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Multisensory chatter detection in band sawing

Primož Potočnik[a,]*, Tilen Thaler[b], Edvard Govekar[a]

[a]*University of Ljubljana, Faculty of Mech. Eng., Aškerčeva 6, SI-1000 Ljubljana, Slovenia*
[b]*PETRA Machines d.o.o., C. Andreja Bitenca 68, SI-1000 Ljubljana, Slovenia*
* Corresponding author. Tel.: +386-1-4771-167; fax: +386-1-2518-567.*E-mail address*: primoz.potocnik@fs.uni-lj.si .

Abstract

With the development and application of expensive, difficult to cut metals and metal alloys, the minimization of waste material for final operations has, together with the quality of the band sawing process, become more and more important. As the onset of chatter can have a very detrimental effect on the quality of the cut, on the quality of the resulting surface, and on process performance in general, the prompt detection of chatter is of high importance. In the paper a multisensory approach is investigated for chatter detection in the band sawing process. In the experiments steel workpieces of geometrically different profiles were used. Based on an analysis of the acquired signals of the cutting forces, machine vibrations and emitted sound, a method involving a set of features for the detection of chatter in a cutting regime has been defined. The proposed method is not affected by the workpiece geometry or the process parameters. Analysis of the individual features extracted from the various process signals has been performed for chatter and chatter-free band sawing regime classification. The paper presents the results obtained using a cross-validation approach, and summarizes the most informative extracted features with respect to the various process signals.

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Keywords: band sawing, chatter detection, feature extraction, multisensory measurements, cross-validation;

1. Introduction

The chatter phenomenon is a well-known cause of surface quality deterioration and tool life reduction in machining by cutting. For this reason considerable effort has been directed towards the detection and suppression of the chatter phenomenon in different areas of machining by cutting. Chatter is caused by instability of the cutting process that is caused by process nonlinearities [1], and by a regenerative effect caused by waviness of the surface [2]. The chatter phenomenon has been extensively investigated in finalizing machining processes such as grinding, milling, turning and drilling, resulting in chatter dynamics characterization [3-6], stability lobes prediction [7,8], different methods for in-process chatter detection [9-12], and chatter suppression [13-17]. Recently, a multisensory approach has been reported for condition monitoring in machining in general [18,19], where it was concluded that sound signals alone can provide sufficient information for chatter detection. A recent review of chatter in machining processes was presented in [20]. Band sawing is usually the first machining operation in a production chain, and as such it does not have a significant effect on the final product quality. For this reason the chatter phenomena in band sawing has not been investigated, and knowledge about metal band sawing has been mainly borrowed from investigations of wood cutting. Chatter studies in the band sawing of wood have described various theoretical models [21-23], and also proposed methods to control chatter [17]. The optimization of band sawing quality and the minimization of waste material has become more and more important with the machining of products made of expensive metals and metal alloys, so that, in band sawing, too, chatter detection and suppression has become ever more important.

The objective of the research was to explore various process signals and to extract informative features for online chatter detection. In the authors’ previous research [24], a feature extraction method in the

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frequency domain was proposed. This method was applied to acoustic signals, with good chatter detection results. In the present study, this method has been extended to multisensory signals, including cutting forces, machine vibrations, and sound. The paper presents the results of experimental chatter detection, based on features extracted from multisensory process signals.

2. Experimental set-up

The experiments were performed on a double column PE-TRA Toolmaster 300DC band saw of 300 mm maximum cutting width capacity. A bimetal cutting blade of length 4150 mm and pitch 2-3 [teeth per inch] was used, and tensioned at approximately 2.0 kN. The characteristics of the band sawing machine and the cutting blade were as follows:

Machine parameters

- max cutting width = 300 mm
- cutting speed range = 15-150 m/min
- feed speed range = 0-500 mm/min
- nominal motor power = 3.0 kW

Blade (cutting tool) properties

- loop length = 4150 mm
- width/thickness = 34/1.1 mm
- teeth pitch = 2-3 teeth/inch
- rake/clearance angle = 10°/32°
- cutting edge material = HSS M42

The band saw was equipped with a set of sensors to measure the cutting force components (F_f, F_c, F_l), the machine vibration components (a_f, a_c, a_l), and the sound pressure (S) generated during machining, where the subscripts c, f, and l denote components in the cutting, feed, and lateral directions. The experimental set-up and the locations of the sensors are shown in Figure 1.

The cutting force components (F_f, F_c, F_l) were measured by a three-component Kistler 9257 dynamometer, whereas the machine vibrations (a_f, a_c, a_l) were measured by a three-component PCB piezo accelerometer mounted on the left blade supporting arm. The supporting arm is in direct contact with the cutting blade and represents one of dynamically most exposed parts of the machine structure. The sound pressure S was recorded by a Brüel & Kjaer microphone positioned above the workpiece. All the sensory data were acquired by a 16-bit resolution A/D data acquisition card, and transferred into a personal computer for subsequent analysis. The sampling frequencies for the cutting force components (F_f, F_c, F_l), the machine vibration (a_f, a_c, a_l), and the sound pressure S signals were 20 kHz, 25.6 kHz and 20 kHz, respectively.

3. Experiments

Various workpiece profiles were used in the experiments in order to collect a variety of cutting conditions. The profiles included a 100x60 mm full profile, a 90x50 mm U-profile, a 50x90 mm hollow profile, and a 40x40 hollow profile. The hollow profiles had a wall thickness of 2.5 mm. The material of the tested workpieces was mild easy-to-machine structural steel, of type St37 according to DIN 17100.

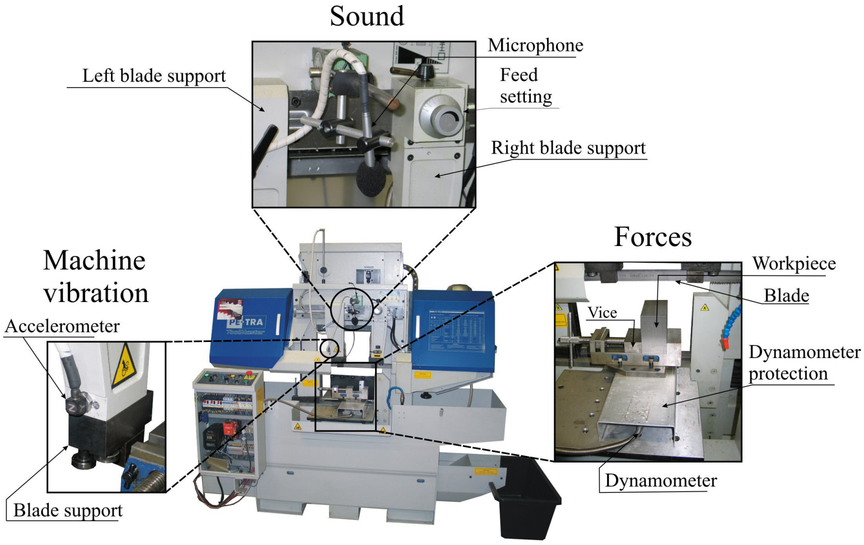

Fig. 1. Experimental set-up, showing the industrial horizontal band saw used in the investigations

The workpieces were cut into 3-5 mm lengths from a 300-400 mm long bar. In the experiment a set of 17 cuts (several per profile) were performed using pre-selected process parameters. The cutting speed ranged between 58-112 m/min, and the down-feed ranged between 70-230 mm/min. During cutting, the signals of the cutting force components, the machine vibrations, and the sound, were measured simultaneously.

Due to the non-stationary operating conditions with various chatter/non-chatter transitions, initial signal pre-processing, based on Short-Time Fourier Transforms (STFT), was applied to the acquired signals.

In order to obtain suitable time-frequency resolution, a Hamming window of length 1024 was applied, which resulted in spectrograms with a time resolution of dt = 25.6 ms.

Examples of spectrograms, extracted from the feed force, cutting acceleration and sound signals detected during the sawing of a 90x50 mm hollow profile, are shown on a logarithmic amplitude scale in Figures 2-4. All three signals show characteristic chatter-induced vibrations at times of t = [4,7], and t = [40,43] seconds. The reference for chatter and chatter-free signals was provided by an expert operator, who detected and recognized chatter based on acoustic perception during the band-sawing process.

In the following section it is shown how a set of informative features was extracted from each type of measured signal, pre-processed by STFT.

4. Feature extraction

With the aim of extracting the most informative features for chatter detection, in the authors' previous research [24] a feature extraction method was proposed. The method is based on comparisons of chatter and chatter-free band sawing regimes, with chatter regions exhibiting several pronounced peaks, whereas in the case of a chatter-free regime, a more broad-band noise-like power spectrum is characteristic. This feature extraction method is based on spectral representation of the signals, and calculates the amplitudes of the major frequency peaks and their harmonics, and the areas between the spectral peaks, as denoted in Figure 5 as $\{z_1,\ldots,z_5\}$. The method is invariant with respect to the workpiece geometry and the process parameters.

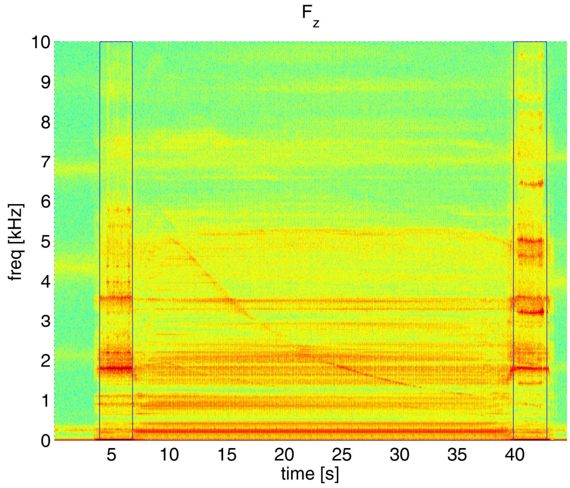

Fig. 2. Spectrogram of the feed force signal F_f.

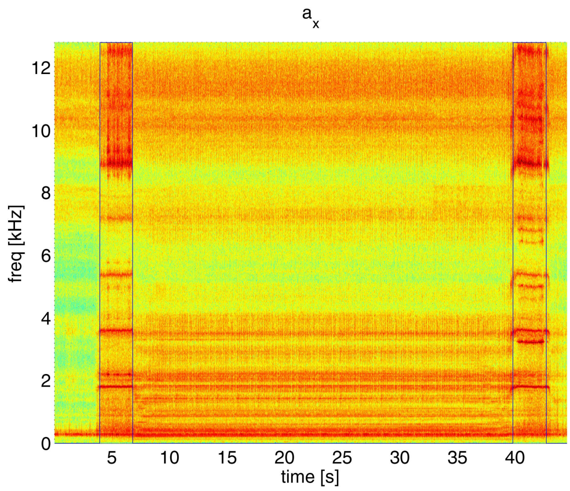

Fig. 3. Spectrogram of the cutting acceleration signal a_c

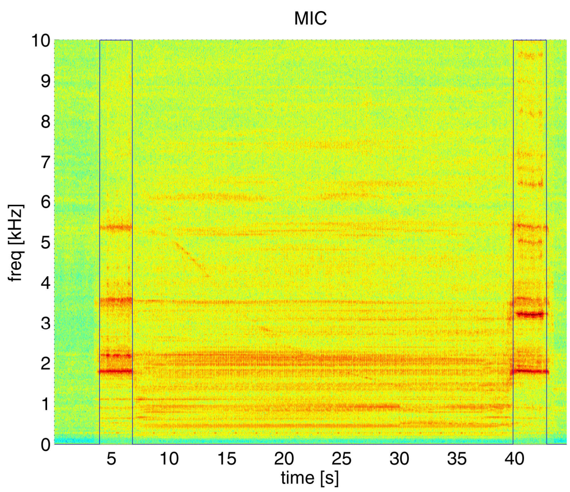

Fig. 4. Spectrogram of the sound signal S

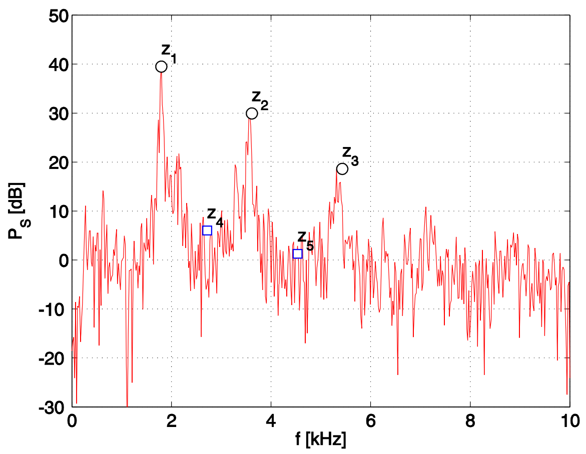

Fig. 5. Feature extraction of spectral peaks (z_1, z_2, z_3) and middle areas between the peaks (z_4,z_5)

The proposed feature extraction method results in a set of simple and combined features, as follows:

a) Simple features

- z_1: amplitude of the 1st maximum peak within a defined frequency range [0, 2] kHz,
- z_2: amplitude of the 2nd harmonic peak,
- z_3: amplitude of the 3rd harmonic peak,
- z_4: amplitude of the middle frequency between the 1st and the 2nd harmonic peaks,
- z_5: amplitude of the middle frequency between the 2nd and the 3rd harmonic peaks,

b) *Combined features* (linear combinations of the simple features)

- z_6: $z_1 + z_2$
- z_7: $z_1 + z_2 + z_3$
- z_8: $z_1 + z_2 - 2z_4$
- z_9: $z_1 + z_2 + z_3 - z_4 - z_5$

The proposed feature extraction method results in 9 features $\{z_1,\ldots,z_9\}$ of the corresponding process signal. The values of the features were determined based on logarithmic power spectra that were also normalized with respect to an average sound level within the time interval of the STFT. Using this step it was possible to achieve invariance of the recorded signal levels, and thus to increase the generality of the method. In the next section, the applicability of the extracted features to detect chatter in various measured signals is described.

5. Chatter detection

Chatter detection analysis was performed based on a set of extracted features for various process signals, including:

- S – sound pressure,
- F_c – cutting force,
- F_f – feed force,
- a_c – cutting vibrations,
- a_f – feed vibrations.

For each signal, a set of features $\{z_1,\ldots,z_9\}$ was extracted. Chatter detection based on individual extracted features was performed through a cross-validation procedure, where a complete set of signals was divided into training and testing sets. The results obtained using this method were the average of both testing cross-validation results.

An objective function was defined by the detection success rate R (expressed as a percentage) that consists of the equal contributions of a chatter detection success rate R_{ch} and a chatter-free detection success rate $R_{reg.}$ This guarantees equal probability of chatter and chatter-free detection, and thus ensures evaluation of a chatter detection success rate which is independent of the actual probability of chatter phenomena. Thus the detection success rate R is expressed as:

$$R = 1/2\, R_{ch} + 1/2\, R_{cf} \quad (1)$$

with R_{ch} and R_{cf} denoting the chatter and chatter-free detection success rates defined as:

$$R_{ch} = 100\, N_{Dch}/N_{ch} \quad (2)$$

$$R_{cf} = 100\, N_{Dcf}/N_{cf} \quad (3)$$

Here, N_{Dch} and N_{Dcf} denote the number of detected chatter and chatter-free samples, whereas N_{ch} and N_{cf} denote the true number of chatter and chatter-free samples, respectively.

Chatter detection thresholds for each feature/signal combination were optimized on the training set before applying them to the test set. Optimization provides the best detection success rate in the case of the training signals.

6. Results

The results of the detection success rate R achieved by using the proposed features $\{z_1,\ldots,z_9\}$ extracted from the various process signals $\{S, F_c, F_f, a_c, a_f\}$ are presented in Table 1. These results refer to the testing data sets, and were obtained by the previously described cross-validation procedure.

The best result R = 96.7 % (marked in orange) was achieved by the extracted feature z_8 from the sound signal S. For the other process signals, the best results are marked in yellow.

Figure 6 presents the values of the extracted feature z_8 obtained from the sound signal S for the band-sawing example previously shown in Figure 4. Regular (chatter-free) and chatter regions (marked in blue and magenta), are shown, together with the optimal chatter detection threshold. A few observed blue points below and magenta points above the threshold denote false recognition of chatter and chatter free regimes.

Table 1. Detection success rate R for each of the features extracted from the various process signals

z	S	F_c	F_f	a_c	a_f
z_1	92.8 %	86.5 %	92.9 %	74.6 %	88.9 %
z_2	90.5 %	71.0 %	79.9 %	87.9 %	80.2 %
z_3	80.2 %	47.4 %	55.1 %	70.4 %	86.6 %
z_4	49.6 %	48.4 %	50.0 %	50.0 %	50.0 %
z_5	48.0 %	49.8 %	52.9 %	49.5 %	50.1 %
z_6	95.5 %	79.1 %	91.0 %	86.5 %	90.5 %
z_7	93.4 %	68.9 %	85.1 %	84.3 %	91.0 %
z_8	96.7 %	88.6 %	94.1 %	95.1 %	93.8 %
z_9	94.4 %	81.9 %	90.6 %	94.2 %	94.4 %

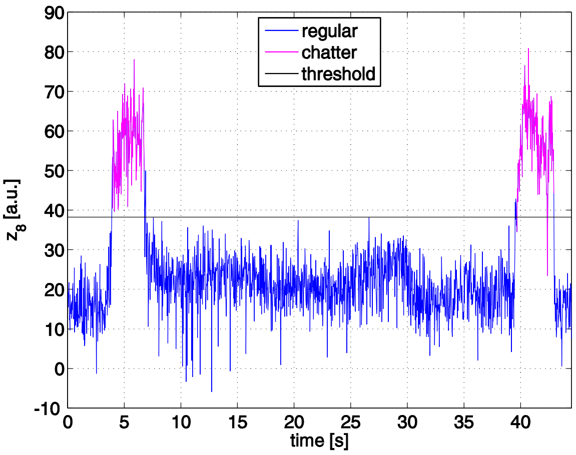

Fig. 6. Example of the extracted feature z_8 from the sound signal S

The results presented in Table 1 can be further condensed in order to obtain an estimate of detection ability of each extracted feature, and also the informativity of the various process signals.

Figure 7 presents the detection success rates for each extracted feature, averaged over all the process signals acquired during the band-sawing of different workpiece profiles. It can be seen that the combined single features $\{z_6,\ldots,z_9\}$ yield a better detection rate than that which can be obtained when the simple features are used, by themselves $\{z_1,\ldots,z_5\}$.

The best combined feature in Figure 7 is z_8, which is extracted from the first two harmonic peaks and the amplitude of the middle frequency between the two harmonics.

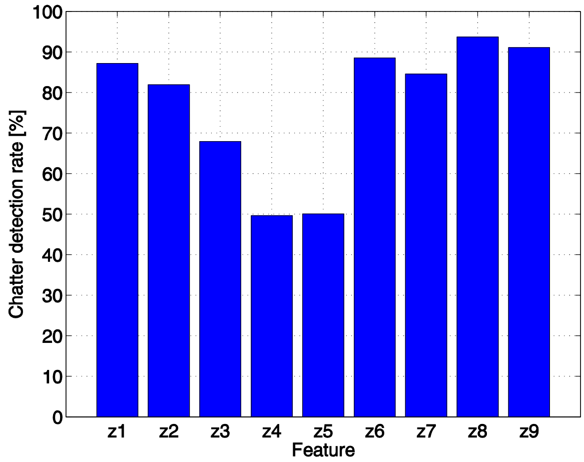

Fig. 7. Average detection rates for each extracted feature $\{z_1,\ldots,z_9\}$

Insight into the informativity of particular process signals can be obtained by averaging the results (Table 1) over all the features for each particular process signal, as shown in Figure 8. This result shows that the best chatter detection performance is obtained from the sound signals S, with only a slightly poorer result being obtained from the feed vibrations a_f. Also, the other process signals offer only slightly poorer performances, and can therefore be considered as a suitable basis for various chatter detection methods.

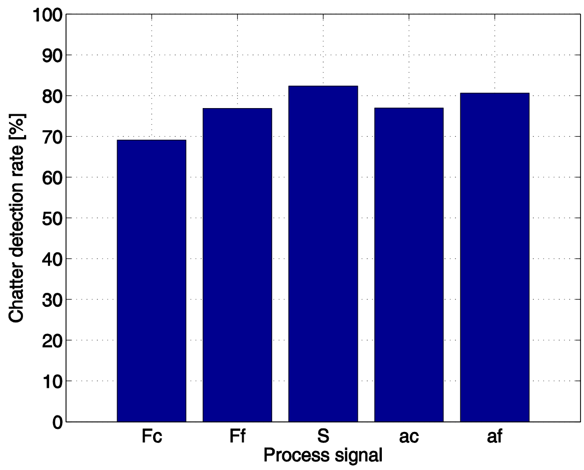

Fig. 8. Average detection rates for each process signal $\{S, F_c, F_f, a_c, a_f\}$

7. Conclusions

The paper presents a method for chatter detection in the band-sawing process, based on cutting forces, machine vibration and sound signals. The method is based on feature extraction from STFT signals in order to extract information about chatter that is independent of the workpiece geometry and the cutting parameters. Experiments were performed with various workpiece profiles and a variety of cutting conditions. The feature extraction method was applied to the measured process signals. The proposed method is not affected by the workpiece geometry and the process parameters. Cross-validation based analysis of chatter detection ability of the extracted features was performed, and the results can be summarized as follows:

- Individual features, such as z_8, can be successfully applied to chatter detection in band sawing, with a detection rate of $R > 95\%$.
- The investigated process signals $\{S, F_c, F_f, a_c, a_f\}$ proved to be informative for chatter detection, with the best results obtained by measured sound pressure (S), followed by feed vibrations (a_f). Feed components appear to be more informative than cutting components.

The results can be interpreted as a recommendation for an online strategy for in-process chatter detectors. Information about chatter occurrence is present in the various process signals, and can be successfully extracted by means of simple feature extraction. The proposed method is fast and suitable for online implementation. Further research will be performed with respect to sensor fusion with features extracted from multiple sensors. It is expected that this may further improve the chatter detection rate, and also increase the robustness of the method.

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