Computer prediction of the tool-workpiece vibration surveillance in modern milling operations

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ABSTRACT. A new approach towards computer prediction of minimising tool-workpiece vibration in modern machine tools basing upon various cutting conditions is considered in the paper. From a view point of the machine tool dynamic properties, because of a danger of losing stability and generation of chatter vibration, the problem is extremely important. Due to varying cutting conditions, a bang-bang strategy of vibration surveillance is developed successfully. Also performance of the approach is simulated and subsequently verified experimentally on vertical milling centre FADAL. Finally, based upon computation and measurement, an efficient procedure of prediction is suggested.

KEY WORDS: dynamics, machine tools, control.

1. Introduction

From a point of view of the machine tool system dynamic properties, tool-workpiece relative vibration during cutting process is extremely inconvenient. In the case of certain conditions, it may lead to a loss of stability and generate self-excited vibration, which is called: chatter. They were trying to counteract it by means of [KAL 99]:
- spindle speed regulation by matching to eigenfrequency of the system [SMI 90].
  It depends on such adjustment of the edge passing frequency, that it should be equal to the one of chatter vibration. Once the chatter vibration is being detected, a feed should be stopped immediately. Otherwise, an accelerated tool wear will be observed. A new switching-on the feed causes suspension time of free vibration being relatively long. Moreover, the edge leaves a wavy trace on
the cutting surface, and then a danger of kinematically excited vibration near resonant zone, really exists;

- the spindle speed pulse control [JEM 84, LIN 90, ALT 92]. Some experiments evidenced that cutting with periodically changing spindle speed prevents generation of the chatter vibration in a wide range of speed values. Recommended amplitudes of the pulse spindle speed are 10 - 15 % of desired values, but pulse frequencies – up to 14 Hz. However, no indication concerning a choice of optimal values has been advised, all the more so as a chatter development is observed in some cases of the performance [SOL 97];

- spindle speed regulation by matching to optimal phase shift between two subsequent passes of tool edges [LIA 96, KAL 99]. A state of vibration is monitored by special computer system, which generates a spindle speed control command in real time. There is no need of the machine tool structure identification and disconnection of the feed during machining;

- permanent raising the cutting speed [SCH 97]. Modern, but fund-consuming production technologies at spindle speeds up to a few ten-thousands rev/min and feed rates up to a few tens m/min guarantee high productivity at more less depths of cutting. They are also coming against high quality requirements of the finishing manufacturing. It results saving in time up to 80%, and in cost of manufacturing up to 30%.

Despite various approaches towards the problem of chatter suppression, no effective method of dealing with it is developed thusfar. Moreover, an experimental research of the strategies of the chatter avoidance is time-consuming and very expensive. Therefore, a new approach towards computer prediction of tool-workpiece vibration surveillance is proposed. It depends upon computer simulation of the cutting model at first, and subsequent real performance of the cutting process.

2. Some requirements the machine tools should meet

The modern machine tools are preferred for the methods of tool-workpiece vibration surveillance being successfully performed. In case of them an investigation of implementation of vibration control strategies is fully reasonable, because they assure all conditions, they concern:

- rigid carrying system whose influence on dynamics of the cutting process is unnoticeable;

- small inertia of the main driving system, which puts in favour position structures having short kinematic chains and motor installed directly on the spindle (so called: electrospindles);

- production process, in which, due to a danger of the chatter occurrence, some problems with technological criteria (e.g. surface quality, tool life, productivity) being satisfied, are observed;

- a possibility of utilising the standard control system CNC of the machine tool for programming some strategies of surveillance;
- a possibility of co-operating between standard control system CNC and external spindle speed control device.

A vertical milling centre VMC FADAL 4020HT (made in USA) has been chosen as an object of the performance, though it satisfies such requirement mentioned above.

3. Cutting process dynamics

Here a face milling process by a slender end mill is a subject of consideration. The cutting using slender tools is observed in modern machining centres very frequently. A technological reason lies in necessity of making difficulty accessible hobblings (e.g. die pockets). It is usually treated as finishing work, so that the depths of milling can reach even a few milimetres. Big depths of cut can also be met during manufacturing of the first row.

A study of the machining process dynamics has been performed basing upon following assumptions:
- several subsystems, which perform desired relative motions, are separated from the machine tool structure: the spindle together with the tool fixed in the holder, and the table with the workpiece. Computer simulation of dynamic behaviour of some flexible machine tools resulted that the ones mentioned above influence the dynamics of cutting process significantly, but contribution of other parts of the machine is rather meagre [KAL 97]. Thus, because of more rigid structure of contemporary machine tools, the rule is really understood;
- only a flexibility of the slender tool has been considered. The other elements of the structure, including also the main driving system, are idealised as perfectly rigid. Former experimental investigation of the cutting process, performed on the VMC FADAL using short end mill, evidenced a lack of any essential influence of dynamic properties of the structure, even at extremely significant values (up to 15 mm) of the cutting depth [KAL 99]. Also measuring procedures of its main driving system disclosed that its first eigenfrequency is very high and lies over 1500 Hz;
- an effect of cutting process has been considered as closed-loop interaction, and coupling elements (CE) have been applied for modelling [KAL 99];
- cutting dynamics has been described using proportional model [KAL 99]. The reason yields from anticipated significant values (i.e. above 100 m/min) of the cutting velocity, and from expected values of the chatter frequency in a range of a few hundreds Hz [TOM 97];
- an effect of first pass of the edge along cutting layer causes proportional feedback, but the effect of multiple passes causes delayed feedback additionally.
Figure 1. A scheme of the face milling process
The reasons above imply a simplified model of the milling process (Fig. 1) being purposed for computer simulation. It counts six degrees of freedom and is composed of beam flexible finite element (DFE) no $e$ with length $L_e$, fixed at its upper end, and coupling elements (CE), whose positions refer to instantaneous positions of mill edge tops and obviously vary with time [KAL 99]. The tool–workpiece conventional contact point $S$ is introduced. Denoted here are generalised directions $x_1$, $x_2$, $x_3$ for this point, as well as generalised co-ordinate system $x_e_1x_e_2x_e_3$ of the DFE.

The tool is spinning with speed of revolution $n$, while the workpiece displaces with desired value of feed rate $f_{min}$. Length of machined specimen is $L_w$, but widths of the milling are: $B_1$ and $B_2$.

An instantaneous position of the edge top of the milling cutter, described by immersion angle $\varphi=\varphi(t)$, is idealised by CE no $l$, but axes $y_lY_lY_l$ are desired axes of the feedback interaction of this CE. Also it has been assumed, that:
- the edge geometry elements are: rake angle $\gamma_b$ inclination angle $\lambda_c$ and main cutting angle $\kappa_r$;
- actual cutting layer thickness is $h_l$ while the cutting force acting along it - $F_{yl}$;
- actual depth of cutting is $a_p$ and desired width $b_D$ is derived from the relationship: $b_D = a_p / \sin \kappa_r$;
- the main cutting force $F_{yl}$ is acting along the cutting speed.

One may transform displacements from the $y_lY_lY_l$ system to the $x_1x_2x_3$ system by the following matrix:

$$T_l(t) = \begin{bmatrix}
1 & 0 & 0 & \cos \varphi_l(t) & -\sin \varphi_l(t) & 0 \\
0 & \sin \kappa_r & \cos \kappa_r & \sin \varphi_l(t) & \cos \varphi_l(t) & 0 \\
0 & -\cos \kappa_r & \sin \kappa_r & 0 & 0 & 1
\end{bmatrix} [1]$$

If we consider proportional description of the cutting process and the effect of inner and outer modulation [KAL 99], instantaneous cutting force components, for CE no. $l$, will be determined as follows:

$$F_{y_l}(t) = \begin{cases}
0, & \text{for } h_{i,c}(t) - \Delta h_l(t) + \Delta h_l(t \cdot T_l) \leq 0,

[k_b a_p \left[h_{i,c}(t) - \Delta h_l(t) + \Delta h_l(t \cdot T_l)\right] & \text{for } h_{i,c}(t) - \Delta h_l(t) + \Delta h_l(t \cdot T_l) > 0.
\end{cases} [2]$$

$$F_{y_l}(t) = \begin{cases}
0, & \text{for } h_{i,c}(t) - \Delta h_l(t) + \Delta h_l(t \cdot T_l) \leq 0,

\left[k a_p a_p \left[h_{i,c}(t) - \Delta h_l(t) + \Delta h_l(t \cdot T_l)\right] & \text{for } h_{i,c}(t) - \Delta h_l(t) + \Delta h_l(t \cdot T_l) > 0.
\end{cases} [3]$$

$$F_{y_l}(t) \equiv 0, [4]$$

where:
$k_d$ - average dynamic specific cutting pressure,

$h_{Dl}(t)$ - desired cutting layer thickness; $h_{Dl}(t) = f_z \sin \varphi(t)$ ($\Delta b \equiv 0$),

$\Delta h_{Dl}(t)$ - dynamic change in cutting layer thickness for time-instant $t$,

$\Delta h_{Dl}(t-T_l)$ - dynamic change in cutting layer thickness for time-instant $t-T_l$,

$T_l$ - time delay between the same position of CE no. $l$ and the previous one (CE no. $l-1$),

$\mu$ - cutting force ratio,

$f_z$ - feed per tooth.

Zero values of the components concern an effect of the tool-workpiece contact loss.

If we suppose that spindle speed changes instantaneously with respect to angular position $\varphi$ (i.e. $n = n(\varphi)$), time $T_l$ can be determined by the form:

$$T_l = \int_{\varphi_i-\varphi_{0l}}^{\varphi_i} \frac{60}{2\pi} \frac{d\varphi}{n(\varphi)}, \tag{5}$$

where:

$\varphi_i$ - current angular position of CE no. $l$,

$\varphi_{0l}$ - difference between the same angular position of CE no. $l$ and CE no. $l-1$,

$n(\varphi)$ - instantaneous spindle speed as a function of angular position $\varphi$.

Using discrete notation, we get:

$$T_l = \frac{60}{2\pi} \sum_{i=1}^{i_n} \frac{\Delta \varphi}{n_i}, \tag{6}$$

where:

$i_n$ - number of angular positions of CE no. $l$,

$n_i$ - spindle speed, referred to position $i$ of CE no. $l$,

$\Delta \varphi$ - angle between subsequent positions of CE no. $l$.

Now we form for CE nr $l$ vector of forces:

$$\vec{F}_l(t) = \text{col} \left( F_{yl1}(t), F_{yl2}(t), F_{yl3}(t) \right), \tag{7}$$

vectors:
\[ \ddot{\mathbf{w}}_i(t) = \text{col} \left( q_{z,i}(t), \dot{h}_i(t), \dot{b}_i(t) \right), \quad [8] \]
\[ \ddot{\mathbf{w}}_i(t-T_i) = \text{col} \left( q_{z,i}(t-T_i), \dot{h}_i(t-T_i), \dot{b}_i(t-T_i) \right), \quad [9] \]
\[ \ddot{\mathbf{F}}_i^0(t) = \text{col} \left( k_d b_{D,i}, h_{D,i}(t), \mu k_d b_{D,i} h_{D,i}(t), 0 \right). \quad [10] \]

where:

- \( q_{z,i}(t) \) - tool-workpiece relative displacement along direction \( y_{n_i} \) at time-instant \( t \),
- \( q_{z,i}(t-T_i) \) - tool-workpiece relative displacement along direction \( y_{n_i} \) at time-instant \( t-T_i \),
- \( \Delta b_i(t) \) - change in cutting layer width for time-instant \( t \),
- \( \Delta b_i(t-T_i) \) - change in cutting layer width for time-instant \( t-T_i \),

matrix of proportional feedback interaction:

\[ \mathbf{D}_{pi} = \begin{bmatrix} 0 & k_d b_D & 0 \\ 0 & \mu k_d b_D & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad [11] \]

and matrix of delayed feedback interaction:

\[ \mathbf{D}_{oi} = \mathbf{D}_{pi}, \quad [12] \]

which is caused by an effect of the trace regeneration.

If we describe them in six-degree-of-freedom space, we will get:

\[ \mathbf{F}_i(t) = \text{col} \left( \ddot{\mathbf{w}}_i(t), 0 \right), \quad [13] \]
\[ \ddot{\mathbf{w}}_i(t) = \text{col} \left( \ddot{\mathbf{w}}_i(t), 0 \right), \quad [14] \]
\[ \ddot{\mathbf{F}}_i^0(t) = \text{col} \left( \ddot{\mathbf{F}}_i^0(t), 0 \right), \quad [15] \]
\[ \mathbf{D}_{pi} = \begin{bmatrix} \mathbf{D}_{pi} & 0 \\ 0 & 0 \end{bmatrix}. \quad [16] \]
After transformation of displacements to generalised co-ordinate system $x_1, x_2, x_3$ of conventional point $S$, an equation of dynamics shall get a form:

$$\ddot{D}_{ol} = \begin{bmatrix} \ddot{D}_{ol} & 0 \\ 0 & 0 \end{bmatrix}. \quad [17]$$

$$\mathbf{F}_i(t) = \mathbf{F}_i^0(t) - D_{pl} \cdot \omega_i(t) + D_{ol} \cdot \omega_i(t - T_i). \quad [18]$$

After transformation of displacements to generalised co-ordinate system $x_1, x_2, x_3$ of conventional point $S$, an equation of dynamics shall get a form:

$$\ddot{\mathbf{M}} \ddot{\mathbf{q}} + \dddot{\mathbf{L}} \ddot{\mathbf{q}} + K^* \mathbf{q} = \mathbf{f}^*, \quad [19]$$

where:

$$K^*(t) = K + \sum_{i=1}^{i_l} T_i^T(t) D_{pl} T_i(t). \quad [20]$$

$$\mathbf{f}^* = \sum_{i=1}^{i_l} T_i^T(t) \ddot{\mathbf{F}}_i^0(t) + \sum_{i=1}^{i_l} T_i^T(t) D_{ol} \cdot \omega_i(t - T_i). \quad [21]$$

$$T_i(t) = T_i(t) S_i(t). \quad [22]$$

$$T_i(t) = \begin{bmatrix} \bar{T}_i(t) & 0 \\ 0 & \bar{T}_i(t) \end{bmatrix}. \quad [23]$$

and:

- $\mathbf{q}$ - vector of generalised co-ordinates of the system,
- $\mathbf{M}, \mathbf{L}, \mathbf{K}$ - matrix of inertia, damping and stiffness of mechanical system,
- $i_l$ - number of “active” coupling elements (CE),
- $S_i(t)$ - matrix of connecting points’ co-ordinates of CE no $i$ in the $x_1, x_2, x_3$ co-ordinate system.

The matrix of transformation $T_i(t)$ is time-dependent, because, as result of motion of the spindle and the workpiece, several edges of the cutter change their positions ourselves. It means that the system becomes one with time-varying coefficients of matrix $K^*$.

4. The tool-workpiece relative vibration surveillance by the pulse spindle speed control
Let us consider the milling process, in which spindle speed \( n(t) \) changes with time in accordance with pulse function, that is to say:

\[
n(t) = n_0 + \delta n \sin(2\pi f_{pul} t)
\]  

where:

- \( n_0 \) - nominal spindle speed [rev/min],
- \( f_{pul} \) - frequency of spindle speed changes [Hz],
- \( \delta n \) - amplitude of spindle speed changes [rev/min].

Because real spindle speed control systems have an ability of adjustment of pulse parameters \( \delta n \) and \( f_{pul} \), the \( n(t) \) function is recognised as programmable time function. The problem of matching correct values of the parameters is not easy and still actual [SOL 97].

Let us consider an incremental change in spindle speed (Eqn [24]). Then we get:

\[
\Delta n = 2\pi f_{pul} \Delta t \cos(2\pi f_{pul} t) \Delta t.
\]  

[25]

It is convenient to consider for simulation, that \( \Delta \phi = \text{const} \). Thus, we obtain:

\[
\Delta t_i = \frac{\Delta \phi}{2\pi n_i}.
\]  

[26]

and finally, an instantaneous increment in spindle speed is derived (Fig. 2):

\[
\Delta n_i = \begin{cases} 
  \pm 2\pi f_{pul} \Delta t_i \sqrt{\delta n^2 - (n_i - n_0)^2}, & \text{if } \delta n^2 - (n_i - n_0)^2 \geq 0, \\
  0, & \text{if } \delta n^2 - (n_i - n_0)^2 < 0.
\end{cases}
\]  

[27]

As result of considerations above, following procedure is suggested:

- Determination off-line of pulse parameters \( \delta n \) oraz \( f_{pul} \)
- Monitoring of vibration by measurement of the tool displacement using proximity sensors
- Chatter detection – an analysis of time-plots by low-pass and band-pass filters, or spectral analysis
- The program-controlled spindle speed on-line – computer simulation or real performance of machining
5. The tool-workpiece relative vibration surveillance by the step-changing spindle speed control

Now let us analyse the milling process again and assume that the spindle speed changes with time in accordance with following inertia step relationship:

$$n(t) = \begin{cases} n_0, & 0 \leq t \leq t_1, \\ n_{j+1} + (n_j - n_{j-1}) \left(1 - e^{-\frac{t-t_{j-1}}{T_j}}\right), & t_{j-1} \leq t \leq t_j, \quad j = 2, \ldots, N. \end{cases}$$

where:

- $T_j$ - time constant of stage no. $j$ of step-changing spindle speed,
- $t_j$ - switching time of stage no. $j$ of step-changing spindle speed.

Thus, a sequence of the $n_1, n_2, \ldots, n_m$ spindle speeds for desired switching time values $t_1, t_2, \ldots, t_m$ should be matched, and subsequently applied for a surveillance. As a result of the consideration above, following procedure is advised:

- Determination off-line of step-changing spindle speed parameters
• Monitoring of vibration by measurement of the tool displacement using proximity sensors
• Chatter detection – an analysis of time-plots by low-pass and band-pass filters, or spectral analysis
• The program-controlled spindle speed on-line – computer simulation or real machining performance

6. An analysis of possibilities of the speed control strategy performance in real vibrating system

The performance of program-controlled spindle speed of the VMC FADAL machine tool can be easily realised using the software controller [KUC 00]. Special computer software is started from external computer PC. It generates step-changing spindle speed, whose values are switched with minimum time 0.08 s. Following that the control command is transmitted to the machine through the RS 232 port. It was appeared a very cheap solution, because it allowed utilising only a standard driving system and a standard control system of the machine, without necessity of modifying the structure. An instantaneous change in spindle speed about ± 350 rev/min at time-constant value 0.1 s is obtained in any case of the performance. There is no evidence in the world biography that such parameters have been achieved thusfar.

7. A procedure of prediction of the tool-workpiece vibration surveillance results

Despite an ability of real performance of the programmed spindle speed strategy being developed, a computer prediction of the results is suggested before. The main reason is that computer simulation appears more economic than real cutting process. It allows making plenty of savings in technology. Thanks to fast computer devices and software, many alternatives of the machining for various cutting parameters can be examined during short time as well. Finally, real performance is applied as delivered concept and a chance of making any mistakes is extremely reduced.

Therefore, following procedure of prediction of the tool-workpiece vibration surveillance results, is advised:

1. Matching the model parameters, based upon a comparison of frequency characteristics (i.e. measured and simulated) observed during vibration without surveillance. Based upon the milling model being introduced, only following parameters are enough in order to match the plots: the $k_d$ average dynamic specific cutting pressure, the $\mu$ cutting force ratio and the $\eta$ damping constant of the tool material.
2. Matching the bang-bang speed plots for prediction, based upon the computer spindle speed programme. Due to inertia of real main driving system (time-
constant about 0.1 s), for noticeable value of switching time the bang-bang plot is step-changing, while for shorter values it becomes pulse-changing.

3. Evaluation of quality of time-plots and frequency characteristics after the bang-bang strategy has been enrolled.

4. A comparison of results of the maintenance: predicted and really performed.

7. An illustrative example

Here is performed computer simulation of the face milling vibration surveillance on the VMC FADAL machine, using slender end mill NOMA 206.016 W-W, which is purposed for high-speed cutting, and considering unsteady model of the process (Eqn [19]). The specimen is made of carbon steel.

Following data is introduced: nominal spindle speed of revolution \( n_0 = 3000 \) rev/min, feed rate \( f_{\text{min}} = 1200 \) mm/min, number of indexible inserts of the mill (cover material: TiN) \( z = 2 \), mill diameter \( D = 16 \) mm, widths of cutting \( B_1 = B_2 = 8 \) mm, length of cutting \( L_w = 60 \) mm, main cutting angle \( \kappa_r = 90^\circ \).

Vibration along direction \( x_1 \) is calculated. The choice is mostly convenient, because it yields an ability of comparison of simulated results with them obtained from measurement. In order to make evaluation, the root mean square (RMS) value of time plot is defined, i.e.:

\[
RMS = \sqrt{\frac{1}{i_\alpha} \sum_{\alpha=1}^{i_\alpha} q_{1\alpha}},
\]  

[29]

where:

\( q_{1\alpha} \) - vibration in point \( \alpha \) of time plot,

\( i_\alpha \) - number of points of time plot,

and the ratio of RMS:

\[
F_{\text{RMS}} = \frac{RMS}{RMS_0},
\]  

[30]

while \( RMS_0 \) denotes the RMS value of time plot without vibration surveillance.

Similarly, a chatter amplitude ratio is defined, that is to say:

\[
F_{\text{ch}} = \frac{q_{\text{ch}}}{q_{\text{ch}0}},
\]  

[31]

where:
A cutting with the depth $a_p=0.2$ mm yields a loss of stability and appearance of strong, developed chatter vibration. In a range of two-edge cutting a level of vibration reached about 0.300 mm, at the RMS=0.111 mm (Fig. 3). Based upon an observation of the amplitude spectrum (Fig. 4) two resonant frequency values are dominant. Maximum resonance amplitude is over 0.100 mm.

Using the trial-and-error approach, following parameters have been determined for simulation: specific dynamic cutting pressure $k_d=2.3\times10^9$ N/m$^2$, cutting force ratio $\mu=0.4$ and damping constant of the tool material $\eta=1.4\times10^7$ Ns/m. Good agreement between frequency curves: measured and simulated, is obtained as result (Fig. 4).

Following that, the model with values of parameters being determined has been employed to computer prediction of results of program-controlled spindle speed strategies bang-bang. Some data for the strategies being examined is completed below (table 1).

<table>
<thead>
<tr>
<th>No.</th>
<th>Type of strategy</th>
<th>$\delta n$ [rev/min]</th>
<th>$f_{pu}$ [Hz]</th>
<th>$n_j$ [rev/min]</th>
<th>$t_j$ [s]</th>
<th>$T_j$ [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Step-changing</td>
<td></td>
<td>3400, 3000,</td>
<td></td>
<td>0.25, 0.5,</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2600, 3000,</td>
<td></td>
<td>0.75, 1.0,</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3400, 3000,</td>
<td></td>
<td>1.25, 1.5,</td>
<td></td>
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<td></td>
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<td></td>
<td>...</td>
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<td>...</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Pulse-changing</td>
<td>350</td>
<td>1.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Pulse-changing</td>
<td>350</td>
<td>2.4</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Values of parameters have been typed, so that all the strategies are possible to be performed on real milling machine.

Results of computer simulations of the strategies above showed that:
- the RMS values of time plots are reduced down to 0.088 mm (Fig. 5), 0.083 mm (Fig. 7) and 0.087 mm (Fig. 9) respectively,
- maximum resonance amplitudes are reduced down to about 0.023 mm (Fig. 6), 0.016 mm (Fig. 8) and 0.020 mm (Fig. 10) respectively,
- behaviour of the milling process is really predicted. A comparison of frequency plots obtained from simulation and measurement (Fig. 6, 8 and 10) means to be in support.
Figure 3. Results of computer simulation of tool vibration along direction $x_1$ – no vibration surveillance. The RMS value is denoted 0.111.

Figure 4. Frequency plots of tool vibration along direction $x_1$ - no vibration surveillance:
   a) computer simulation of the cutting model behaviour,
   b) result of measurement during machining.
Following that, also the values of $F_{RMS}$ and $F_{ch}$ from computer prediction have been compared with suitable ones from measurement (Fig. 11 and 12).

8. Conclusions

The method of prediction tool workpiece vibration surveillance by the program-controlled spindle speed strategy bang-bang is developed in the paper and the results have been successfully verified. There has been emphasised an importance of the tool-workpiece vibration surveillance methodology from a view-point of its usefulness for as well the computer prediction, as real performance. Thus, the goal of searching optimal spindle speeds in order to minimise tool-workpiece vibration during cutting process is successfully resolved in the paper.

Although computer simulation has been performed for particular case of the face milling, a comparison of the approaches above may produce some generalisations towards application of the method. A comparison of RMS ratio values $F_{RMS}$ (Fig. 11) and chatter amplitude ratio values $F_{ch}$ (Fig. 12) evidenced that all the approaches produce the results being improved with respect to one without surveillance. Also results of computer prediction converge with them of real performance. The latter is thanks to simple, but true model of the milling process, whose parameters have been easily matched. It caused the method of prediction being effective and reliable. Suitable computer simulations, in which the original software has been applied, allowed to expect accurately behaviour of real cutting process.

Further development of the research will be focused on enrolment of the strategies described in the paper for surveillance of vibration being observed during various machining operations.

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References


Figure 5. Results of computer simulation of tool vibration along direction $x_1$ – a surveillance with switching time 0.25 s. The RMS value is denoted.

Figure 6. Frequency plots of tool vibration along direction $x_1$ - a surveillance with switching time 0.25 s:

a) computer simulation of the cutting model behaviour,
b) result of measurement during machining
Figure 7. Results of computer prediction of tool vibration along direction $x_1$ - a surveillance with pulse frequency 1.7 Hz. The RMS value is denoted.

Figure 8. Frequency plots of tool vibration along direction $x_1$ - a surveillance with pulse frequency 1.7 Hz:
- a) results of prediction - computer simulation of the cutting model behaviour,
- b) result of measurement during machining
Figure 9. Results of computer prediction of tool vibration along direction $x_1$ - a surveillance with pulse frequency 2.4 Hz. The RMS value is denoted.

Figure 10. Frequency plots of tool vibration along direction $x_1$ - a surveillance with pulse frequency 2.4 Hz:

a) results of prediction - computer simulation of the cutting model behaviour,

b) result of measurement during machining
Figure 11. A comparison of RMS ratio values for the program-controlled spindle speed strategy – VMC FADAL.
1. Step - changing spindle speed - switching time 0.25 s;
2. Pulse spindle speed – frequency 1.7 Hz;
3. Pulse spindle speed – frequency 2.4 Hz

Figure 12. A comparison of chatter amplitude ratio values for the program-controlled spindle speed strategy – VMC FADAL.
1. Step - changing spindle speed - switching time 0.25 s;
2. Pulse spindle speed – frequency 1.7 Hz;
3. Pulse spindle speed – frequency 2.4 Hz


