Influence of parameters of adaptive control system on vibratory drilling efficiency

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Abstract. One of the necessary conditions of ensuring the quality of deep hole drilling during manufacturing pieces from hard-to-machine metals is chip control. It can be ensured by applying harmonic oscillations to a drill bit in the direction of rotation axis. One possible way of maintaining such vibrations is to use a vibratory drilling head which contains an elastic element. This element allows axial displacements of the tool. If stiffness of the elastic element and the machining parameters are chosen correctly, self-actuating of axial vibrations of a drill bit in compliance with regenerative effect may occur. It is advisable to add control response, which is determined in the feedback loop, to this mechanism because of the significant damping in the cutting zone. The control response maintains the required process characteristics to ensure chip control. The algorithm of vibratory drilling dynamics adaptive control has been examined in this paper. The additional impact, which is proportional to axial speed of the drill bit, is supposed to be made on the vibration system according to this algorithm. The feedback gain is determined in the adaptation loop comparing the current value of peak-to-peak displacement and its target value. The dynamics modeling of closed loop non-linear system “elastic system-machining process-control system” has been carried out. The graphs of vibratory drilling integral characteristics plotted against processing characteristics and vibratory head parameters have been presented in this paper. These graphs are based on the multivariant modeling. The influence of the adaptation algorithm parameters on the quality of vibratory processing has been also studied.

1. Introduction

The continuous chip formed during drilling can be wound on the tool, leading to a drill bit seizing and a tool breakage. This problem is especially relevant when drilling hard-to-machine materials and tough alloys. Chip disposal from a drill bit is a hardly-automated operation that requires a standstill of production job, so it is highly recommended to implement chip control. In this case drilling can be carried out without halting, increasing the productivity and quality of processing.

One of the ways to ensure chip control is the use of vibratory drilling, during which the cutting edges oscillate in the feed direction. The oscillation amplitudes should be sufficiently high [1] in this case. A possible way to ensure such an oscillatory motion is the use of a special vibratory drilling head, which is shown in figure 1. It contains an elastic element, selecting the stiffness of which in combination with the right processing modes it is possible [2], [3] to provide the required vibratory
mode with chip control. At the same time, a regenerative effect is used to convert the energy of the main operation process into vibratory energy.

Figure 1. The vibratory drilling head with built-in slotted elastic element [4]

The problem of vibratory drilling has been dealt with in the investigations of many authors [2] - [11]. The original idea of using a vibratory head with a built-in elastic element was proposed by A.M. Gouskov [2]. More detailed research on vibratory drilling has been carried out in papers [8], [9] with special focus on the influence of damping along the flank face of the cutting part of the tool. A study of vibratory drilling taking into account the bending compliance of the drill has been performed in [10], [11].

The application of the described method of chip control using a vibratory head is restrained by the fact that there is energy dissipation in the cutting zone [8], [9], [12], especially on the drill web. It is difficult to predict the dissipation parameters and they change while the tool is wearing and sinking into the hole. That is why it is necessary to add external control response, which is determined in the feedback loop, to a “regenerative effect” mechanism. The influence of dissipation parameters change can be compensated by adapting the feedback gain. This requirement can be met by implementing adaptive control systems that are able to provide the necessary parameters of the vibratory drilling process for various processing modes.

The dynamics of a closed nonlinear system "elastic system-machining process-control system" has been researched in this paper. This research is a continuation of the papers [13] - [16], in contrast to which the influence of the parameters of the law of adaptation on the quality of the implemented vibratory process is additionally considered here. The following sections provide a mathematical model and modeling results for various combinations of elastic element parameters, processing parameters, and adaptation law parameters.

2. Mathematical model
The schematic model used in the simulation is depicted in figure 2. The equations of the vibratory drilling dynamics model with control have been derived in [17]. Here they are just given in the unitless form:

$$\frac{1}{(2\pi p)^2}\ddot{q} + \frac{\zeta}{\pi p}\dot{q} + q = P_c + q_0$$  \hspace{1cm} (1)

$$\eta(\tau)=[\Lambda(\tau-1)+1-q(\tau)]H[\Lambda(\tau-1)+1-q(\tau)]$$  \hspace{1cm} (2)

$$P_c = k_e \eta^r$$  \hspace{1cm} (3)

$$\Lambda(\tau) = \Lambda(\tau-1) + 1 - \eta(\tau)$$  \hspace{1cm} (4)

where $q$ – the unitless axial coordinate of the tool in fractions of the feed per cutting edge; $p$ – is the natural frequency of the vibratory head vibrations divided by the frequency factor of the cutting edges;
ζ – the unitless damping coefficient of the system;  
$P_c$ – the unitless cutting force, in fractions of the product of the stiffness of the elastic element and the feed value;  
$q_0$ – the unitless kinematic excitation value, in fractions of the feed value;  
$\eta$ – the unitless cut-off thickness which is measured in fractions of the feed value;  
$\tau$ – the unitless time, which is measured by the period factor fractions of the cutting edges (the period of rotation divided by the number of cutting edges);  
$\Lambda$ – the unitless axial coordinate of the machined surface;  
$k_c, r$ – the empirical constants determined by the properties of the material being processed and the diameter and geometric shape of the cutting tip of the drill bit.  

(1) - the model of the dynamics of the vibratory head and tool, (2), (4) – the model of surface shaping, (3) - the phenomenological model of cutting forces.  
$r$ and $\zeta$ are assumed 0.7 and 0.1 respectively in the calculations.

$$\boxed{q_0 = k_c b \dot{q}}$$

Figure 2. The computational model of controlled vibratory drilling dynamics with external kinematic impact

The following control law is used in this paper:

$$q_0 = k, b \dot{q}$$

where $k_r$ – is the unitless gain coefficient of the control signal, $b$ is the feedback gain determined by the controller. The feedback gain should be changed depending on the peak-to-peak displacement of $q$ value.

The following adaptation algorithm is used in this paper [18]:

$$b = \begin{cases} 
  b_{\text{max}}, & A < (1-g_1) A_0 \\
  -c_1 \left( \frac{A}{A_0} - 1 \right) - c_2 \frac{A}{A_0}, & (1-g_1) A_0 \leq A \leq (1+g_2) A_0 \\
  b_{\text{min}}, & A > (1+g_2) A_0 
\end{cases}$$

where $b_{\text{max}}$, $b_{\text{min}}$ – the highest and lowest values of the feedback gain; $A$ is the current value of the unitless pick-to-peak displacement; $A_0$ is the target value of the unitless pick-to-peak displacement; $c_1, c_2, g_1, g_2$ – parameters of the law of adaptation. It is assumed in further calculations $A_0=1.5$, $g_1=g_2=0.1$, $b_{\text{max}}=b_{\text{min}}=1024$, $k_r=5.0 \cdot 10^{-5}$, the parameters $c_1, c_2$ vary, the default value of which is 500.

All calculations are performed in a nonlinear non-stationary formulation, the equations are solved iteratively by the fixed-point iteration method. More details are given in [17], [18].

3. The simulation results

The simulation results for cases without and with control are shown in figures 3 and 4 respectively. As it can be seen from a comparison of the figures, the implementation of control allows to excite vibrations with the required peak-to-peak displacement $A_0 = 1.5$ and at the same time the cutting force periodically hits zero and the chip control is on.
Figure 3. The relation between the unitless displacements (on the left) and unitless cutting forces (on the right) and time in case control is off, $k_c=0.3$ and $p=1.5$

Figure 4. The relation between the unitless displacements (on the left) and unitless cutting forces (on the right) and time in case control is on, $k_c=0.3$ and $p=1.5$

The peak-to-peak displacement $A$, which is the difference between the highest and lowest values of the unitless displacement $q$ in the steady-state section of the vibratory process, is used to present the results of multivariate calculations more clearly. In order to represent the dependence of the peak-to-peak displacement $A$ on the machining parameters, the special maps have been used, the drawing of which are to be carried out as follows. Initially, using the multivariant modeling, the dependence of $A$ on the parameters $p$, $k_c$ is to be determined. Then a set of contour lines of the obtained surface is needed to be built. The space between the contour lines is to be painted over with the same color.

The peak-to-peak displacement maps for the cases with and without control are shown in figure 5. As it can be seen from this figure, the implementation of control ensures a constant peak-to-peak displacement in a wide range of processing parameters, and at the same time the areas in which the vibrations are excited has increased. The regions of no excitation are on this graph due to the limited feedback gain $b$. To illustrate the influence of control in a more detailed way, the one-dimensional dependences of the peak-to-peak displacements on the parameter $k_c$ are shown in figure 6. It can be seen that starting with the certain threshold value $k_c \approx 0.2$, the peak-to-peak displacement is approximately equal to its target value $A_0$. 
Let us analyze the influence of the parameters $c_1$, $c_2$ of the adaptation law on the control efficiency. The corresponding maps of the dependence of the peak-to-peak displacement and the average control power capacity on $c_1$, $c_2$ are shown in figure 7. The average capacity is measured in fractions of the power required for the axial feed of the tool in the drilling mode without vibration.

As it can be seen from the figure, the parameter $c_2$ has the greatest influence on the quality of control provided that $c_1$ is significantly greater than zero (approximately $c_1 \geq 500$). The influence of $c_2$ is as follows. The control objective is fulfilled with sufficient accuracy when approximately $c_2 \leq 8000$, so it is advisable to consider values that satisfy this restriction. On the other hand, the higher $c_2$ value, the less power of vibrations excitation. This is a positive effect since it leads to a decrease in the heating of the actuator regardless of its type. Therefore, it is advisable to take the highest values of $c_2$ within the limits indicated above. It should be noted again that the restrictions described above are approximate and it is needed to refer to the maps in figure 7 to establish the exact values of $c_1$, $c_2$.

A comparison of displacements graphs for two different combinations of the parameters of the adaptation law is shown in figure 8. As you can see, when choosing the parameters $c_1$, $c_2$ in accordance with the recommendations described above, a steady-state vibration mode with a target peak-to-peak displacement is obtained. Otherwise, the quality of the vibration process is lower, and the target peak-to-peak displacement is not obtained.
Figure 7. The maps of dependencies of the peak-to-peak displacement values (on the left) and control capacity (on the right) on adaptation law parameters $c_1, c_2, p = 1.5, k_c = 0.3$

Figure 8. The dependencies of the displacements on time for cases $c_1=4000, c_2=1000$ (on the left) and $c_1=4000, c_2=20000$ (on the right), $p = 1.5, k_c = 0.3$

4. Conclusion
The research has been carried out to assess the influence of adaptation parameters on the quality of the resulting vibratory process based on the developed model of vibratory drilling dynamics with adaptive control. It has been shown that if the adaptation parameters are chosen incorrectly, it is possible that the goal of the control will not be reached in terms of the peak-to-peak displacements. The ranges of parameter values have been determined, which allows to, on the one hand, fulfill the control objective and, on the other hand, ensure minimization of the actuator power capacity. The developed model can be used to design control systems for vibratory heads with a built-in actuator.

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