Solving optimization problems in the design of fixtures for flexible manufacturing systems

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Abstract. This article discusses one of the technologies of digital production, expressed in the application of CAD/CAM systems and methods of mathematical optimization to the design of technological equipment intended for use in flexible production systems. The authors offer a solution of the problem of increasing the reliability of the manufacturing process on the machine by eliminating collisions of elements of technological equipment, by selecting the parameters of the technological system. The application of mathematical optimization methods for selecting parameters of technological equipment is considered. Optimization criteria for solving this problem and optimization parameters for this problem are derived and justified. The results of the solution are based on computer simulation of processing on a specific machine.

1. Introduction
Currently, flexible production systems are widely used in mechanical engineering. One of the integral parts of a flexible production system is the technological equipment, which includes device for clamping workpieces. Due to the specifics of flexible production systems, namely the possibility of rapid changeover to different types of products [1], the equipment for these systems must have its own characteristics [2], in particular, they are required:

- quick changeover of devices for various types of manufactured products;
- quick change of the device on the machine;
- high accuracy of basing.

Modern requirements to ensure competitiveness [3] also impose high requirements to reduce the time of technological preparation of production [4] and to ensure high reliability of the technological process. The latter, in particular, implies the exclusion of accidents in the form of collisions of elements of the technological system [5]. To meet these requirements it is rational to use computer modeling and simulation of production processes [6-8].

2. Features of using multi-position devices.
One of the types of devices often used in flexible production systems is multi-position devices [9]. These devices are convenient because on each side of the basic part of such equipment, you can assemble a separate device for a specific size of the processed workpieces (Fig. 1). Thus, such devices allow you to quickly switch to different types of processed products almost without changing the machine.
The main part of this device is a cube 1, which is attached to the faceplate 2 of the rotary table 3, which, in turn, is mounted on the table 4 of a three-coordinate milling machine 5. This combination allows you to process inclined surfaces of the part, as well as quickly proceed to the processing of different parts 6, which can be installed on different faces of a given cube. On each face of the cube is attached a fixture, which consists of a basic quick-change plate 7, on which the mounting elements 8 for a particular part are located. The workpiece is clamped using jaws 9, which are driven by a pneumatic drive 10.

The disadvantages of such devices include:
- limited dimensions, which does not allow processing large-sized workpieces;
- limited working space, which complicates tool access during multi-axis machining.

Figure 1. Multi-position device.

In particular, when manufacturing some parts, especially parts of complex shape [10], it is necessary to ensure the processing of holes located at an angle. In this case, as can be seen from Fig. 2, the tool or tool holder touches the mounting elements of the device located in an adjacent position. This does not allow processing of this hole.

The solution of this problem is to increase the tool length, but this leads to a decrease in the rigidity of the technological system, an increase in vibration, and, as a result, to a decrease in productivity [11,12]. In some cases, it is not possible to perform processing at all under these conditions [13]. One of the methods to solve this problem is to select the sizes of the device that would allow processing the specified holes with minimal tool length and, as a result, with the specified performance. However, the choice of the dimensions of the device by trial and error method requires a lot of time and does not guarantee the determination of the optimal dimensions of this device [14]. On the other hand, the requirements of modern production include reducing the time spent on design and technological preparation of production, which requires reducing the time, including when designing and starting production of technological equipment [15,16]. Thus the selection and design of technological equipment by trial and error method does not meet the requirements of modern production preparation.
Figure 2. The collision in the processing of parts.

3. Optimization of parameters of multi-position fixture.

To select the optimal parameters of the device, you can use optimization methods, that is, search for the minimum or maximum of the target function [17, 18]. As can be seen from Fig. 3, in order to solve the main problem, that is, to avoid a collision between the elements of the device and the tool mandrel, it is necessary to ensure that these elements do not overlap with each other.

The purpose of optimizing the design is to avoid contact of the drill and the chuck with the points 1, 2 and 3 of the device. If we consider these elements in the coordinate system \(YOZ\) associated with the workpiece, the task is to ensure that the \(Y\) coordinates of the specified points are greater than the \(Y\) coordinates of the drill edge and the chuck edge. Thus, as the optimization target function, we can take the difference of the \(Y\) coordinates of the tool point and the fixture point, and it is necessary to require that this difference be positive:

\[
\Delta y_{1sv} = y_1 - y_{sv} \\
\Delta y_{2sv} = y_2 - y_{sv} \\
\Delta y_{3sv} = y_3 - y_{sv} \\
\Delta y_{1pt} = y_1 - y_{pt} \\
\Delta y_{2pt} = y_2 - y_{pt} \\
\Delta y_{3pt} = y_3 - y_{pt}
\]

where \(y_i\) - \(Y\) coordinates of the corresponding points (Figure 3), \(y_{sv}\) - the \(Y\) coordinate of the drill edge, it is obvious that:

\[
y_{sv} = \frac{d_{sv}}{2}
\]

\(d_{sv}\) - drill diameter; \(y_{pt}\) - \(Y\) coordinate of the chuck edge:

\[
y_{pt} = \frac{d_{pt}}{2}
\]

\(d_{pt}\) - diameter of the chuck.

The optimization parameters are the dimensions of the fixture and the tool, namely the number of faces of the cube \(2n\), the width of the face of the cube \(a\), the height of the installation element 3 of the device \(h_i\), the width of the installation element of the device \(b_i\), the tool 4 length \(l_i\). Moreover, some of
the parameters are connected to each other. For example, the distance from the edge of the cube element to the mounting fixture $l_i$ should not be more than the difference between the face width $a$ and the width of the installation element of the device $b_i$.

Figure 3. Dimensional relationships in the fixture.

There are also restrictions on the parameters determined by the design features and characteristics of the working area of this machine. Thus, according to the layout requirements, the width of the face of cube $a$ is determined by the radius of the circle $R_{\text{max}}$, which is allowed to be installed on this rotary table:

$$a \leq 2R_{\text{max}} \sin \left( \frac{180^\circ}{n} \right)$$  \hfill (9)

Coordinate $y_1$ of the edge of the fixture is defined (Fig. 3) as:

$$y_1 = \left( lkr_{11}^2 + lkr_{12}^2 \right)^{1/2} \cdot \cos(\alpha_1)$$  \hfill (10)

where $l_{kr11}$ is the distance from the tool insertion point to point 1 in the $Y1$ direction:

$$lkr_{11} = a - b_i - l_i + l_{det}$$  \hfill (11)
where $ldet$ – distance from the insertion point to the edge of the cube in the direction $Z1$; $lkr12$ - distance from the tool insertion point to point 1 in the $Z1$ direction:

$$lkr_{11} = h_{det} + h_i$$

(12)

where $h_{det}$ – distance from the insertion point to the edge of the cube in the direction $Y1$; $\alpha_1$ - the angle between the $Z$ axis and the direction to point 1:

$$\alpha_1 = 90^\circ - \alpha_{otr} - \alpha_{kr1}$$

(13)

where $\alpha_{otr}$ – the angle of the hole position relative to the horizontal, taken from the drawing; $\alpha_{kr1}$ – the angle between the $Y1$ axis and the direction to point 1:

$$\alpha_{kr1} = \arctg \left( \frac{lkr_{11}}{lkr_{12}} \right)$$

(14)

Coordinate $y_2$ of the edge of the fixture is defined (Fig. 3) as:

$$y_2 = \left( lkr_{21}^2 + lkr_{22}^2 \right)^{1/2} \cdot \cos(\alpha_2)$$

(15)

where $lkr_{2i}$ is the distance from the tool insertion point to point 2 in the $Y1$ direction:

$$lkr_{21} = a - b_i - l_i + l_{det} + l_i \cdot \sin(\theta) + h_i \cdot \cos(\theta)$$

(16)

$lkr_{22}$ - distance from the tool insertion point to point 2 in the $Z1$ direction:

$$lkr_{21} = h_{det} + h_i + l_i \cdot \cos(\theta) + h_i \cdot \sin(\theta)$$

(17)

$\alpha_2$ - the angle between the $Z$ axis and the direction to point 2:

$$\alpha_2 = 90^\circ - \alpha_{otr} - \alpha_{kr2}$$

(18)

where $\alpha_{kr2}$ – the angle between the $Y1$ axis and the direction to point 2:

$$\alpha_{kr2} = \arctg \left( \frac{lkr_{21}}{lkr_{22}} \right)$$

(19)

$$\theta = \beta_mn - 90^\circ$$

(20)

where $\beta_mn$ - angle at the top of the cube:

$$\beta_mn = \frac{n-2}{n} \cdot 180^\circ$$

(21)

Coordinate $y_3$ of the edge of the fixture is defined (Fig. 3) as:

$$y_3 = \left( lkr_{31}^2 + lkr_{32}^2 \right)^{1/2} \cdot \cos(\alpha_3)$$

(22)

where $lkr_{3i}$ is the distance from the tool insertion point to point 3 in the $Y1$ direction:

$$lkr_{31} = lkr_{11} + l_i \cdot \sin(\theta) + \left( h_i^2 + b_i^2 \right)^{1/2} \cdot \cos(\theta)$$

(23)

$lkr_{32}$ - distance from the tool insertion point to point 3 in the $Z1$ direction:

$$lkr_{31} = lkr_{12} + l_i \cdot \cos(\theta) + \left( h_i^2 + b_i^2 \right)^{1/2} \cdot \sin(\theta)$$

(24)

$\alpha_3$ - the angle between the $Z$ axis and the direction to point 3:

$$\alpha_3 = 90^\circ - \alpha_{otr} - \alpha_{kr3}$$

(25)

where $\alpha_{kr3}$ – the angle between the $Y1$ axis and the direction to point 3:

$$\alpha_{kr3} = \arctg \left( \frac{lkr_{31}}{lkr_{32}} \right)$$

(26)
To calculate the optimal parameters of the device, we perform optimization of the target function. As an target function, we take the convolution of criteria (1) – (6) as a weighted sum. Since all criteria (1) – (6) have equal weight, the target function is written as:

$$\Delta y = \Delta y_{1sv} + \Delta y_{2sv} + \Delta y_{3sv} + \Delta y_{1pt} + \Delta y_{2pt} + \Delta y_{3pt}$$  (27)

The target function was optimized by the least square method [19, 20] in MathCAD Prime 3.0. The solution resulted in a vector with optimization parameters:

$$\begin{bmatrix} l_i \\ a \\ b_i \\ n \\ h_i \end{bmatrix} = \begin{bmatrix} 12.665 \\ 52.665 \\ 40 \\ 4 \\ 5 \end{bmatrix}$$  (28)

As a result of the solution, the specific sizes of the devices were obtained and three-dimensional models of the device in the NX system were built in accordance with this. To check for the absence of a collision, a simulation of the processing of this part was performed on the machine in the NX CAM module (Fig. 4).

![Figure 4. Positions of technological equipment elements during processing in the optimized design of the device.](image)

The simulation shows that there is no collision between the tool and the device throughout this machining pass, from the approach of the tool to the end of the working stroke and retraction. Thus, this solution made it possible to ensure the design of devices with the specified technological parameters in the shortest possible time.

4. Conclusion
This article presents the application of digital production methods, expressed in the design of devices using 3D modeling in combination with simulation of processing on the machine. This CAD / CAM design, combined with mathematical optimization methods, allows you to dramatically save the time of design and technological preparation of production, increase the reliability of the technological process due to the exclusion of accidents. Moreover these characteristics are guaranteed to be provided even at the pre-production stage.
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