

Experimental Chatter Characterization in Metal Band Sawing

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One of the most detrimental instability phenomena in metal band sawing is chatter, i.e. high amplitude vibrations of the tool and/or workpiece. In this paper, the influence of the cutting speed and of the distance between the blade supports on chatter phenomena is investigated. For this purpose a series of experiments with triangular cutting speed variation at several pre-selected distances between the blade supports was conducted on structural steel (St37, DIN 17100) workpieces. A feature for chatter detection was extracted from the power spectra of the machine vibration signal, and a set of characteristics was introduced for experimental chatter characterization. The results showed the presence of a chatter hysteresis which depended on the cutting speed. Additionally, apart from the blade support distance, the cutting speed was shown to be a strongly influencing parameter, and as such also promising for chatter control in band sawing processes.

Keywords: chatter, metal band sawing, empirical characterization

0 INTRODUCTION

In cutting processes, chatter can be characterized as the self-excited, high amplitude vibrations of the cutting blade and/or workpiece [1]. It is caused by the instability which occurs in a nonlinear cutting process, and can result in harmful effects on process performance from the point of view of quality, economy, and ecology [1] and [2]. The chatter phenomenon has been intensively researched in finalizing machining operations such as turning [3] and milling (removal rate maximization and chatter suppression) [4] and [5]. Grinding is also highly susceptible to the occurrence of chatter, so several researchers have contributed to the understanding of the chatter phenomenon by non-linear coarse-grained entropy rate analysis [6], non-linear modelling of the grinding process and chatter prediction [7], as well as chatter detection [8] and stability lobe prediction [9].

As opposed to these machining operations, band sawing is most often used at the beginning of the machining chain, and as such does not influence the final product properties as significantly as the finalizing processes. However, with the development of expensive and sometimes difficult-to-cut metal alloys and other materials, such as mono-crystalline silicon, minimization of waste material and of the time for final machining operations, as well as maximisation of the corresponding surface quality, have become increasingly important.

In band sawing, the negative impact of chatter on the quality of products was first noticed in lumber cutting [10] and [11], and was reflected in the so-called wash-boarding [10] of the cut surface. To be able to understand, predict and avoid chatter vibrations in band sawing, several mathematical models were derived.

Their aim was to predict the natural frequencies of the moving continuum, representing the band saw blade. In order to predict the natural frequencies, which are related to the chatter phenomenon, models based on bending [10] and torsional deformations [11] were developed, as well as several models that were based on a moving plate with respect to tangential loading [12], parametric excitation [13], and non-conservative force excitation [14]. Experimental studies of the band saw blade vibrations showed that tensioning of the blade increases the fundamental torsional frequency, but does not affect the lateral bending frequency [15]. Current experimental and model-based solutions for chatter avoidance in band sawing suggest control of the cutting speed [10] and [16], avoidance of excitation at the natural frequencies of the cutting blade, and maximizing the tension of the cutting blade [15]. However, the relevance of complex, theoretical models based on band sawing process characterization is determined, to a high degree, by the approximations of the material characteristics, friction and temperature effects in the cutting zone, all of which are non-linear. For this reason in this research the experimental characterization was chosen for chatter characterization. In our previous research, several features based on spectral analysis were defined and successfully applied for chatter detection in band sawing [16]. The aim of this paper is to apply the most relevant chatter detection feature [16] for the characterization of chatter and related chatter hysteresis. Information on chatter and related chatter hysteresis characteristics is important for the implementation of chatter control and process optimization in the near-chatter regions.

In the following section, the experimental setup and experiments are described. Band sawing

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experiments with different distances between the blade supports L_b and varying cutting speeds v_c were performed in order to collect experimental data about chatter. In the section: "Analysis and characterization of chatter", the most informative feature for chatter detection is defined as the basis for further analysis. It is applied to the acquired experimental data, and the results are presented, indicating the strong influence of the cutting speed and the distance between the blade supports on onset of chatter and the characteristics of the observed chatter hysteresis. Finally, the results are summarized in the conclusions, where the most significant contribution of this work is presented and possible implementation issues in band sawing are discussed.

1 EXPERIMENTAL SETUP

The cutting experiments were conducted on a double column PE-TRA Toolmaster 300DC band saw with a 300 mm maximum cutting width. The maximum cutting width is defined by the distance between the vertical cutting blade supports L_b , as shown in Fig.1 right. This distance L_b can be pre-set within the range from 230 to 420 mm. A bimetal cutting blade of length 4150 mm was tensioned by 2.0 kN. The characteristic parameters of the cutting blade are given in Table 1.

Table 1. Cutting blade parameters

Parameter	Value
Material	M42
Loop length	4150 [mm]
Width/Thickness	34/1.1[mm]
Teeth pitch	2 to 3 [teeth per inch]
Rake/Clearance angle	10/32 [°]

In order to measure and control the cutting speed v_c , the band saw machine is equipped with a frequency inverter, a controller, and software for controlled variation of the cutting speed.

A three-component Kistler 9257B dynamometer, a three-component PCB 356A16 piezo accelerometer, a Brüel & Kjaer 4190 microphone, a preamplifier 2669, and an amplifier 2691-OS1 were used to detect cutting forces, machine vibrations and sound emitted by the cutting process. The frequency responses of the dynamometer and accelerometer were, in terms of their first natural frequency and according to the manufacturers, 2 and 10 kHz respectively for the applied type of mounting. The microphone frequency response was ± 2 dB in the frequency range 3.15 Hz to 20 kHz. Placement of the sensors is shown in Fig. 1. The workpiece was mounted on the threecomponent dynamometer, in order to measure the cutting force components $F = (F_f, F_c, F_l)$. The subscripts $c, f,$ and l denote the components in the cutting, feed, and lateral directions. In order to measure the machine vibrations $a = (a_f, a_c, a_l)$ the three-component accelerometer was mounted on the left cutting blade support. The blade supports are in direct contact with the cutting blade and represent one of the most dynamically exposed parts of the machine structure. The emitted sound pressure p was measured by the microphone, which was positioned 32 cm above the workpiece and directed toward the cutting zone.

All the sensory data obtained during the band sawing process were acquired by a 16bit resolution A/D data acquisition system, and were transferred to a computer for off-line analysis and chatter characterisation. The sampling frequencies for the cutting force components (F_f, F_c, F_l) , the machine

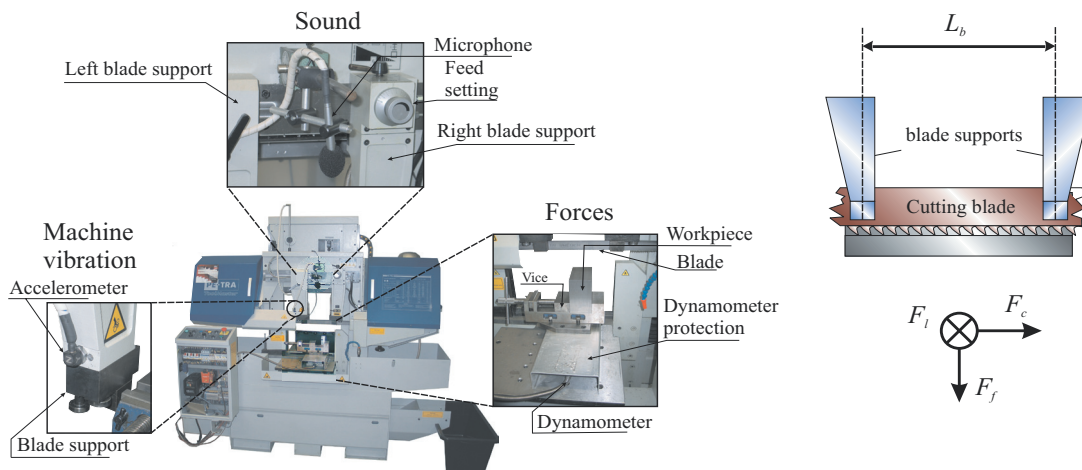


Fig. 1. Double-column horizontal band saw experimental set-up

vibration (a_f , a_c , a_l), and the sound pressure p signals, were 20, 25.6 and 20 kHz, respectively.

1.1 Experiments

The experimental set-up on the multi-sensory double column horizontal band saw provided the basis for the chatter characterization. In the band sawing experiments, rectangular solid profile workpieces with a width of 100 mm and a height of 60 mm, made of structural steel type St37 (according to DIN 17100), were used. The main control parameters of the experiments were the cutting speed v_c and the distance between the blade supports L_b .

In order to investigate the influence of the cutting speed $v_c(t)$ on the band sawing process dynamics and the related chatter, the cutting speed v_c was varied in a triangular manner as shown in Fig. 2a. The experiments started with the cutting speed v_c set to 34 m/min. During the cutting the v_c was linearly increased so that in 30 seconds it reached maximal value 133 m/min. After a second the cutting speed was decreased at a constant rate so that the minimal value of 34 m/min was again reached in 30 seconds, and the cutting experiment, at the preset distance between the blade supports L_b , was stopped.

To investigate the influence of the distance between the blade supports L_b the signals of the cutting forces F , accelerations a , and sound pressure p were acquired during a set of 35 experiments at seven preset distances between the blade supports $L_b = [250, \dots, 400]$ mm with increments of 25 mm. At each preset distance between the blade supports, 5 experiments were performed, which resulted in the total number of 35 experiments. The number of 5 repeated experiments was chosen as a compromise between achieving sufficient statistical significance of the acquired data, and minimizing the wear of the cutting edges of the blade during the complete set of experiments.

The process parameters depend on the selected workpiece material and are recommended by the cutting blade manufacturer. Based on this, the experiments were performed at feed rate of $v_f = 45$ mm/min. At this feed rate, the feed component of the cutting force F_f was within the recommended limits, i.e. less than 70 N per cutting tooth of the band saw blade. The corresponding cutting rate was 100 mm²/s.

Examples of the acquired signals of feed force F_f , the acceleration in the cutting direction a_c , and the sound pressure p measured during the band sawing of the workpieces at a preset distance between the

blade supports of $L_b = 350$ mm, are shown in Fig. 2 b, c and d. In the presented signals the regions of low amplitude oscillations related to the regular chatter-free cutting are marked in blue, and the regions of large amplitude vibrations related to the cutting by chatter are marked in red.

More in detail, during the linear increase of the cutting speed v_c an abrupt increase in the amplitudes of the acquired signal a_c can be observed at time $t \approx 9.7$ s and a cutting speed of $v_c \approx 67.1$ m/min respectively. The large amplitude oscillations terminate at $t \approx 12.5$ s and are re-excited at $t \approx 19.5$ s and $v_c \approx 97.3$ m/min. The excited high amplitude oscillations remain present until $t \approx 41.3$ s, when the cutting speed v_c is decreased to $v_c \approx 100.2$ m/min. Similarly as during the increase of the cutting speed v_c large-amplitude oscillations of short duration are excited again at time $t \approx 48.6$ s and $v_c \approx 75.1$ m/min.

The observed high amplitude vibrations at $v_c \approx 67.1$, 97.3 and 75.1 m/min are caused by the instability of the regular chatter free cutting, where an abrupt transition to chatter takes place. Additionally, a small cutting velocity hysteresis can be observed with respect to the first chatter onset at $v_{co} \approx 67.1$ m/min and the last chatter termination velocity $v_{ct} \approx 66.8$ m/min. This observation, together with the observed abrupt changes in the oscillation amplitude, indicates that band sawing process instability and related chatter phenomena can be described by sub-critical Hopf bifurcation [1].

2 ANALYSIS AND CHARACTERIZATION OF CHATTER

In general it has been observed that all of the acquired signals appear to be informative with respect to chatter [16]. However, a time-dependent mean value of the feed force component can be observed due to the change in the cutting speed and the effects of the workpiece geometry [17] and [18]. The mean value of the feed force is proportional to the number of the teeth in the cut and the depth of the cut [18]. Thus, the geometry of the workpiece, as well as the cutting speed variation, causes the non-stationarity of the feed force component observed in Fig. 2. In the acceleration and sound measurements there are no evidences of the workpiece geometry influence. Accelerometers also have several on-site advantages compared to the dynamometers and microphones, so the acceleration signal in the cutting direction a_c was used in the following analysis for the characterization of chatter in band sawing.

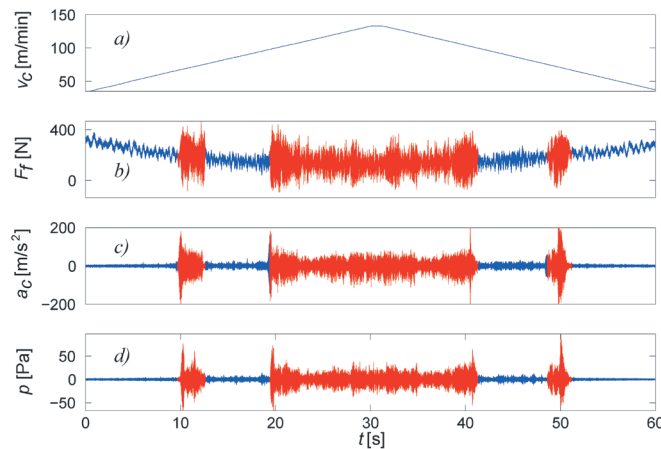


Fig. 2. a) the cutting speed $v_c(t)$ triangular profile; examples of the corresponding acquired signals at the blade support distance of $L_b = 350$ mm; b) feed force F_f , c) the acceleration in the cutting direction a_c and, d) the sound pressure p ; low amplitude regular cutting is marked in blue and large amplitude chatter cutting is marked in red

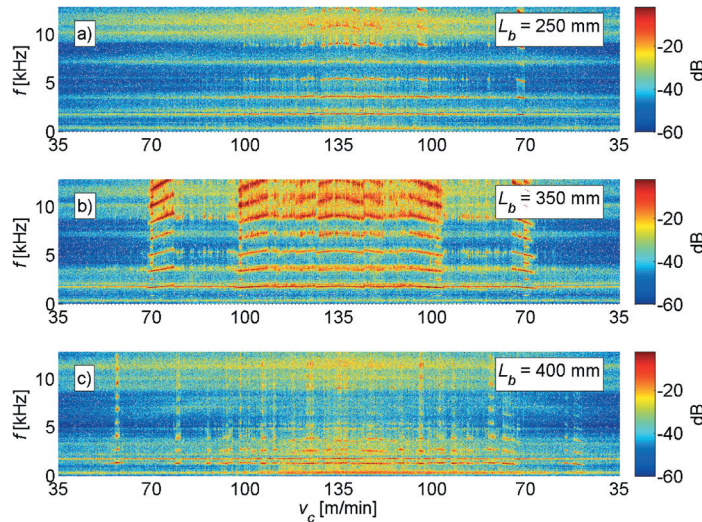


Fig. 3. Spectrogram of the acceleration signal a_c versus the cutting speed v_c at three different distances between the blade supports L_b

2.1 Data Analysis

Chatter in cutting is reflected in high amplitude oscillation of the feed force F_f , the acceleration in the cutting direction a_c , and the sound pressure p were presented with indicated chatter regions (Figs. 2b, c and d). Since chatter is a dynamical phenomenon, apart from the observed chatter-related high amplitude vibrations, chatter can be more precisely characterized by changes and amplification of the power spectra components at the specific harmonic frequencies [16], [19] and [20] in the power spectra of the acquired signals. Fig. 3 shows examples of spectrograms of the acceleration signal in the cutting direction a_c acquired during the band sawing process, with variation of the

cutting speed v_c performed at three different distances between the blade supports, i.e. $L_b = 250, 350$ and 400 mm. The pronounced horizontal bands of amplified frequencies in the spectrograms were found to be characteristic for chatter cutting, whereas a relatively uniform, low power frequency pattern is characteristic for the regular chatter-free cutting. Based on the frequency pattern observed in the spectrograms we can see that chatter is the most present at the distance $L_b = 350$ mm what indicates a nonlinear influence of distance L_b on chatter in band sawing.

Typical a_c signal power spectra of the chatter and chatter free cutting regimes are shown in Fig. 4. As already evident from the spectrograms in the chatter

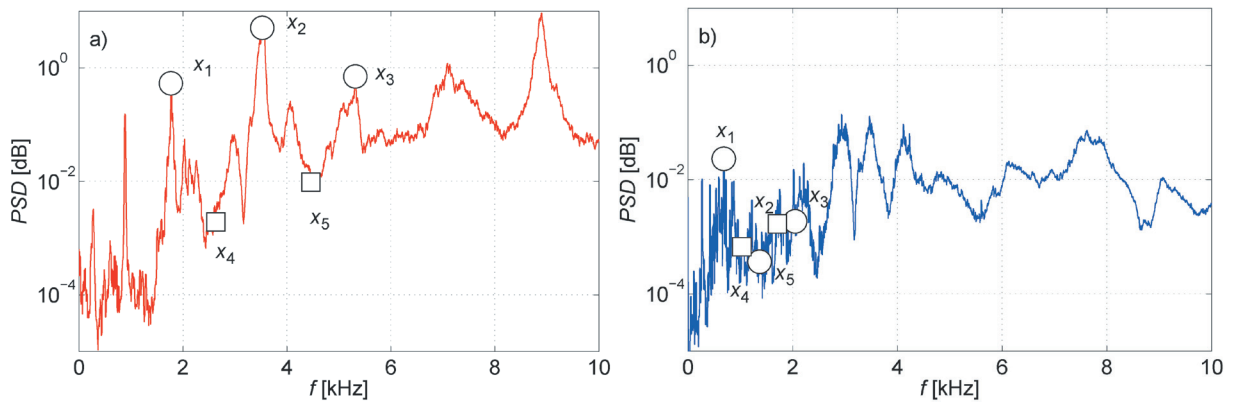


Fig. 4. Characteristic power spectra and defined basic power spectra features $x_1 \dots x_5$ of the acceleration signal a_c in; a) chatter and, b) chatter-free cutting

power spectrum (Fig. 4a) pronounced peaks at certain frequencies are characteristic.

For more detailed analysis and chatter characterisation a quantitative power spectra chatter feature y was defined as a linear combination of the basic normalized power spectra features y [16]:

$$y = x_1 + x_2 + x_3 - x_4 - x_5. \quad (1)$$

The basic power spectra features x_1, \dots, x_5 are denoted in Fig. 4 and are defined as:

- x_1 : amplitude of the 1st maximal peak in the frequency range [0, 2] kHz,
- x_2 : amplitude of the 2nd harmonic peak,
- x_3 : amplitude of the 3rd harmonic peak,
- x_4 : amplitude in the middle between the 1st and the 2nd harmonic peak,
- x_5 : amplitude in the middle between the 2nd and the 3rd harmonic peak.

The defined feature y characterizes the properties of the power spectra as they are related to chatter and chatter-free cutting. The feature's value is high for spectra with a high peak-to-valley difference, which is generally the case in the chatter regime with more deterministic signals. On the other hand the value of the feature y is low for regular cutting regimes, whose signals resemble a stochastic process.

2.2 Results

Fig. 5 shows the values of the feature y of the acceleration signal a_c in dependence of the cutting speed v_c during the increasing of the cutting speed (blue curves), and during the decreasing of the cutting speed (red curves), for five repetitions of the cutting experiment at a distance between the blade supports of $L_b = 350$ mm.

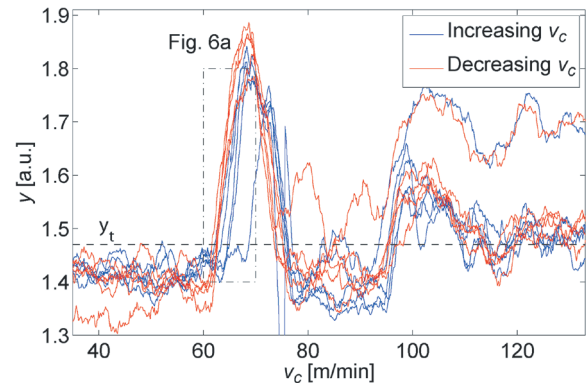


Fig. 5. Feature y plotted against the increasing (blue) and decreasing (red) cutting speed v_c , and corresponding chatter threshold $y_t = 1.47$

The feature y maintains relatively low values in chatter free cutting regime until the cutting speed reaches a value of approximately $v_c \approx 61$ m/min. At this breakpoint cutting speed v_c , y starts to increase rapidly. This rapid increase in y is caused by the transition from chatter free to chatter cutting. The threshold value y_t of the feature y which indicates the onset of chatter cutting, was defined as an average value of the feature values y at the breakpoint cutting speed v_c . In Fig. 5 the calculated chatter threshold value $y_t = 1.47$ is denoted by a dashed horizontal line. Thus values of the feature y which lie below and above the threshold line y_t indicate chatter-free and chatter cutting respectively. The high values of y in the interval around $v_c \approx 70$ m/min and $v_c \approx 104$ m/min are indicators of strong chatter.

A closer inspection of the feature y in the region around the breakpoint is provided in Fig. 6a, where the values of the feature y during increasing (solid) and decreasing (dashed) cutting speed v_c can be seen. It is

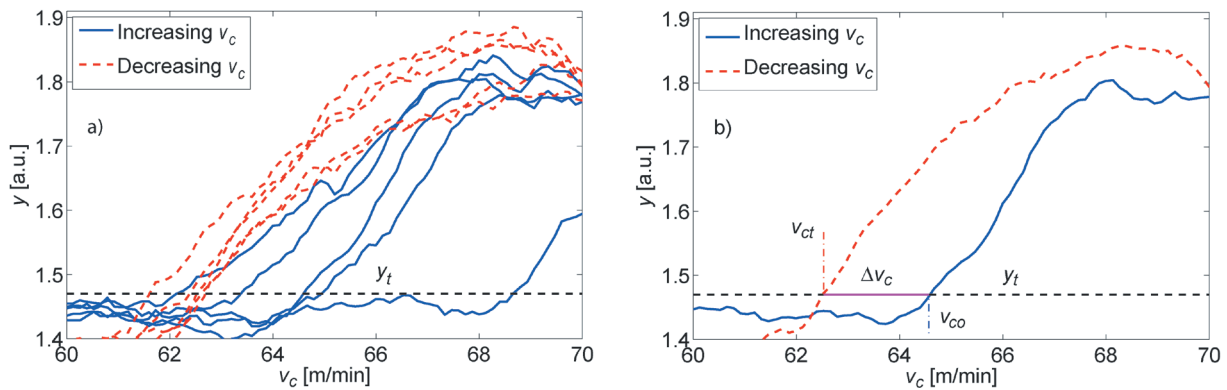


Fig. 6. a) Detailed view of the feature y vs. increasing (solid) and decreasing (dashed) cutting speed v_c and corresponding threshold value y_t . b) Mean values of the feature y and defined chatter hysteresis characteristics with respect to the threshold value y_t

evident from the Fig. 5 that in the case of increasing cutting speed, the feature y on average crosses the threshold value y_t at higher cutting speeds v_c , than in the case of decreasing cutting speed. This indicates the presence of a hysteresis in the band sawing process with respect to the cutting speed v_c , which is more clearly observed in the plot of the feature y mean value during the increasing (solid) and decreasing (dashed) cutting speed v_c , shown in Fig. 6b. The presence of the hysteresis further indicates that, in the case of the band sawing process, the instability, which causes the onset of chatter, is the same as that observed in turning processes, and can be attributed to sub-critical Hopf bifurcation [1].

For further analysis and characterization of the observed chatter hysteresis, several characteristics as shown in Fig. 6b were defined. The characteristic of chatter onset v_{co} was defined by the cutting speed v_c at which the feature y (solid) at increase of v_c crosses the threshold value y_t . Similarly the characteristic of chatter termination cutting speed v_{ct} was defined by the cutting speed v_c at which the feature y (dashed) at decrease of v_c crosses the threshold value y_t .

Table 2. Chatter characteristics

Characteristic	Symbol
Chatter onset cutting speed [m/min]	v_{co}
Chatter termination cutting speed [m/min]	v_{ct}
Chatter hysteresis width [m/min]	Δv_c
Relative chatter duration [%]	t

By the difference of the chatter onset v_{co} and chatter die-out v_{ct} cutting speeds, the width of the chatter hysteresis Δv_c was defined. Further, as an additional chatter characteristic, the relative chatter duration τ , was defined as the ratio between chatter duration and the duration of the entire experiment

which lasted 60 seconds. The proposed set of chatter characteristics is presented in Table 2.

In the following the dependence of the defined characteristics versus the distances L_b of the cutting blade supports are shown by mean of the box plots.

The box plots were obtained based on 5 experiments of cutting speed variation at each considered distance L_b . The central horizontal line in the box indicates the median, whereas the upper and lower box boundaries are located at the 1st and 3rd quartiles respectively, with whiskers placed at 3-times the standard deviation of the sample, and single points (+) outside the whiskers representing outliers.

In Fig. 7, the box plot of chatter onset v_{co} , (solid) and chatter termination cutting speed v_{ct} , (dashed) against the distance between the blade supports L_b are shown.

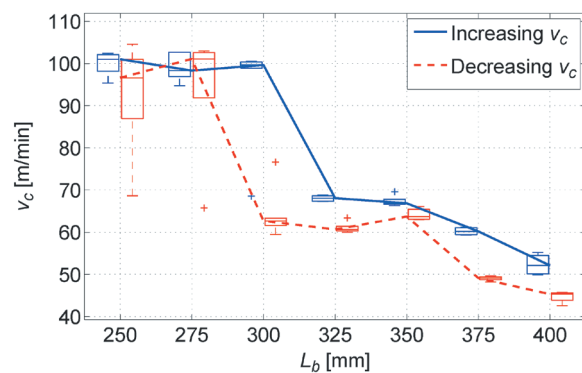


Fig. 7. Box plot of the chatter onset v_{co} (solid) and chatter termination v_{ct} cutting speeds (dashed) vs. the distance between the blade supports L_b

From the box plot (Fig. 7) it can be seen that both the chatter onset and chatter termination median cutting speeds are around 100 m/min for the first two shorter distances L_b . At a distance of $L_b = 300$ mm,

the median chatter termination cutting speed drops to $v_{ct} = 62.4$ m/min, whereas the median chatter onset cutting speed remains at $v_{co} = 100$ m/min. With a further increase in the distance to $L_b = 325$ mm, the median cutting speed of chatter onset drops to approximately $v_{co} = 68.1$ m/min, and further decreases to a value of $v_{co} = 53.4$ m/min at a distance of $L_b = 400$ mm. The median chatter onset cutting speeds v_{co} are always somewhat higher than the corresponding chatter termination cutting speeds v_{ct} , represented by the solid and dashed lines respectively. The connecting lines of the median chatter onset and termination speeds reveal the chatter hysteresis at all distances between the blade supports where $L_b > 275$ mm.

The influence of the distance between the blade supports L_b on the width of the chatter hysteresis Δv_c is shown in Fig. 8.

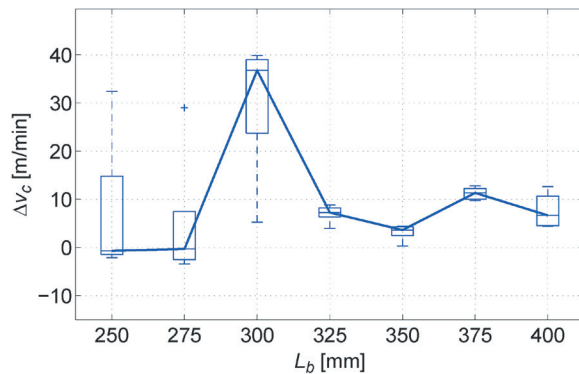


Fig. 8. Width of the cutting speed hysteresis Δv_c vs. the blade support distance L_b

In the case of distances $L_b \leq 275$ mm, the median values of Δv_c are close to zero and hysteresis cannot be observed. The largest median hysteresis width $\Delta v_c = 34.8$ m/min occurs at a blade support distance of $L_b = 300$ mm, denoting the largest bi-stable region of the band sawing process. With further increases in the blade support distance L_b , the length of the cutting speed hysteresis Δv_c decreases, and scatters around $\Delta v_c = 8$ to 10 m/min. The observed cutting speed differences Δv_c between the chatter onset v_{co} and chatter termination v_{ct} cutting speeds, as they depend on the blade support distance L_b , additionally confirm the presence of the hysteresis, which is characteristic for the onset of a non-linear chatter phenomenon in cutting [1] and [21].

The box plot of the relative chatter duration τ against the distance between the blade supports L_b is presented in Fig. 9. Considering the median values of τ , it can be seen from Fig. 9 that the relative chatter duration τ is short in the case of short distances L_b , and

is not affected by the distance L_b . In case of distances $L_b > 275$ mm, the relative duration of the chatter τ increases as the blade support distance L_b increases.

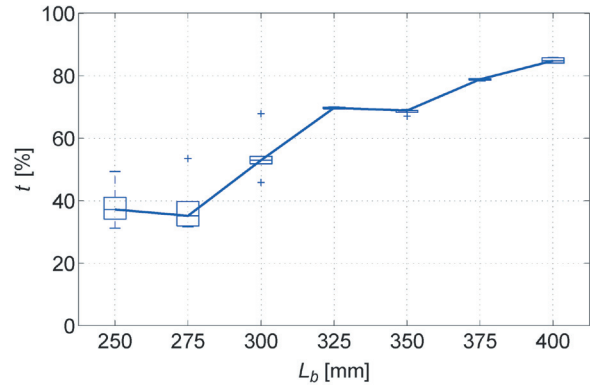


Fig. 9. Relative duration of chatter τ vs. the blade support distance L_b

The longest relative duration of the chatter $\tau = 85\%$ took place in the case of the largest blade support distance $L_b = 400$ mm.

3 CONCLUSIONS

In the paper the characterization of chatter phenomena in metal band sawing process is considered. This characterization is based on an analysis of the acquired acceleration signals in the cutting direction a_c during the band sawing process. In particular, the influence of the cutting speed v_c and of the distance between the blade supports L_b on chatter occurrence were investigated. For chatter detection a feature is extracted from the power spectra of the machine vibration signal, and a set of characteristics is introduced for chatter characterization. The set of characteristics beside the relative chatter duration t includes: chatter onset cutting speed v_{co} , chatter termination cutting speed v_{ct} , and the width of the cutting speed hysteresis Δv_c .

Based on the analysis of the influence of the cutting speed v_c , the following conclusion can be drawn:

- In general, chatter onset takes place at higher cutting speeds v_{co} , and terminates at lower cutting speeds v_{ct} . The observed cutting speed differences Δv_c between the chatter onset and chatter termination cutting speeds indicate the presence of hysteresis, which is characteristic for subcritical Hopf bifurcation based instability of the cutting process and the related onset of the chatter phenomenon in cutting.

- The results of the analysis of the influence of the distance between the cutting blade supports L_b show that:
- With an increase in the distance between the cutting blade supports L_b there is a decrease in both the chatter onset cutting speed v_{co} and in the chatter termination cutting speed v_{ct} .
- The relative chatter duration τ increases with the increase of the distance between the cutting blade supports L_b .

The observed influence of the distance between the blade supports on the chatter onset speed v_{co} and the chatter termination speed v_{ct} as well as on the relative chatter duration τ , suggest that the blade supports should be as close to the workpiece as possible.

Furthermore, apart from the blade support distance L_b , which is defined by the geometry of the workpiece, the cutting speed v_c is shown to be a promising parameter for chatter control in the band sawing processes, with the potential for optimal cutting in near-chatter regions. Although not considered in the paper, it can be expected that the type of material under test, as well as the tool material and wear, will have a significant effect on the chatter onset and hysteresis characteristics.

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