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# Stability diagrams and chatter avoidance in horizontal band sawing

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ABSTRACT

The paper presents recurrence plot based stability analysis of the horizontal band sawing process of structural steel profiles. The analysis is performed in the parameter space defined by the cutting speed, the distance between the blade supports, and the feed rate. The corresponding stability diagrams have been constructed using the recurrence plot characteristic, the determinism of the sound pressure emitted by the process, which quantifies the process predictability. The topology of the experimentally obtained stability diagrams revealed non-linear non-monotonic dynamic behaviour, which made two different chatter avoidance strategies possible by cutting speed variation.



## 1. Introduction

Instability related chatter phenomena are commonly observed in various machining processes [1]. Consequently instability related phenomena in these processes have received considerable attention since high-amplitude vibrations can cause striations on the cut surface, the so-called 'wash-boarding' effect [2], which means that additional treatment is needed if the final functionality of the product is not to be reduced.

Band sawing is a process which involves the use of a multi-cutting edge tool and has at least two main adjustable process parameters (cutting speed and feed rate). There are also phenomena of dynamic force excitation, non-linear friction in the cutting zone, and non-linear plastic deformation of the workpiece in the cutting zone, all of which add to the process complexity. Since analytical treatment of the problem of cutting process stability analysis is difficult to adapt to industrial conditions, experimental approaches are very often applied.

Power spectrum characteristics in the frequency domain [3–7] and the wavelet transform [8] of various sensory signals are most often use for the experimental characterization of stability and related chatter during cutting processes. However, the drawback of using power spectrum or wavelet based characterization is that the informative frequency components depend on the modal parameters of the mechanical system being tested. In order to avoid this, and to give the presented analysis more inherent physical merit, it is proposed that recurrence plots, as first introduced by Eckmann et al. [9], could be used for the construction of stability diagrams in band sawing. Such recurrence plots, together with the corresponding recurrence quantification analysis (RQA), have been shown to be applicable for the characterization of dynamic behaviour in various fields of science and engineering [10,11]. Notably, recurrence plots have already been used for chatter characterization and detection in turning [12], where it was qualitatively established that chatter is similar to a deterministic process, while chatter-free cutting has the properties of a stochastic process.

In this paper a novel RQA has been employed for the construction of stability diagrams in a band sawing parameter space defined by the cutting speed, the distance between the blade supports, and the feed rate. The method requires estimation of the selected RQA statistic, which is calculated from the fluctuations of the sound pressure emitted by the process. Values of the statistic close to zero are characteristic of chatter free, whereas values close to one are characteristic of chatter band sawing. Finally the adequacy of the constructed stability diagrams was investigated in a chatter avoidance experiment, which showed that chatter avoidance with increasing cutting speed is more appropriate than with decreasing cutting speed.

## 2. Experimental setup

Experiments were conducted on a double column PE-TRA Toolmaster 300DC band saw with a maximum cutting width of 300 mm. A bimetal cutting blade, hawing the parameters shown in Table 1, and tensioned at 2.0 kN was used. The band saw was equipped with a Brüel & Kjær microphone in order to measure the sound pressure $p(t)$, and with a Kistler three-component dynamometer in order to measure the cutting force $\boldsymbol{F}(t)$ that were generated during the band sawing process. The positions of the microphone and the dynamometer are shown in Fig. 1. Data about

**Table 1**
Cutting blade parameters.

| Parameter | Value |
|---|---|
| Material | HSS M42 |
| Loop length [mm] | 4150 |
| Width/Thickness [mm] | 34/1.1 |
| Teeth pitch [teeth per inch] | 3–4 |
| Rake/Clearance angle [°] | 10/32 |

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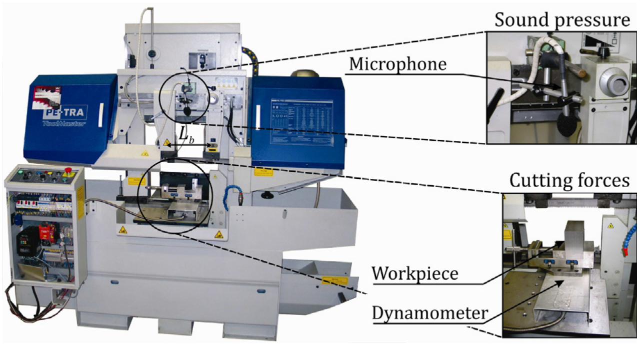


**Fig. 1.** Double-column horizontal band saw machine used in the experiments and placement of the sensors.

the sound pressure $p(t)$ and the cutting force $\boldsymbol{F}(t)$ were acquired by means of a 16-bit resolution A/D data acquisition card, and transferred into a personal computer for further off-line analysis. The sampling frequency was 20 kHz.

### 2.1. Experiments

In order to characterize the band sawing process and construct corresponding stability diagrams, a set of 21 cutting experiments were performed during which the cutting force $\boldsymbol{F}(t)$ and sound pressure $p(t)$ signals were acquired. The experiments were performed on a full rectangular profile workpiece of width 100 mm and height 60 mm, made of structural steel (St37 according to DIN 17100). The main process parameters considered in the experiments were the time-dependent cutting speed $v_c(t)$, the feed rate $v_f$, and the horizontal distance $L_b$ between the vertical blade supports. In the cutting experiment the time variation of the cutting speed $v_c(t)$ was defined as shown in Fig. 2, with the aim to initiate a spontaneous onset and dying-out of the chatter. As evident from Fig. 2, the cutting speed $v_c(t)$, was linearly increased over a period of 30 s, from $v_{cmin} = 34$ m/min to the maximum cutting speed $v_{cmax} = 133$ m/min. After reaching and remaining for 2 s at the maximum cutting speed $v_{cmax}$, the cutting speed $v_c(t)$ was linearly decreased at the same rate back to the minimum value $v_{cmin} = 34$ m/min. During the experiment with variation of the cutting speed $v_c(t)$, the feed rate $v_f$ and the distance $L_b$ between the blade supports were held constant at a preselected value of $v_f = [21, 33, 45]$ mm/min, with $L_b$ ranging from 250 mm to 400 mm, with steps of 25 mm. The feed rate $v_f$ was chosen such that the forces on the teeth of the cutting blade did not exceed 70 N per cutting tooth. The experiments were performed at randomly preselected values of $v_f$ and $L_b$ in order to remove possible bias from the blade wear effect and other system-related effects.

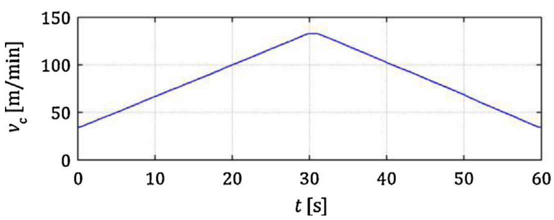


**Fig. 2.** Time dependent cutting speed profile $v_c(t)$.

Examples of the sound pressure signals $p(t)$ acquired during the cutting experiment with variation of the cutting speed $v_c(t)$ at nine selected different combinations of the feed rate $v_f = [21, 33, 45]$ mm/min and distance $L_b$ = [250, 325, 400] mm are shown in Fig. 3. In the signals $p(t)$, chatter cutting (plotted in red) is distinguished from chatter free cutting (plotted in blue). The distinction was performed based on the auditory perception of experts and by inspection of the corresponding spectrograms. It can be seen that the cutting speed $v_c$ and the distance $L_b$ have significant effects,

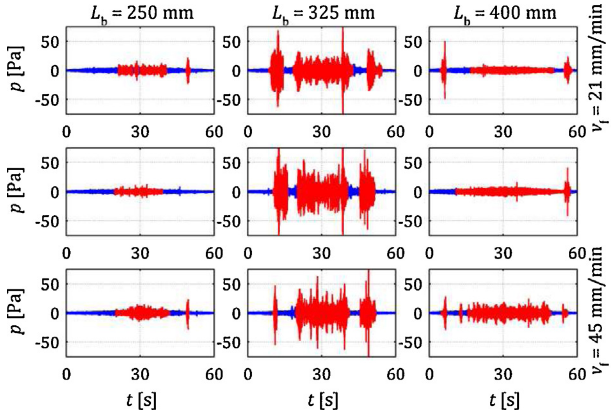


**Fig. 3.** Sound pressure $p(t)$ signals in blue, with the presence of chatter indicated plotted in red, at three different distances $L_b$ and feed rates $v_f$.

whereas the feed rate $v_f$ has a smaller effect on process stability and related chatter occurrence.

## 3. Theoretical background of recurrence plots analysis

In this section an advanced method for time series analysis, known as recurrence plots, is presented. The advantage of using recurrence plots (RP) and their quantitative analysis (RQA) is that they are suitable for the analysis of noisy, non-linear and/or non-stationary time series. Recurrent behaviour is an inherent property of oscillating systems and can be mathematically expressed by an $N \times N$ binary matrix with elements [11]

$$\boldsymbol{R}_{ij} = \theta(\varepsilon - \|\boldsymbol{x}_i - \boldsymbol{x}_j\|); \quad \boldsymbol{x}_i \in \mathbb{R}^m; \quad i, j = 1, \ldots, N. \tag{1}$$

In Eq. (1) $\boldsymbol{x}_i$ is the $i$th state point in the $m$-dimensional state space, $N$ is the number of points in the state space, $\varepsilon$ is a predefined threshold, $\theta(\cdot)$ is the Heaviside function and $\|\cdot\|$ is some chosen, in our case Euclidian norm. The value of the $\boldsymbol{R}_{ij}$ is either 1 or 0, depending on the distance between $\boldsymbol{x}_i$ and $\boldsymbol{x}_j$ and the selected threshold $\varepsilon$. Graphical presentation of the recurrence matrix $\boldsymbol{R}_{ij}$, with "ones" shown in colour and "zeros" shown in white, is known as a recurrence plot. In order to reconstruct the state space from a time series, the embedding theorem [13] can be employed where the states are determined by the delay vectors

$$\boldsymbol{x}_i = (x_i, x_{i-\tau}, \ldots, x_{i-(m-1)\tau}), \tag{2}$$

where $x_i = x(i\Delta t)$ is a scalar time series with a sampling time $\Delta t$, $\tau$ is the time delay, and $m$ is the embedding dimension. Assuming that the time series originates from a deterministic dynamic system and is stationary, then for a large enough embedding dimension $m$ the theorem states that the reconstructed state space is bound to have the same dynamic properties as that formed by the original variables of the observed system [13]. Whereas these restrictions are crucial to methods of non-linear time series analysis [14], they are not so vital with regard to recurrence plots. With respect to the latter, the problem of finding proper embedding dimension may be an elusive one, so that an embedding dimension of $m = 10$ is routinely used [15,16]. Besides the embedding parameters $\tau$ and $m$ it is important to carefully choose the threshold $\varepsilon$. For this purpose various options have been proposed and are summarized in [17], but it is vital that a common criterion is chosen when comparing different time series. When analysing non-stationary data it is instructive to choose $\varepsilon$ such that the recurrence rate is equal for all the compared recurrence plots. Additionally, when a windowed RQA is performed at least 1% of the recurrence rate needs to be assured in every segment (window) of the time series [18]. The recurrence plots generated from the sound pressure signals $p(t)$ of chatter free and chatter cutting are shown in Fig. 4.

For the analysis of the stability of the band sawing process, sound pressure signals $p(t)$ were partitioned into window segments of $t_w = 50$ ms. The recurrence plot for each segment