Self-oscillations of the cutting cutters

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Abstract. The design and construction of products that are subjected to variable forces during operation should be based on calculations of the dynamic properties of the structures being created. This applies most to structures that contain thin-walled elements. In this regard, the development of a reliable method for determining the own dynamic characteristics of cutting tools in the form of cutting circles and cutters is relevant. An engineering method for calculating the frequencies and forms of natural oscillations of disk cutting mills of variable thickness in the radial direction is considered. The results of the calculation were confirmed by the proposed method using data from experiments conducted using unique modern equipment. Thus, it was established that the proposed method can be applied to the analysis of the dynamic properties of the considered type of disk cutting tools and their design with the specified dynamic characteristics. The results obtained are necessary for evaluating the critical operating conditions of the mills under study.

1. Introduction

Technical progress and the creation of fundamentally new mechanical engineering products requires the production of critical parts of complex spatial configuration, including thin-walled elements. This causes increased requirements for dimensional accuracy and surface quality of the resulting part when machining its workpiece, and their implementation is an urgent problem in the processing industries of mechanical engineering. Currently, its solution is carried out both on the basis of studies of factors that affect the rigidity of processing equipment [1,2], and on the results of studying the course of material cutting processes [3]. The development of dynamic models of cutting tools is also one of the promising directions in the implementation of this task [4].

Increasing the efficiency of using blade tools and cutting circles in the form of round plates (disks), depending on the cutting speed, involves increasing their rotation speeds. To avoid the occurrence of
resonant modes when processing materials and to ensure the specified fatigue strength and durability of tools [5], it is necessary to select cutting parameters taking into account previously found their dynamic characteristics. So used in the processing of materials cutting cutters, manufactured to date in accordance with GOST 2679-93 " slotted and cut-off Cutters "(Fig.1), as a rule, have variable thickness h in the radial direction, so the analysis of their dynamic characteristics requires the creation and application of appropriate methods. The purpose of this work is to develop methods for determining the main dynamic characteristics of disk cutters and cutting wheels of variable thickness. Reliable data on their own (dynamic) characteristics are necessary not only for calculating the operating modes of these tools, but also for evaluating and controlling their manufacturing quality and special preparation for work.

2. Calculation method
Search of dynamic properties in milling of thin circular plates (disks) in diameter and variable thickness h along the radius, involves the use of a system of differential equations of free oscillations [6-7], written in vector-matrix form, represented by one equation.

\[ \frac{d}{dr} \{Y\} = [B] \{Y\}. \]

Here \( \{Y\} = (y_1, y_2, y_3, y_4)^T \), \( y_1 = \tilde{w}; y_2 = \tilde{q}; y_3 = \tilde{M}; y_4 = \tilde{V}; \)

\([B]\) – matrix \((4 \times 4)\) of variable coefficients:
which depend on the frequency $\tilde{\Omega}$, waveform (number of nodal diameters $n$), and Poisson's ratio $\mu$.

Dimensionless parameters in equation (1): displacements $\tilde{w}$ of points of the plate (disk), $\tilde{\vartheta}$ angles of rotation of its sections, $\tilde{M}$ internal distributed radial moment, internal reduced transverse distributed force $\tilde{V}$ and radius of the disk $\tilde{r}$, are translated into dimensional form using the formulas

$$
\tilde{w} = \frac{h_0}{\eta h_0} w, \quad \tilde{\vartheta} = \frac{h_0^3}{\eta h_0^3} \vartheta, \quad \tilde{M} = \frac{c^3 \eta h_0^3}{E h_0^3} M, \quad \tilde{V} = \frac{c^3 \eta h_0^3}{E h_0^3} V, \quad k_h = h / h_0, \quad \tilde{\Omega}^2 = \frac{c^4 \eta h_0^3}{E h_0^3} \Omega^2, \quad \tilde{r} = r / c ,
$$

where $E$ is the modulus of elasticity; $\rho$ - the density of the material; $h_0$ - the characteristic thickness of the disk, $\eta = 12(1 - \mu^2)$, $C = D / 2$, ($D$-the diameter of the cutter).

For sliding pinching of the disk with diameter flanges $D_\phi$, the boundary conditions are as follows:

$$
\tilde{w} = 0, \quad \tilde{\vartheta} = 0 \quad \text{at} \quad \tilde{r} = \tilde{b}; \quad \tilde{M} = 0, \quad \tilde{V} = 0 \quad \text{at} \quad \tilde{r} = 1 ,
$$

where it is accepted $\tilde{b} = D_\phi / D$.

The calculation of free oscillation frequencies based on equation (2) was carried out using the method of initial parameters of the MNP. In the process of using it, a system of linear algebraic equations is constructed for the selected waveform with the number of nodal diameters $n$ and a value $\tilde{\Omega}$ that is obviously smaller than the value of the natural frequency-to satisfy the boundary conditions on the external contour. By changing the frequency value $\tilde{\Omega}$, the value is determined at which the determinant is composed of coefficients that stand for the parameters taken by the initial [6],

$$
\begin{bmatrix}
\tilde{d}_{ij}
\end{bmatrix} = 0, (i, j = 1, 2).
$$

It corresponds to the desired frequency of free oscillations.

The advantage of using the proposed numerical method is shown in its versatility, high degree of algorithmization and, consequently, ease of use. In particular, the last clarification concerns the calculation of the behavior of plates (disks) with variable characteristics.

3. Results of calculations using the proposed method

Dynamic properties were determined using the example of a cutting mill with a diameter of $D = 6.3 \cdot 10^{-2}$ m and a thickness of $0.5 \cdot 10^{-3}$ m (Figure 1, version 2). The diameter of the cutter mounting flange is adopted $D_\phi = 2.38 \cdot 10^{-2}$ m.

Initial data for calculations:
physical and mechanical properties of the mill material:
$E = 2.1 \cdot 10^5$ Mpa, $\rho = 8750kg \cdot m^{-3}$, $\mu = 0.3$;

geometric parameters of the thickness in the radial direction of the cutter:
при $0.2661 \leq \tilde{r} \leq 0.52$: $k_h = 1.5$; при $\tilde{r} > 0.52$: $k_h = 0.7 + 0.2(\tilde{r} - 0.52)/0.48$

The natural oscillation frequencies calculated by these methods are summarized in the table. The natural oscillation frequencies calculated by this method are summarized in the table.

| Natural oscillation frequency of the cutter, Hz |
|-----------------------------------------------|
| first             | second           | third            |
| $n = 1$           | $n = 2$          | $n = 3$          |
| 1115             | 1136             | 1279             |

4. Experimental study
To confirm the validity of the considered calculation method for determining the dynamic characteristics (natural frequencies and vibration patterns) of the cutter, vibration tests were carried out on special equipment. The Data Physics vibrometer was used to excite the mill vibrations, and the Polytec PSV-3D laser scanning vibrometer was used to obtain data on the system vibrations. On Fig. 2 shows a milling cutter mounted on a vibration stand.

Figure 2. Installing the cutter on the vibration stand

The laser vibrometer is based on the Doppler effect. Processing of measurements is performed based on the results of fixing the values of vibration velocities of the object points when the frequency of forced vibrations changes.

The main component of each Polytec system is a laser Doppler vibrometer - a high-precision optical sensor for determining vibration speed and vibration displacement at a given point. The principle of its operation is based on the Doppler effect and consists in detecting the frequency shift of laser radiation reflected from the moving surface of the measured object [8].

For effective use of the Polytec measuring system, it is necessary to perform tests according to the manufacturer's recommendations [8], [9]. The system works as follows: the exciter creates vibrations of the object of research; the measuring beam from the interferometer located in the scanning head is
positioned using mirrors at the scanning point on the object and reflected; the reflected beam interacts with the reference beam in the scanning head; the photodetector registers the interference of rays; the controller decoder generates a voltage proportional to the vibration speed in the direction parallel to the measuring beam; the voltage is digitized and processed as a vibrometer signal.

The results of the experiments and their satisfactory agreement with the calculated data presented in Fig. 3 can serve as a basis for using the proposed calculation methods in studies of the dynamic characteristics of mill structures.

![Figure 3](image)

| n = 1 | n = 2 | n = 3 |
|------|------|------|
| 1124 (-0.8%) | 1135 (+0.08%) | 1253 (+2%) |

**Figure 3.** Experimentally found eigenforms and oscillation frequencies of the mill under study and corresponding (in parentheses, the percentage deviation of the calculated data from the experimental data: minus - less, plus - more)

**Conclusion**

An effective method has been developed necessary for the design and targeted design of cutting mills with the required dynamic characteristics. The advantage of the method lies in the simplicity and accessibility of its application for assessing the influence of the selected configuration and material properties on the dynamic characteristics. The legitimacy of using the developed method is confirmed by the data of experiments.

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