The optimization of machining cutting zone based on improved genetic algorithm

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Abstract. The processing accuracy in the machining cutting zone is uneven. The condition of processing parts is most sharply worsened, when the guides junction occurs opening (the graph of pressure in the guides’ surfaces is not distributed over their entire length). The aim of this paper is optimization of the effective cutting zone (ECZ) of machining tool, in which graph of the guides pressure is always distributed on all surfaces. The layout of machining tools must ensure the largest zone of ECZ. The optimization of the objective function could change these parameters of layout, such as the vector of cutting forces, the weighting centre of the support, the coordinates of applied force from driving system, the width and length of guides. The task of optimization is a nonlinear extreme. According to the structural parameters of the machine tool, the pressure equation of the guide rail is established. For finding the optimal value, the method for determining extremum of the objective function used improving genetic algorithm (GA). Application of the method GA has allowed approximately ten times to raising the speed of determining of the layout parameters that ensure the largest ECZ.

1. Introduction
The layout of the machine tool is an integral structure, which is composed of a fixed and a plurality of moving units, separated by linear or circular guide rails. Each moving block has a certain movement of the coordinate. The number of guide rails is equal or slightly lower than the basic motion of number, specified by the structure of machine tool. The accuracy of machining guide rail plays an important role in the accuracy of the whole machine tool system [1, 2]. In recent years, scholars of China and abroad have carried out extensive and in-depth research on geometric error of machining guide rail.

Hwang and others used a three-probe measuring system to measure the parallelism and straightness errors of the ultra-precision of machining guide rail [3]. In order to have a deeper understanding of the aerostatic guideway, Ekinci and others established the relationship model between the movement error and the guideway geometric error by considering the internal mechanism of the movement error [4]. Sun Mingnan and others proposed an optimized method for the dynamic parameters of the guide joint that integrates the modal experimental data and the finite element of analysis model [5]. Qi and others proposed a moving linear error of predictive method, and took hydrostatic guide as an example to study the influence of 3D shape error on straightness and average error [6], the experience of using methods for optimizing parameters of in machining layout building is presented in the Ershov’s work [7]. In the works of Chernyansky P., for the first time, a hypothesis was stated about the possibility of optimizing the design of lathes based on the choice of their layout parameters, that provide the largest area of the effective cutting zone (ECZ) of machining tool [8, 9]. If the coordinates of the movable cutter are in the ECZ, then the opening of the joint does not occur in the guides of the machine.
The machining process is based on the relative movement of the workpiece and cutting tool. The processing accuracy in the cutting zone is uneven. The condition of processing parts deteriorates most sharply when the guides joint is opened (the graph of pressure in the guides’ surfaces is not all distributed over their entire length). The purpose of this work is to develop a methodology for determining the guides’ parameters of the machining layout, in which the ECZ has the largest area. As the optimized objective function, the factor $\eta$ is assumed to be the maximum value, which is equal to the ratio of the ECZ to the complete cutting zone (CCZ).

The optimization of the factor $\eta$ could change these parameters of layout, such as the vector of cutting forces, the weighting centre of the support, the coordinates of applied force from driving system, the width and length of guides. The task of the optimization is a nonlinear extreme. For to search the optimal values of the parameters of the machining layout, it is necessary to abandon simple enumeration of their possible values (in practice, it's the dozens of hours of computer time). In this case, it is advisable to use the methodology of the genetic algorithm (GA) of mathematical modeling [10, 11].

In general, this method is an adaptive search method and has been used to solve optimization problems recently. They use both genetic inheritance mechanism simulation and natural selection simulation. The simplified biological terms and the basic concepts of linear algebra are retained from the industrial point of view, genetic algorithm is an effective optimization algorithm. It is feasible to apply it to the optimization of industrial equipment, and it has been widely used [12, 13]. Application of the method GA has allowed approximately ten times to raising the speed of determining of the layout parameters that ensure the largest ECZ.

2. The optimizing method of CCZ based on the pressure diagram in machining guides

In order to calculate the ECZ of the machine tool, the pressure diagram of the machining guides must be calculated. Let's study the method of determining specific pressure of machining guides in the example of model CNC lathe. 16K20T1 (Fig. 1). The shape of guide rail is rectangle and triangle ($\alpha=55^\circ$ – degree of guide rail A and X-axis; $\beta=45^\circ$ – degree of guide rail B and X-axis).

When the tool holder moves on the machining guide rails, it is acted upon by the components of the cutting force ($F_x, F_y, F_z$), the gravity of the tool holder $G$, and the traction force $Q$, that moves the tool holder. As a result of the actions of these external forces, the reaction forces arise in guide rails, which determine the pressure diagram. take into account all the forces on the axis, the sum of the moments about the axes, and write down the equations of statics:

$$\{F\} = \sum [T_{kn}] \cdot \{F_k\} = \begin{bmatrix} F_x, \\ F_y + G, \\ F_z + Q, \\ F_z \cdot y_p + Q \cdot y_Q - F_y \cdot z_p - G \cdot z_G, \\ F_z \cdot x_p - F_y \cdot z_p + Q \cdot x_Q, \\ F_z \cdot y_p - G \cdot x_G - F_y \cdot x_p \end{bmatrix};$$  \hspace{1cm} (1)

$$\{R\} = \sum [T_{vn}] \cdot \{R_v\} = \begin{bmatrix} R_A \sin \alpha - R_B \sin \beta, \\ -(R_B \cos \beta + R_A \cos \alpha + R_C), \\ f (R_A + R_B + R_C), \\ R_C \cdot z_c + R_B \cos \beta \cdot z_b + R_A \cos \alpha \cdot z_A, \\ R_C \cdot f \cdot x_c + Q \cdot x_Q + R_B \sin \beta \cdot z_b - R_A \sin \alpha \cdot z_A, \\ R_C \cdot x_c \end{bmatrix}. \hspace{1cm} (2)$$
where: $f$ - the coefficient of friction in the guides.

**Fig. 1** Calculating diagram of forces acting in the guides of lathe 16K20T1

For calculating the equations defines the Equivalent width of triangular guides [9, 14]:

$$e = b \cos^2 \beta + a \cos^2 \alpha$$  \hspace{1cm} (3)

From the system of equations (1)-(3) it is possible to obtain the parameter $p$ of the pressure diagram in the guides.

In Fig. 2 shows the diagram for determining the ECZ and its maximum diameter $D$ of the machined part of the lathe 16K20T1.

**Fig. 2** The diagram for determining the ECZ and its maximum diameter $D$:

1 - machined part; 2 - cutting tool; 3 - ECZ

Determine the area of machining $S_E$ by the following formula:

$$S_E = \int \int f(x_p, z_p, p) dxdz$$  \hspace{1cm} (4)
Where: \( x_p, y_p \) – the coordinates of the cutter in the CCZ, in which the graph of pressure in the guides’ surfaces is all distributed over their entire length; \( X, Z \) - limits of the coordinates in the CCZ. The factor \( \eta \) determines:

\[
\eta = \frac{S_E}{S_C}
\]  

(5)

Where: \( S_C \) – the area of CCZ.

The larger the factor \( \eta \), the greater the range of processed parts we will get the potential for higher processing accuracy. The ECZ of the lathe 16K20T1 is performed in the MATLAB and shown in Fig. 3.

![Figure 3](image)

Fig 3. The coefficient \( \eta \) and its maximum diameter \( D \) of area ECZ at different values of cutting forces of the lathe 16K20T1

The objective function \( \eta \) is larger, then the area of ECZ is larger, and so, for the larger number of machining parts, will get the potential for higher processing accuracy. In order to find the maximum of the objective function \( \eta \), we could optimize such the variable parameters of the machining structure as the position of the cutting force (coordinates \( x_F, z_F \) of the cutting tip in the coordinate system of the guides), the weighting force \( G \) and position \( x_G, z_G \) of the support, the width \( x_w \) and length \( l \) of guides, and the coordinates \( x_Q, y_Q \) of applied force from driving system. The task of objective extremum \( \eta \) is a nonlinear extreme, so the optimizing method used improved GA.

GA is the search for the optimal (maximum or minimum) value of the objective function with the corresponding varied parameters. In the application of the method GA for solving various kinds of optimizing problems, a great contribution was made by Konak A [15], Atthew Hall [16], Malhotra, R [17] and others.

The method for estimating the extremum of the objective function \( \eta \) using GA has two processes: obtaining the objective function from the system of equations from the input variable parameters and searching for the extreme objective function using GA processes.

The search for the optimum of the objective function \( \eta \) based on the improved GA is performed in two stages: 1) calculation of the objective function \( \eta \) from the system of equations; 2) search for the maximum of the objective function \( \eta \). The conceptual calculating diagram of objective extremum \( \eta \) is shown in Fig. 4 [18, 19]. The above variable parameters of the machining layout are determined the value \( \Phi \) in the GA method:

\[
\Phi = [x_F, z_F, G, x_G, z_G, x_Q, y_Q]
\]  

(6)
The intervals of input variables → Generation of initial colony → Input parameter \( \eta \) coordinates \( x(i), z(i) \) of cutting force \( a \) CCZ → Calculating fitness \( \eta \) → Colony mutation → Colony crossover → Colony selection → Calculating new fitness \( \eta \) → Calculating fitness \( \eta \) → Pressure \( p \) calculation → Pressure \( p > 0 \) → No → yes → Output coordinates \( x(j), z(j) \) \( b \) ECZ → objective function \( \eta \) → the values of optimizing input variable \( \phi \) and objective function \( \eta \) → Termination condition → No → yes → the values of optimizing input variable \( \phi \) and objective function \( \eta \)

**Fig. 4**  The conceptual calculating diagram of objective extremum \( \eta \)

Each generation of evolution contains 1000 values of the objective function \( \eta \). The determined average and maximum value of fitness (objective function \( \eta \)) GA from each generation of colony (101 in total) is shown in Fig. 5.

![Graphs showing average and maximum values of fitness](image)

(a) average value of fitness \( \eta \)  
(b) maximum value of fitness \( \eta \)

**Fig. 5**  Average and maximum value of fitness (objective function \( \eta \)) GA from each generation of colony

From Fig. 5 We see that, generations of colony evolution are sufficient for the correct solution of the optimizing task. The area ECZ, coefficient \( \eta \) and the maximum diameter \( D \) of the processed part for the new machining layout are shown in Fig. 6.
Compared to the initial layout of lathe 16K20T1, the maximum diameter $D$ (343 mm) of the workpiece, in which the guides joint will not opened during processing, is bigger (for the initial layout, $D = 220$ mm).

3. Conclusions

A new possibility of increasing the processing efficiency of machining layout is shown. In this paper for the specific extensive modern machine tool 16K20T1, completed the model of the contact process of guides rails, calculation of the area ECZ, objective function $\eta$ and maximum diameter $D$ of the machined part, in which the guides junction not opened always.

1) The search for the possibility of increasing the ECZ and the objective function $\eta$ is determined by changing the basic design parameters of machining layout, such the variables as the vector of cutting forces, the weighting centre of the support, the coordinates of applied force from driving system, the width and length of guides could be changed.

2) Determining the maximum of the objective function $\eta$ is the multiparameter optimizing problem, and was solved by using improved GA.

3) After optimizing the machining structure based on GA, its ECZ and maximum diameter $D$ of the processed part is increased a significant performance.

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