New developed software for processing and analysing of the cutting forces records verified when machining by modern circle-segment end mills

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Abstract. At present, 5-axis machining is often realized with ball end mills that do not achieve the advantages of the modern circle-segment end mills. In recent studies, these tools have been compared concerning the quality of the machined surfaces, machining times and cutting forces. An essential part of the research was an analysis of the force loading of the used tools. To get accurate data about force acting during the machining process, it was necessary to undergo experimental measuring using a cutting force dynamometer. For a force records analysis, the new software was developed based on the MATLAB platform. Evaluated results obtained by the new software are presented in the paper and compared with recent studies.

1. Introduction
Demands for increasing productivity in 5-axis machining of complex components lead to extensive research in the way of cutting tools design. The novel developed circle-segment tools are attracting considerable interest due to their advantages compared to conventionally used ball-end cutters. The circle-segment tools have a significantly increased radius of the cutting edge, which allows having larger path distance accompanied by the same or even better surface quality compared to ball-end cutters (see figure 1) [1].

Figure 1. a) A circle-segment end mill, b) a ball end mill.
In the new researches carried out by Trcka [2] and Sebesta [3, 4] these tools are compared concerning the quality of the machined surfaces, machining times and cutting forces. An essential part of the research was also an experimental cutting force measuring of the tools. The uses and benefits of the experimental measurement are well known [5]. Force measurement can be performed by indirect or direct method, which is more accurate. The most used types of dynamometers for measuring cutting forces during machining are based on the piezoelectric effect. Rotary dynamometers (e.g. type 9170A by company Kistler) have an advantage in direct measurement of force components \(F_c\) (cutting force) and \(F_{cN}\) (normal cutting force) over stationary dynamometer. This is due to the rotation of the dynamometer coordinate system together with the tool. This characteristic becomes more effective in continuous 5-axis CNC milling [5].

The approach used for the processing of measured data is not well established and differs depending on the experience of the author. Filtering and evaluation are often performed in the Microsoft Excel. To establish a less time-consuming approach to cutting force signal processing and analysing, the software presented in this paper has been developed. For verification of the functionality, the results obtained by the new software are compared with the published results of experiments.

2. Development of the data processing system
Developing the software for automatisation of processing and analysing of forces records requires an understanding of the whole process of experimental forces measuring. A brief overview of the process is described in figure 2.

Input data for the processing are cutting forces records saved in the file with the .txt suffix. As an example of these data it is possible to use data from the program DYNOWARE by the company KISTLER. However, it is also possible to process data from other sources with the following features:
- The text file has an identical format with standard ASCII
- The separator of decimal space is a dot.
- The order of measured data columns must be observed: time-\(F_x\)-\(F_y\)-\(F_z\)-\(M_z\) when the first four columns must be filled. Moment \(M_z\) is optional.
- The length of each measured force record must be identical.

At the same time, the following mathematical relationship for total force \(F\) and measured forces \(F_{xM}\), \(F_{yM}\), \(F_{zM}\) (forces in the coordinate system of the dynamometer), must be validated:

\[
F = \sqrt{(F_{xM})^2 + (F_{yM})^2 + (F_{zM})^2}
\]  

For the creation of the software an interactive developing environment was used within the program MATLAB App Designer. This Matlab toolbox allows creating a Graphic User Interface (GUI) with use of the UIControl objects which are set in the integrated editor into the form of default app.

Structure of the new software consists of four modules and GUI (see figure 3). Together with the
default MATLAB toolbox, a toolbox for the signal processing (Signal Processing Toolbox), statistic evaluation of data (Statistics and Machine Learning Toolbox) and wavelet transformation (Wavelet Toolbox) were also used.

**Data import module:** this module is responsible for the loading of the measured force's records in the text format. Furthermore, it verifies completeness of input data and in the case of incompleteness, asks the user via a dialogue window for the data re-entering.

**Data processing module:** this module processes data before the analyses. Processing methods include, for example, numeric filtering of a cutting forces record, drift compensation or automatic detection of a cutting process signal area.

**GUI:** Graphic User Interface connects all modules and allows operating of the program both via the MATLAB interface and the stand-alone application with the support of the Runtime toolbox. Another task is to handle the input/output data, enabling their quick edits and displays the results of the analysis.

**Data analysis module:** this module allows analysing the input data. The module consists of three parts: statistical analysis, frequency analysis and time-frequency analysis of the measured data.

**Data export module:** this module enables the export of the analysed data. Graphs can be exported into the formats JPG, GIF or EPS and if it is needed, statistical data can be exported to the format XLS.

![Figure 3. Concept of the software.](image1)

![Figure 4. Graphical user interface of the program.](image2)

3. **Cutting force data processing and analysing**

This part aims to describe how the program works. After the successful uploading the files and entering the necessary cutting conditions, the software automatically processes the input data. During this phase, the signal is numerically filtered by the function `findpeaks` [6] to find the local maximums of the force records. The next step is the automatic detection of the signal area related to the machining process. For this task, the program uses an algorithm based on two functions: `findchangepts`, which detects change points in the signal and `midcross`, which detects the time instants where each transition of the signal crosses the 50% reference level [6]. Once the signal is processed, the user has an option to edit the selected area of a cutting process signal or choose multiple intermittent segments of the signal. The next possibility of processing is signal smoothing and denoising. In this case, the user can use the Savitzky-Golay Filter [6] or the Wavelet denoising method [7]. The program also has a function for automatic drift compensation. After the processing, the user has several options on how to analyse the data:

- statistical analysis in the time domain,
- frequency analysis,
- time-frequency analysis.
3.1. Statistical analysis

The statistical analysis is an essential method of a cutting forces study. The main goal of the statistical analysis is to display the statistical characteristics of the analysed process. To get these characteristics, the program uses function `datastats` [8]. Statistical parameters which might be calculated are number of analysed values, minimum and maximum value, mean value, median, range of variation and standard deviation. For graphic interpretation of the statistical data, the user has at his disposal three types of graphs: a bar chart, boxplot and histogram. In the section "Normality test", normality of analysed data through the Anderson-Darling test can also be investigated [8]. In the case of the normally distributed data, the user can use the Grubb’s test for filtration of outliers.

3.2. Analysis in the frequency domain

To transfer the signal from a time domain to a frequency domain, the program uses the algorithm of Fast Fourier Transformation (FFT). The FFT output is the graph determining the power of each frequency in the force record. Based on analyses of the frequency spectrum of the signal, it is possible to recognise the dominant frequency of a force record or filter unwanted frequencies. In the case of machining, the dominant frequencies are usually related to the tooth passing frequency or the spindle speed frequency.

3.3. Analysis in the time-frequency domain

A disadvantage of the signal transforming to the frequency domain by Fourier transformation is the loss of time information. Wavelet transform (WT) decomposes a time signal into the time-frequency domain. In the time-frequency domain, it is possible to monitor the progress of cutting tool wear or analyse the cause of the vibration. Wavelet transformation can also be used for signal denoising. For the purpose, the program uses the Matlab function `wdenoise` [7].

4. Verification of functionality of the software

For verification of the software, the experiments with the circle-segment cutters were evaluated. The results obtained by the software have been compared with published results of these experiments. The presented experiments were performed at the Institute of Manufacturing Technology of the Faculty of Mechanical Engineering BUT. The measuring instruments used in the both cases consist of the table piezoelectric dynamometer KISTLER 9257B, multichannel charge amplifier KISTLER 5070A11000 and DYNOWARE software.

4.1. Trcka’s experiment

a) Design of the experiment

The first experiment carried out by Trcka [2] deals with the milling of a workpiece made by the additive manufacturing (AM) technology SLM (selective laser melting) from the powder material Ti-6Al-4V. For the experiment, solid carbide circle-segment end mill (EMUGE-FRANKEN 3540L.12250A) was used. The primary interest was an investigation of the cutting speed influence on the cutting forces and the roughness of the machined surface. During the experiment, two measurements were made at cutting speeds of 65 and 80 m.min\(^{-1}\). The published results (total forces indexed as \(F_{pr}\)) for the cutting speeds are stated in table 1.

| \(v_c\) [m.min\(^{-1}\)] | \((F_{pr})\) [N] | \(s(F_{pr})\) [N] |
|--------------------------|-----------------|-----------------|
| 65                       | 173.2276        | 1.371993        |
| 80                       | 146.9638        | 1.54645         |
b) Data processing
In figure 5 all input data managed by the program can be seen. Both the cutting force records were automatically processed by numerical filtration and searched by an algorithm to find the relevant cutting process area for statistical analysis. The results of the data processing can be seen in figure 6.

c) Results
The mean value of the total cutting force compared to the published results differs in the case of the first measurement by 0.12 \% (0.21 N) and the second case by 0.39 \% (0.57 N). The choice of different criteria of numerical filtration of the data resulted in different values of the standard deviations. The results of the total cutting force are graphically illustrated via a bar chart and boxplots (see figure 7). In figure 8 and figure 9, frequency and time-frequency representation of the signal can be seen.

| Input data: |
|-------------|
| **a)** $v_c$ [m.min$^{-1}$] : 65 |
| $n$ [min$^{-1}$] : 1724 |
| $v_f$ [mm.min$^{-1}$] : 207 |
| **b)** $v_c$ [m.min$^{-1}$] : 80 |
| $n$ [min$^{-1}$] : 2122 |
| $v_f$ [mm.min$^{-1}$] : 255 |
| $d_D$ [mm] : 12 |
| $f$ [mm] : 0.04 |
| $a_p$ [mm] : $\approx$7 |
| $a_\theta$ [mm] : 0.2 |
| $z$ [-] : 3 |
| $F_s$ [Hz] : 5908 |
| time [s] : 30 |
| samples [-] : 177240 |

**Figure 5.** Program inputs.
Figure 6. Data processing.

| Data processing |
|-----------------|
| a) \( v_c \) 65 |
| \[ \begin{array}{c|c|c|c|c} \hline x & F_x & F_y & F_z & F \ \hline 500 & -152.485 & -71.4396 & 41.04275 & 173.0191 \ \hline \end{array} \] |
| b) \( v_c \) 80 |
| \[ \begin{array}{c|c|c|c|c} \hline x & F_x & F_y & F_z & F \ \hline 500 & -128.228 & -63.0894 & 33.37319 & 146.3934 \ \hline \end{array} \] |

Figure 7. Statistical analysis.
4.2. Sebesta’s experiment

a) Design of the experiment
The second experiment carried out by Sebesta [3, 4] deals with the 3+2 and 5-axis milling of the bottom of the pocket. The workpiece material was aluminium alloy EN AW 7075-T6. The main goal was to investigate the benefits of the circle-segment end mill (EMUGE-FRANKEN 3540L.1615AA) in comparison with the ball end mill (EMUGE-FRANKEN 2550A.008). In this paper, only 3+2-axis milling with an inclination angle of the circle-segment end mill 20° takes apart. In ŠEBESTA’s research, there is no published statistical data, so only the data processing results can be compared.

b) Data processing
Two main issues of the measured signal can be seen in figure 10 a). The first issue is a signal drift and the second is a signal noise level. In figure 10 b), results of the automatic algorithm for the drift compensation can be seen. In the first step, the straight line between the starting and ending area
where no cutting process occurs is computed. In the second step, the line is subtracted from the measured signal. This process repeated for all measured channels. In the last step, relevant areas for statistical analysis were chosen (see figure 10 c).

c) Results
The statistical analysis has been performed for two cases: a) a signal with noise and b) a denoised signal. The wavelet denoising was performed by using the db2 wavelets, with five-level of decomposition. The results for the both cases are presented in figure 11. As can be noted from the tables, the mean values of the signal with noise and the signal after wavelet denoising are different about 2 N.

| Input data | Data processing |
|------------|------------------|
| n [min⁻¹]  : 10 000 | a) |
| v_c [m.min⁻¹] : 503 | F [N] |
| f_z [mm] : 0,03 | 10  |
| a_e [mm] : 0,5 | 15  |
| øD [mm] : 16 | 20  |
| z [-] : 3 | 25  |
| F_s [Hz] : 600 | 30  |
| time [s] : 50 |                      |
| samples [-] : 30 000 |                      |

![Program inputs & data processing](image)

**Figure 10.** Program inputs & data processing.
5. Conclusion
The software for processing and analyzing of the cutting force’s records has been developed and verified with evaluating the already published experiments. The obtained results are demonstrating software functionality with the following conclusions:

(1) Results obtained by the new software differ only slightly with the published results of the experiments.

(2) The software is suitable for evaluating more cutting force records simultaneously with the possibility of comparing results with each other.

(3) In contrast with the use of conventional tools, the new software enables automatic data processing which significantly shortens the time that is needed to evaluate the experiment.

(4) All required tools for data processing and analysis are integrated into one software, which makes it easier for data handling.
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