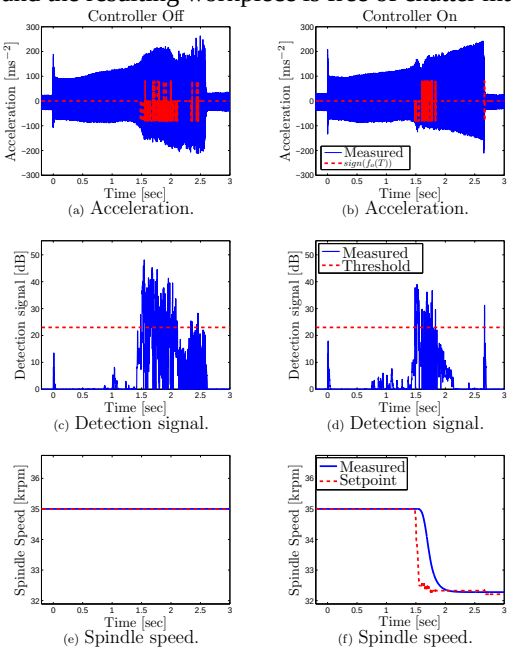
$$K_{harm} = \left\{ \frac{60 f_c(T)}{Zn(T)} \right\}, \tag{12}$$

with initial conditions $c(0) = 0$ and $p(0) = 0$ and $n_{set}(T)$ is the calculated new spindle speed setpoint determined by the controller $1 + c(T)$. Furthermore, $\Delta(T)sign\, f_o(T)$ is the gradient for determining the trajectory of $c(T)$, $p(T)$ is the low-pass filtered power of $\hat{a}_u(T)$ with cut-off frequency $f_{cut} = ln(\lambda)/(2\pi T_s)$ and $\{.\}$ indicates rounding off towards the nearest integer and $0 < \mu \leq 1$ is a user-defined controller parameter.

4.3 Experimental results

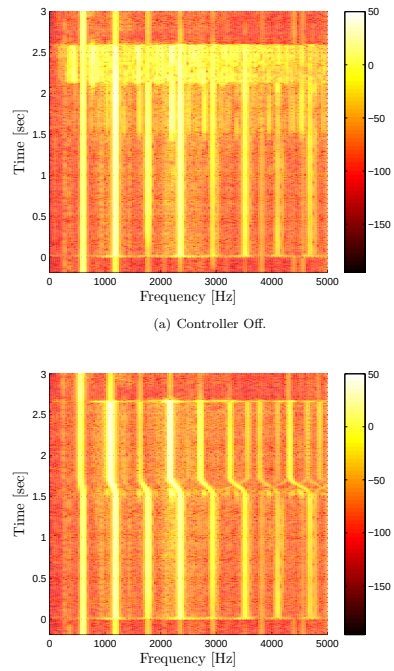
The control strategy, as proposed in Section 4.2, is implemented on a Mikron HSM700 machine. The manual control module is modified such that spindle speed and feed override can be automatically controlled using an external electric potential. For the purpose of detection, the acceleration is measured at the lower non-rotating part of the spindle, near the lower spindle bearing using an accelerometer. The real-time detection algorithm presented in Section 4.1 is implemented in the data-acquisition system dSpace with the sampling time set to $T_s = 1 \cdot 10^{-4}$ s. Full immersion cuts have been made in aluminium 50ST using a Jabro Tools JH421 cutter (2 flute cutter with a diameter of 10 mm and length of 57 mm) mounted in a Kelch HSK40 shrink-fit holder. Figure 5 presents the results for the case where the depth of cut is increased from 1.5 mm to 2.5 mm over a path length of 600 mm. The initial spindle speed n_{init} is set to 35000 rpm. To compare the influence of the real-time detection and control strategy, the cut is made twice. The first cut is performed with the controller off (left figures in Figure 5), during the second cut the controller is switched on with $\mu = 0.002$ (right figures in Figure 5). As can be seen, for both cuts chatter is detected at the same time which corresponds with the marks seen on the workpiece (in the uncontrolled case). For the cut where the controller is switched off it can be seen that after a while the detection signal drops below the threshold value. This is due to the fact that when chatter is fully grown the process is fully nonlinear while the prediction is based on a linear estimator. With the controller turned on, the spindle speed is altered towards the nearest lobe via $sign(f_o(T))$. In this particular case the spindle speed is decreased. With decreasing spindle speed the detection signal decreases towards zero. However, when considering the magnitude of the acceleration signal it can be seen that for both cases the magnitude increases. This can be explained by realising that the amplitude of the periodic solution is linearly related with the depth-of-cut (which, in turn, is increased linearly in time). The frequency content of the acceleration signal in both cases is totally different (see Figure 6). For the uncontrolled case, next to tooth passing frequencies also chatter frequencies are present in the signal ($a_p(T), a_u(T) \neq 0$). When the controller is switched on, the perturbation signal tends to zero ($a_u(T) \rightarrow 0$) and therefore only frequencies related to the tooth passing frequency are present in the signal. It can be observed that this takes approximately 0.65 sec. This is exactly the time it takes for the spindle speed to reach the set-point. This settling time is due to: 1) delay in the controller of the Mikron HSM700 (typically between 40 and 70 msec) and 2) the large inertia of the spindle in combination with the standard spindle-speed controller of the Mikron HSM700 which is not specifically tuned for

tracking relatively fast changes in spindle-speed. Figure 7 shows two detailed pictures of the workpiece. Clearly, it can be seen that when the controller is switched off, the wall of the workpiece is non-smooth due to the occurrence of chatter. This is not the case when the controller is switched on; then the wall of the workpiece remains smooth. During the experiments the spindle speed is changed, while the milling continues (i.e. the feed remains nonzero). If the feed would have been stopped, this would have led to marks on the workpiece. From the obtained experimental results it can be concluded that the proposed real-time in-process detection and control strategy works in practice. A stable working point is ensured and the resulting workpiece is free of chatter marks.



(a) Acceleration. (b) Acceleration. (c) Detection signal. (d) Detection signal. (e) Spindle speed. (f) Spindle speed.

Figure 5: Experimental results for a cut made at 35000 rpm with increasing depth-of-cut from 1.5 to 2.5 mm in 2.7 sec. Left figures: controller off; right figures: controller on.



(a) Controller Off.

(b) Controller On.

Figure 6: Spectrogram of the measured acceleration for control off and on.

5 CONCLUSIONS

In this paper a procedure for guaranteeing chatter free machining operations is presented. The procedure is based on (offline) chatter prediction and real-time in-process chatter detection and control. From model-based stability lobes diagrams an initial stable working point is chosen. Due to modelling inaccuracies

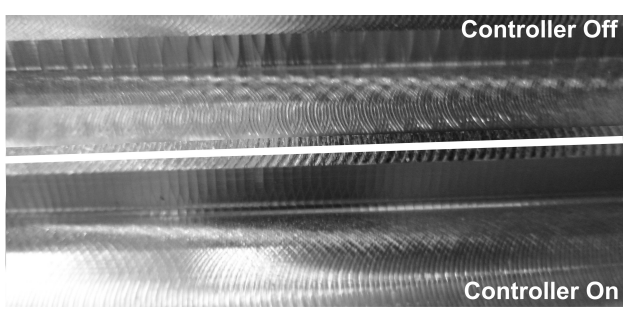


Figure 7: Detail of the workpiece with and without chatter.

at spindle speed above 27000 rpm and changing process conditions the initial stable working point may become unstable. To ensure a robustly stable process, a real-time in-process detection and control strategy is developed and implemented on a state-of-the-art high-speed milling machine. Experimental results show that by using this strategy chatter-free machining is ensured. The resulting workpiece is free of chatter marks, while the feed remains nonzero during the entire cut. While in this paper the detection algorithm is used for control, the strategy can also be used for in-process identification of stability lobes diagrams. In this way the modelling inaccuracies at higher spindle speed can be overcome.

6 ACKNOWLEDGEMENTS

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