Chatter Detection Using the Main Cutting Force

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Abstract: - The coherence function between two crossed accelerations is used in the reference material to identify chatter in turning. The accelerations are in two directions, axial X and vertical Z, measured by two accelerometers mounted on the tool shank. In the frame of an experiment, focused on the monitoring of a lathe, the accelerations of the cutter-holder was registered, for different cutting wear classes (c1 ÷ c6), where c6 means “Chatter”. Twelve monitoring indices were calculated, among: $x_5 \rightarrow F_z$ variation range; $x_6 \rightarrow$ number of inter-sections of oscillogram $F_z$ with its average value $\bar{F}_z$. The histograms of the column matrices corresponding to the monitoring indices $x_5$ and $x_6$, shown for each class, underline the accurate use of these indices values for chatter detection. The coherence function between the accelerations in the directions Y and Z was calculated, by using the function COHERE from MATLAB. The class recordings c6 (Chatter) falls, with one exception, under the criterion from reference material, but it can be seen that 75 % recordings from the class c2 take the maximum value of the coherence function equal to or greater than 0.91. For these recordings the first 6 monitoring indices were calculated. According to a new criterion (which operate with the monitoring indices $x_5$ and $x_6$), these recordings are not within the class c6, but class c2. As a conclusion, we believe that the new criterion is much more efficient than those at reference material.

Key-Words: - chatter, turning, coherence function, main cutting force

1 Introduction

The coherence function between two crossed accelerations is used in [4] to identify chatter in turning. The accelerations are in two directions, axial X and vertical Z, measured by two accelerometers mounted on the tool shank. The value of the coherence function reaches unity at the onset of chatter. This effect is explained as follows: at the onset of chatter, the distribution of the vibration energy converges to the frequency of chatter. The vibration signal also undergoes a transition from random to periodic behavior when the vibrations of the tool shank in two perpendicular directions are coupled. The above effect leads to the change in the coherence function between the crossed accelerations of the cutter-holder.

In a frame of an experiment which aimed at the monitoring of a lathe [1] the accelerations of the cutter-holder was registered, for distinct tool wear classes. In table 1 the classes (tool conditions) are shown.

In order to obtain the monitoring indices the following were used:
- strain gauges glued on the cutting-tool, which measure the components of the cutting force ($F_y$ - the radial force, $F_z$ - the tangential force);
- accelerations of cutter holder vibrations ($a_x$, $a_y$, $a_z$).

The signals of the sensors are registered simultaneously with the device SPIDER 8 (Hottinger).

2 The Experimental Setup

Forces $F_y$ and $F_z$ were calculated on the basis of the experimental study of the cutting tool bending and with the help of two strain gauges l and 2 (fig. 1), stuck on the cutting tool and connected to SPIDER. The cutting tool is bent by force $F_z$ and compressed by $F_x$. Measuring relative deformations $\varepsilon_1$ and $\varepsilon_2$, the unit forces shown in figure 1 may be calculated:

$$\sigma_1 = E \varepsilon_1, \quad \sigma_2 = E \varepsilon_2$$

(1)

The unit forces of compressing and bending are:

$$\sigma_z = F_z / (a b),$$

$$\sigma_y = M / W = (F_y h - F_z a / 2) / (b a^2 / 6).$$

The conclusion of this study is: the strains produced by $F_y$ can be neglected and only the main cutting force is measured by means of strain gauges system

$$F_z = a^2 b \sigma / (6 h),$$

(2)

where: $\sigma = (\sigma_1 + \sigma_2) / 2.$

(3)
The process developed as follows:

a) The gauges were stamped by statically charging the cutting tool on recess face, near the top, with a weight $G = 10 \text{ daN}$. The two acquired signals have values of opposite signs:

$$\varepsilon_1^{\text{inr}} = -0.0051 \quad \varepsilon_2^{\text{inr}} = 0.0037.$$  

On average:

$$\varepsilon_{\text{inreg}} = (5.1 + 3.7) \times 10^{-3} / 2 = 4.4 \times 10^{-3} \quad (4)$$

The weight $G$ provokes a relative stretching:

$$\varepsilon = \sigma / E = M / (E W) = G h / (E b a^2 / 6) = = 6 \times 3.7 / (2.1 \times 10^{-6} \times 2.33) \times G ;$$

$$\varepsilon = 0.869 \times 10^{-6} \times G \quad \rightarrow \quad \varepsilon_{\text{real}} = 8.69 \times 10^{-6} \quad (5)$$

The relative stretching scale:

$$K_F = \varepsilon_{\text{real}} / \varepsilon_{\text{inreg}} = 1.957 \times 10^{-3} \quad (6).$$

b) During the longitudinal turning of a OLC 45 cylinder 191 recordings were made. The formula (2) becomes:

$$F_z = 1136(\varepsilon_2^{\text{inr}} - \varepsilon_1^{\text{inr}}) \ [\text{daN}], \quad (7)$$

### 2.1 Cutter-Holder Accelerations

Three Bruel&Kjaer 4329 type accelerometers were solidly mounted on a plate which was solidary with the cutter holder.

There exists the relation:

$$a_{\text{real}} = \frac{a_{[mV]}}{s[mV/g]} = \frac{a_{\text{reg}} \cdot g = 9.81}{s} \cdot a_{\text{reg}} [m/s^2] ,$$

where $a_{\text{reg}} [mV]$ is the input into Spider, and $s$ is the sensitivity; the PC recorded value are:

$$a_x^{\text{real}} = 0.785 \cdot a_x^{\text{reg}} ; \quad a_y^{\text{real}} = 0.853 \cdot a_y^{\text{reg}} ; \quad a_z^{\text{real}} = 0.727 \cdot a_z^{\text{reg}} \quad (9)$$

### 2.2 Tool Wear

After each passing, the tool wear was measured with the help of a Brinell lens. The wear spot looked irregular (like a triangle), so the wear criterion $V_B_{\text{max}}$ was used.

### 3 Experimental Results

191 recordings were made and the parameters of the Spider device were dependent on: sampling frequency $= 9600 \text{ /s}$, no. of periods $= 1$ and samples / period $= 4800$; i. e. the device samples the received signals with a frequency of 9600 Hz, but can send a
recording with 4800 samples to the PC, which corresponds to 0.5 sec.

Each working session lasted nearly 30 sec., and for half of this time the Spider device was connected for one second.

3.1 Validation of Recordings
(a) Recordings $43 \div 63, 72 \div 75, 77 \div 87$ fit into class “c1” ($VB_{\text{max}} \leq 0.2$ mm), i.e. 36 Recordings (with 4800 samples each), which will be split into 5 groups (with 960 samples each), noted with a $\div$ e. Therefore there are 180 recordings;
(b) class “c2” ($0.2 < VB_{\text{max}} \leq 0.4$ mm) $\rightarrow 89 \div 94, 96 \div 112 \Rightarrow 23$ Recordings x 5 groups = 115 recordings;
(c) class “c3” ($0.4 < VB_{\text{max}} \leq 0.6$ mm) $\rightarrow 113 \div 118, 124 \div 130, 132 \div 144, 146 \div 163 \Rightarrow 44$ Recordings x 5 groups = 220 recordings;
(d) class “c4” ($0.6 < VB_{\text{max}} \leq 0.7$ mm) $\rightarrow 164 \div 171, 174 \div 177, 179 \Rightarrow 13$ Recordings x 5 groups = 65 recordings;
(e) class “c5” ($VB_{\text{max}} > 0.7$ mm) $\rightarrow 180, 182 \div 184 \Rightarrow 4$ Recordings x 5 groups = 20 recordings;
(f) class “c6” (Chatters) $\rightarrow 64, 67, 76, 95, 131, 172, 185 \Rightarrow 7$ Recordings x 5 groups = 35 recordings; for example, Figs 2a and b show recording 131c.

The numbers on abscissa in this figure and in the similar figures below shows the multiples of the sampling time interval:

$$Dt = 0.5 / 4800 = 1.041666 \times 10^{-4} s. \quad (12)$$

Fig. 2 a- The force $F_z$ in experiment no. 131 “Chatter”

Fig. 2 b- The acceleration $a_z$ in experiment no. 131 “Chatter”

Remark: only with class $c_6$ a periodical vibration appear in diagram $F_z$, whereas $a_z$ deploys the phenomenon of “beats”. With the other classes the variations are random.

(g) class “c7” (Idle turning) $\rightarrow 187 \div 191 \Rightarrow 5$ Recordings x 5 groups = 25 recordings.

4 Data Processing

We choose at random 22 recordings: 1-054-c1; 2-057-c1; 3-080-c1; 4-084-c1; 5-087-c1; 6-089-c2; 7-090-c2; 8-091-c2; 9-093-c2; 10-100-c2; 11-105-c2; 12-114-c3; 13-115-c3; 14-116-c3; 15-117-c3; 16-124-c3; 17-127-c3; 18-131-c6; 19-149-c3; 20-168-c4; 21-171-c4; 22-179-c4.

The “c” parts of these 22 recordings were inputed into an EXCEL table (only columns “a_z” and “F_z”) and then they were transferred into MATLAB.

Twelve monitoring indices were calculated:

- $x_1 = v$ → the cutting speed;
- $x_2 = t$ → the cutting depth;
- $x_3 = s$ → the longitudinal advance;
- $x_4 = F_z \rightarrow$ the average value of the main cutting force;
- $x_5 \rightarrow F_z$ variation range (the 960 data points were split into four equal parts of 240 points each and the maximum and minimum value were calculated for each part; $X_5$ is the difference between the maximum and minimum average values);
- $x_6 \rightarrow$ number of intersections of $F_z$ with its average value $F_{\bar{z}}$;
- $x_7 \rightarrow$ the average of $F_z$ power spectral density in the frequency range $1 - 2400$ Hz;
- $x_8 \rightarrow$ the average of $F_z$ power spectral density in the frequency range $2401 - 4800$ Hz;
- $x_9 \rightarrow$ the average of $F_z$ power spectral density in the frequency range $4801 - 9600$ Hz;
- $x_{10} \rightarrow$ the average of $a_z^{\text{inc}}$ power spectral density in the frequency range $1 - 2400$ Hz;
- $x_{11} \rightarrow$ the average of $a_z^{\text{inc}}$ power spectral density in the frequency range $2401 - 4800$ Hz;
- $x_{12} \rightarrow$ the average of $a_z^{\text{inc}}$ power spectral density in the frequency range $4801 - 9600$ Hz.

These indices, which were calculated for the 22 data sets, make up the matrix $x$, with 22 rows and 12 columns, which is shown in Table 2.

Table 2, sixth column (of index $x_6$) shows only 3 values of two digits (among which the one in row 18, corresponding to recording no. 131, from class “c6” (Chatter), the rest being of three digits.

It is concluded that the other two recordings (row 9 $\rightarrow$ Recording 093 and row 22 $\rightarrow$ Recording 179) belong to $c_5$, instead of $c_2$, $c_3$ respectively. This fact is sustained in column $x_5$, the value of this index for the 3 recordings being of two digits, and the rest of one digits.
Based on the values of the $x_6$ and $x_5$ monitoring indices, recordings 72 - 75 (in class $c_1$) and 180 (in $c_5$) were moved into class $c_6$.

4.1 The Histograms

The histograms of the column matrices corresponding to the monitoring indices $x_5$ and $x_6$ found for each class, but illustrated only for the classes: e2 (fig. 3) and e6 (fig. 4), underline the accurate use of these indices values for chatter detection: most recordings that belong to the first 5 wear classes takes the values of $x_5 \in [6, 10]$, the maximum value being 14 (except for 3 values of 15
Fig. 4 b- The histogram for monitoring index $X_6$ for class $c_6$ and 16 at $c_2$ and one value of 15 at $c_5$), while at class $c_6$ (Chatter) the minimum value is 10, most recordings take $x_3 \in [10, 24]$, and at 3 recordings $x_3 \in [50, 55]$.

At $c_5$ the maximum value of $x_6$ is 200, most of them being within [40, 100], while with the first 5 classes, except a few, the minimum value is 150.

### 4.2 The Coherence Function

Considering the relations between the cutting force components:

$$F_x = (0.25 \div 0.35) F_z; \quad F_y = (0.35 \div 0.50) F_z,$$

and taking into account that:
- the force $F_y$ brings about the distortion $\Delta y$ which influences directly the dimensional precision and the cylindrical form;
- the force $F_z$ it is not significant because the distortion $\Delta z$ spreads only in little measure and is conversely proportional with the diameter of the piece;
- the force $F_x$ depends, mainly, of the speed of the longitudinal advance, being possible the omission of this component, if it is working with small advances, the coherence function between the accelerations in the directions $Y$ and $Z$ are calculated, by using the function COHERE from MATLAB.

The coefficients in (9) of accelerations amplification (for ex.: $a_x = K_x a_x$) affect the self- and inter-correlation functions:

$$R_{xx} = K_x^2 R'_{x'x'}; \quad R_{yx} = K_y K_x R_{x'y'};$$

along with the spectral and inter-spectral density functions:

$$P_{xx}(\omega) = \int_{-\infty}^{\infty} R_{xx}(\tau) \cdot e^{-i\omega \tau} \cdot d\tau = K_x^2 \cdot P_{x'x'}$$

and analogous $P_{yy} = K_y K_y P_{y'y'}$.

However they do not affect the coherence function:

$$C_{xy} = \frac{|P_{xy}|^2}{P_{xx} \cdot P_{yy}} = \frac{K_x^2 K_y^2 |P_{x'y'}|^2}{K_x^2 P_{x'x'} \cdot K_y^2 P_{y'y'}} = C_{x'y'};$$

therefore the recordings non amplified with the coefficients in (9) can be made.

The coherence function was calculated for at least 2 recordings in each class; the results (for a few classes) are presented in fig. 5 ÷ 7 and the table 3.

Fig. 5- Class $c_2$: 1 $\rightarrow$ Rec. no. 090; 2 $\rightarrow$ 091; 3 $\rightarrow$ 096; 4 $\rightarrow$ 111

Fig. 6- Class $c_4$: 1 $\rightarrow$ 166; 2 $\rightarrow$ 176

Fig. 7- Class $c_6$: 1 $\rightarrow$ 064; 2 $\rightarrow$ 067; 3 $\rightarrow$ 072; 4 $\rightarrow$ 131; 5 $\rightarrow$ 179

Because the majority of the recordings reach the maximum of the coherence function at the first
frequency values (the maximum which is not considered significant), the first three frequency values were eliminated when this maximum and its position (the frequency when the maximum is reached) were determined. These values are shown in Table 3.

5 Concluding Remarks
The recordings from class C6 fall (except for one) under the criterion from [4]. However it can be seen that 3 out of the 4 recordings in class C2 take a maximum value of the coherence function equal to or greater than 0.91. Table 4 presents – for these 3 recordings – the first 6 monitoring indices, the first column showing the number of recordings.

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