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Research article

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Simulation of loads on operating device of peat-cutting unit with regard to errors in the cutting elements arrangement

K.V. Fomin
Tver State Technical University, Tver, Russian Federation
✉ *fomin_tver@mail.ru*

Abstract
The practice of using units with milling-type operating devices showed their insufficient reliability, which leads to deterioration of the units' performance. The reasons for this are high dynamic loads in structural members, which are caused by external resistance forces on a milling cutter. They have random, sharply variable nature due to structural heterogeneity of a peat deposit, its random physical and mechanical properties, the presence of wood inclusions in it, as well as periodic interaction of blades with the deposit, and many other factors. In this case, the parameters of actual milling cutter, due to manufacturing and installation errors, differ from those specified in the "ideal" design. In addition, wear and irreversible deformations of cutting elements (blades) occur during operation. As a result the position of blades in a cutter body differs from the "ideal" positioning pattern. The purpose of the paper is to develop a model of section moment on a milling cutter when interacting with a peat deposit in the process of technological operations, taking into account the influence of the error of blade positioning on a cutter body. Expressions for calculating the moment spectral density were obtained. Its characteristic features were analyzed. Errors in positioning of cutting elements on a cutter body lead to changes in the magnitude and nature of the load and its frequency content. In this case, new, additional components appear at frequencies multiple of the cutter's angular velocity, enriching the load spectrum and increasing its variance. Their magnitude is determined by the cumulative value of the errors. As an example, an analysis of the influence of the error in positioning cutting elements on the spectral density for the operating device of MTP-42 deep milling machine is given. The study results are of practical value and should be taken into account in the calculation of dynamic loads in designing structural members of milling units, especially if their operating devices have a large number of blades, use fine feeds, and when the natural frequencies of the structural members are equal to or multiple of the angular speed of a milling cutter.

Keywords
peat milling unit, milling cutter, blade positioning errors, probabilistic load model, section moment, spectral density

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ГОРНЫЕ МАШИНЫ, ТРАНСПОРТ И МАШИНОСТРОЕНИЕ

Научная статья

Моделирование нагрузок на рабочем органе торфяного фрезерующего агрегата с учетом погрешности расстановки режущих элементов

К.В. Фомин
Тверской государственный технический университет, г. Тверь, Российская Федерация
✉ *fomin_tver@mail.ru*

Аннотация
Практика использования машин с исполнительными органами фрезерного типа показывает их недостаточную надежность, что приводит к ухудшению технико-экономических характеристик агрегатов. Причиной этого являются высокие динамические нагрузки в элементах конструкции, которые возникают в результате действия сил внешнего сопротивления на фрезе. Они имеют случайный, резко переменный характер, который вызван структурной неоднородностью торфяной залежи, ее случайными физико-механическими свойствами, наличием в ней древесных включений, а также периодическим взаимодействием ножей с залежью и многими другими факторами. При этом параметры реальной конструкции фрезы ввиду погрешностей изготовления и сборки отличаются от заданных при проекти-

ровании. Кроме того, в процессе эксплуатации происходят износ и необратимые деформации режущих элементов. Это приводит к тому, что ножи расположены с некоторым небольшим сдвигом на корпусе фрезы относительно «идеальной» схемы размещения. Цель статьи заключается в разработке модели момента сопротивления на фрезе при взаимодействии с торфяной залежью в процессе выполнения технологической операции, учитывающей влияние погрешности расстановки ножей на корпусе фрезы. Получены выражения для расчета спектральной плотности момента. Проанализированы его характерные особенности. Ошибки размещения режущих элементов на корпусе фрезы приводят к изменению величины и характера нагрузки, ее частотного состава. При этом появляются новые, дополнительные составляющие на частотах, кратных угловой скорости фрезы, обогащая спектр нагрузки, увеличивая ее дисперсию. Их величина определяется суммарным значением ошибок. В качестве примера дан анализ влияния погрешности расположения режущих элементов на спектральную плотность для исполнительного органа машины глубокого фрезерования типа МТП-42. Результаты исследования имеют практическую ценность и должны учитываться при расчете динамических нагрузок в элементах конструкции фрезерующих агрегатов при их проектировании, особенно если рабочие органы имеют большое количество резцов, используют малые подачи и когда собственные частоты элементов конструкции агрегата равны или кратны угловой скорости фрезы.

Ключевые слова
торфяной фрезерующий агрегат, фреза, ошибки расстановки ножей, вероятностная модель нагрузки, момент сопротивления, спектральная плотность

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Introduction

The use of milling units in peat industry allows increasing productivity and improving the quality of process operations and provides the possibility of their integrated mechanization [1–3].

The practice of using machines with milling type executive bodies showed their insufficient reliability [4, 5]. The reasons for this are high dynamic loads in the structural elements, which result from the action of external resistance forces on a milling cutter [5]. They have random, sharply variable nature [5] due to structural heterogeneity of a peat deposit [6, 7], its random physical and mechanical properties, the presence of wood inclusions in it [5–7], as well as periodic interaction of blades with the deposit, and many other factors [5].

At present, to calculate loads on operating devices, simulation modelling methods using computer technology are used (N.M. Karavaeva, O.A. Golovnina, V.F. Sinitsyn, F.A. Shestachenko) [5]. They are universal, but time-consuming in solving these problems.

The application of experimental methods by means of strain-measuring facilities [8] makes it possible to obtain information about forces and moments and their probabilistic characteristics. However, they are labor-intensive, expensive, and provide information about the load only for a given milling unit in specific operating conditions.

In [5, 9], analytical methods of investigating loading moments on milling-type operating devices were developed. Models of force factors in their interaction with a peat deposit were proposed. Expressions for calculating spectral densities were developed. They take into account the design of a milling cutter, the unit operating modes and the physical and mechanical properties of peat. In [10], approaches for determining mutual spectral moment densities for milling units with several operating devices are considered.

In this case, all the dependences were obtained for an "ideal" operating device, when cutting elements (blades) are positioned in the specified points on the milling body in line with design documentation.

It should be taken into account that the parameters of an actual operating device differ from the design ones due to assembly and manufacturing errors [11, 12]. As a result the position of blades in a cutter body differs from the "ideal" positioning pattern. In addition, wear and irreversible deformations, and even destruction of the cutting elements occur during operation. In this regard, cutting angles, the shape of cutters, their height, the position of cutting edges, and the kinematic characteristics of cutting change [11–13]. This all, in fact, changes both the arrangement of cutting elements (blades) and the conditions of blades interaction with a peat deposit. This causes changes in the magnitudes, nature and frequency properties of the force factors on an operating device and affects the formation of loads in the unit structural members.

Research objectives

The purpose of the paper is to develop models of the formation of loads on an operating device when milling a peat deposit taking into account the influence of errors in blade arrangement on a cutter body and expressions for calculating the moment spectral density.

Research materials, models and methods

The random nature of the section moment arising on an operating device in the process of operation requires the use of approaches of statistical dynamics of mechanical systems [14–16] for analyzing loading of a milling unit and calculating its reliability indicators [16, 17].

The experience of their use in solving similar problems in mining industry [18–20] allows considering one-dimensional and two-dimensional characteristics of loads only when using both analytical and numerical methods [21, 22].

As a rule, probabilistic characteristics of forces and moments, such as mathematical expectation, dispersion and spectral density, are considered [20, 22].

Let us consider a milling cutter with working width B, radius $R_Ф$, rmilling depth $H_Ф$, horizontal rotation axis with M cutting planes and K blades in plane.

Position of blades on a milling cutter body is determined by the angles between the reference point and blades in the m-th cutting plane φ_m (an "ideal" operating device) and the angles between neighboring blades in a plane φ_T (in case of uniform arrangement). We will take into account that each cutting element (blade) can be shifted by the value of the error determined by the angle δ_{mk} relative to the "ideal" arrangement of blades (Fig. 1). When a blade is shifted in the direction of blade movement, the magnitude of error has "plus" sign, while in the opposite direction, "minus" sign.

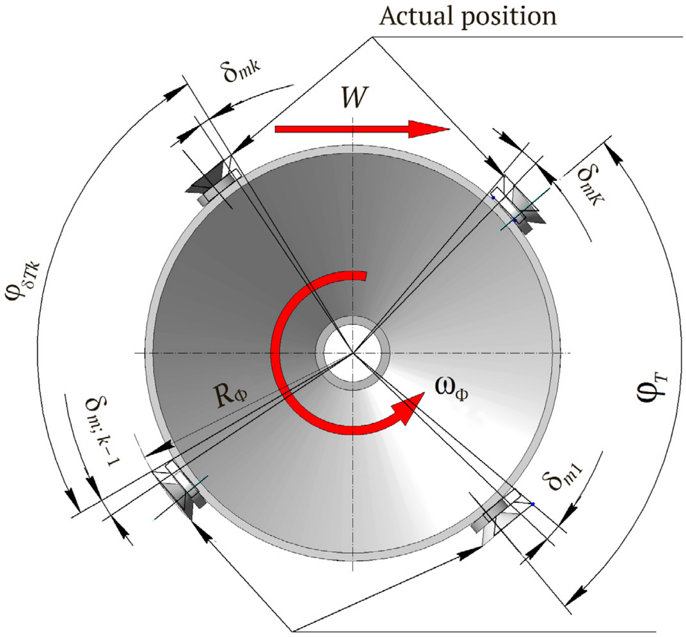

Fig. 1. Error in blades positioning by angle in m-th cutting plane

If a unit depth of milling, operation modes and physical and mechanical characteristics of a peat deposit change rather smoothly during several revolutions of an operating device, so that within one revolution they can be considered to be constant [5, 9], the section moment is described by the following expression:

$$M(t) = \sum_{m=1}^{M} \sum_{n=-\infty}^{\infty} M_{mn}(t - t_m - nT_Ф; P_{mn}), \quad (1)$$

where $M_{mn}(t; P_{mn})$ – is moment on blades of the m-th cutting plane during one revolution of the operating device; t_m – is time interval between the reference point and the load in the m-th cutting plane $t_m = \varphi_m / \omega_Ф$; $T_Ф$ – is duration of one revolution $T_Ф = 2\pi / \omega_Ф$, where $\omega_Ф$ – is angular velocity of the milling cutter; P_{mn} – is random parameters of pulses at the n-th revolution of the operating device in the m-th cutting plane.

Expression (1) can be used to describe the section moment both for an "ideal" operating device and an actual one (taking into account errors of blade positioning on the cutter body). The values of $M_{mn}(t; P_{mn})$ will be different in this case.

The amplitude value of the section moment is proportional to the feed [2], the value of which for the "ideal operating device" is $c = W\varphi_T / \omega_Ф$, and taking into account the blade arrangement error:

$$c_k = W\frac{\varphi_{\delta Tk}}{\omega_Ф} = W\frac{\varphi_T + \Delta\delta_{mk}}{\omega_Ф},$$

where W – is speed of advance of a milling unit; $\varphi_{\delta Tk}$ – is angle between the blades in the cutting plane (more precisely between the cutting edges), taking into account the error of their positioning on the milling cutter body (Fig. 1); $\Delta\delta_{mk} = \delta_{mk} - \delta_{m;k-1}$ – is the difference between the errors for the adjacent blades in the m-th plane (if $k = 1$, then $k - 1$ corresponds to K).

Correspondingly, for the moment in the m-th cutting plane within one revolution, taking into account the errors of the blades arrangement, the expression takes the following form:

$$M_{mn}(t;P) = \sum_{k=1}^{K} \frac{\varphi_T + \Delta\delta_{mk}}{\varphi_T} M_0\left[t - (k-1)T - \tau_{mk}; P_{mn}\right],$$

where $M_0(t; P)$ – is the change of section moment on a blade within the angle of contact with a deposit; $T = \varphi_T / \omega_Ф$ – is the period of repetition of the interaction of blades in the cutting plane with a deposit; $\tau_{mk} = \delta_{mk} / \omega_Ф$ – is pulse time delay caused by the error of the k-th blade position in the m-th cutting plane.

Moment (1) is a random function. Its spectral density depends on a milling cutter design, the unit operation modes, the milling depth, which is determined by the terrain and the type of the cutter suspension, the oscillations caused by cutting forces and their imbalance, physical and mechanical properties of the peat deposit and their probabilistic characteristics [5, 9].

The spectral density of the process (1) can be determined from the following relation [23, 24]:

$$S(\omega)=\lim_{N\to\infty}\frac{2}{(2N+1)T}m_1\left\{\left|Z^{(k)}(j\omega)\right|^2\right\}-2\pi m^2\delta(\omega),\quad (2)$$

where N – is number of pulses; T is repetition period; $m_1\{\}$ – is averaging sign; $Z^{(k)}(j\omega)$ – spectrum of the k-th implementation of the process (we omit index k hereafter); m is mean value of the process; $\delta(\omega)$ – is delta-function (Dirac function) [24].

Squared absolute value of the section moment spectrum (1) containing $(2N+1)$ pulses is:

$$\begin{gathered}\left|Z_M(j\omega)\right|^2=\\ =\sum_{m=1}^{M}\sum_{l=1}^{M}\sum_{k=1}^{K}\sum_{s=1}^{K}\sum_{n=-N}^{N}\sum_{i=-N}^{N}S_0(\omega;\,\omega_\Phi;P_{mkn})S_0^*(\omega;\omega_\Phi;P_{lsi})\times\\ \times\frac{\varphi_T+\Delta\delta_{mk}}{\varphi_T}\frac{\varphi_T+\Delta\delta_{ls}}{\varphi_T}\times\\ \times\exp\left[-j\frac{\omega}{\omega_\Phi}(\varphi_m-\varphi_l)\right]\exp\left[-j\frac{\omega}{\omega_\Phi}(k-s)\varphi_T\right]\times\\ \times\exp\left[-j\frac{\omega}{\omega_\Phi}(\delta_{mk}-\delta_{ls})\right]\exp\left[-j\frac{\omega}{\omega_\Phi}2\pi(n-i)\right],\end{gathered}\quad (3)$$

where the asterisk denotes complex conjugate value; $S_0(\omega;\,\omega_\Phi;\,P)$ – is spectrum $M_0(t;\,P)$:

$$S_0(j\omega;\omega_\Phi;P)=\int_0^{\varphi_k/\omega_\Phi}M_0(t;P)\exp(-j\omega t)dt,$$

where φ_k – is the angle of blade contact with peat deposit.

Substituting (3) into (2), considering stationarity of the unit operating conditions (the probabilistic characteristics of parameters depend on the mutual arrangement of pulses only $p=n-i$), using the approaches presented in [5, 9], we obtained an expression for single-sided spectral density of section moment taking into account the errors of cutting element positioning on a cutter body at fixed angular speed ω_Φ:

$$\begin{gathered}S(\omega;\,\omega_\Phi)=\frac{4}{T_\Phi}\left[\frac{1}{2}\sum_{q=1}^{Q_1}\left[\frac{\partial^2F_1(\omega;\,\omega_\Phi)}{\partial P_q^2}\right]_m D_q\sum_{m=1}^{M}\mathrm{A}_m(\omega;\,\omega_\Phi)-\right.\\ -\frac{1}{2}\sum_{q=1}^{Q_2}\left[\frac{\partial^2F_2(\omega;\,\omega_\Phi)}{\partial P_q^2}\right]_m D_q\sum_{m=1}^{M}\mathrm{A}_m(\omega;\,\omega_\Phi)+\Psi(\omega;\,\omega_\Phi)+\\ +\left(F_1(\omega;\,m_q)+\frac{1}{2}\sum_{q=1}^{Q_2}\left[\frac{\partial^2F_2(\omega;\,\omega_\Phi)}{\partial P_q^2}\right]_m D_q\right)\times\\ \left.\times\sum_{m=1}^{M}\sum_{l=1}^{M}\exp\left[-j\frac{\omega}{\omega_{\hat{o}}}(\varphi_m-\varphi_l)\right]\mathrm{A}_{ml}(\omega;\,\omega_\Phi)\omega_\Phi\sum_{r=1}^{\infty}\delta(\omega-r\omega_\Phi)\right],\end{gathered}$$

where the following notations are introduced:

$$F_1(\omega;\,\omega_\Phi)=\left|S_0(\omega;\,\omega_\Phi;P_{1mn}...P_{Qmn})\right|^2;$$

$$F_2(\omega;\,\omega_\Phi)=S_0(\omega;\,\omega_\Phi;P_{1mn}...P_{Qmn})S_0^*(\omega;\,\omega_\Phi;P_{1li}...P_{Qli});$$

$$\mathrm{A}_m(\omega;\,\omega_\Phi)=\sum_{k=1}^{K}\sum_{s=1}^{K}\frac{\varphi_T+\Delta\delta_{mk}}{\varphi_T}\frac{\varphi_T+\Delta\delta_{ms}}{\varphi_T}\times$$
$$\times\exp\left[-j\frac{\omega}{\omega_\Phi}(\delta_{mk}-\delta_{ms})\right]\exp\left[-j\frac{\omega}{\omega_\Phi}(k-s)\varphi_T\right];$$

$$\mathrm{A}_{ml}(\omega;\,\omega_\Phi)=\sum_{k=1}^{K}\sum_{s=1}^{K}\frac{\varphi_T+\Delta\delta_{mk}}{\varphi_T}\frac{\varphi_T+\Delta\delta_{ls}}{\varphi_T}\times$$
$$\times\exp\left[-j\frac{\omega}{\omega_\Phi}(\delta_{mk}-\delta_{ls})\right]\exp\left[-j\frac{\omega}{\omega_\Phi}(k-s)\varphi_T\right];$$

Q_1, Q_2 – number of parameters for $F_1(\omega;\,\omega_\Phi;\,P)$ and $F_2(\omega;\,\omega_\Phi;\,P)$, respectively; D_q – is parameters dispersions; $\Psi(\omega;\,\omega_\Phi)$ – is correlational relationship function, taking into account correlations between uniform and different parameters of load pulses, varying both in the direction of unit motion and in a direction transverse to it:

$$\begin{gathered}\Psi(\omega;\,\omega_\Phi)=\sum_{q<g}\left[\frac{\partial^2F_1(\omega;\,\omega_\Phi)}{\partial P_q\partial P_g}\right]_m\sum_{m=1}^{M}K_{qg}\mathrm{A}_m(\omega;\omega_\Phi)+\\ +\sum_{q<g}\left[\frac{\partial^2F_2(\omega;\,\omega_\Phi)}{\partial P_{\hat{q}m}\partial P_{gl}}\right]_m\sum_{m=1}^{M}\sum_{\substack{l=1\\ m\neq l}}^{M}\exp\left[-j\frac{\omega}{\omega}(\varphi_m-\varphi_l)\right]K_{qgml}\mathrm{A}_{ml}(\omega;\,\omega_\Phi)+\\ +2\sum_{q<g}\left[\frac{\partial^2F_2(\omega;\,\omega_\Phi)}{\partial P_{qmn}\partial P_{gl;n-p}}\right]_m\sum_{m=1}^{M}\sum_{l=1}^{M}\mathrm{A}_{ml}(\omega;\,\omega_\Phi)\sum_{p=1}^{\infty}K_{qgmlp}\times\\ \times\exp\left[-j\frac{\omega}{\omega_\Phi}(\varphi_m-\varphi_l)\right]\cos\left(\frac{\omega}{\omega_\Phi}2\pi p\right),\end{gathered}$$

where m_q – are mathematical expectations of the pulse parameters: K_{qg}, K_{qgml}, K_{qgmlp} – correlation and cross-correlation moments of the parameters.

In the case of the parameters stationarity and smoothness of changes, the correlation and cross-correlation moments K_{qgml} and K_{qgmlp} are determined by correlation functions of peat characteristics and working conditions (peat strength, density, and milling depth) in the moments of interaction of blades with the peat:

$$K_{qgml}=K_{Pqsy}\left[(m-l)h\right];$$

$$K_{qgmlp}=K_{Pqsxy}\left[cp;(m-l)h\right],$$

where $K_{Pqsy}(y)$ – are correlation and cross-correlation functions of changes in the characteristics of peat deposit in a direction transverse to the unit movement; $K_{Pqsxy}(x,\,y)$ – are correlation functions of random parameters, taking into account spatial variability of characteristics (both in the direction of movement and in a direction transverse to it); x and y are point coordinates for the corresponding parameters; m, l – numbers of the corresponding cutting planes; h – distance between cutting planes.

Thus, for a milling cutter that has errors in the blade arrangement on the cutter body, new components of the section moment that are multiples of the angular velocity of the cutter rotation arise. While, for the “ideal” operating device, there are loads in the spectrum that are multiples of the recurrence period of the cutting elements interaction with peat deposit [9].

The findings of experimental study [5] confirm such qualitative description of the influence of the error in blades positioning on the cutter body on the frequency composition of resistance forces.

In the process of operation, as a result of the action of a random section moment on the operating device, a random change in the cutter's angular velocity occurs. Taking this factor into account, spectral density can be described as follows:

$$S_M(\omega)=\int_{-\infty}^{\infty} S(\omega;\ \omega_\Phi)W(\omega_\Phi)d\omega_\Phi,$$

where $W(\omega_\Phi)$ – is ω_Φ distribution density.

Given that [23, 24]:

$$\int_{-\infty}^{\infty} f(x)\delta(cx-x_0)dx=\frac{1}{|c|}f\left(\frac{x_0}{c}\right),$$

for $S_M(\omega)$ we get:

$$S_M(\omega)=\frac{4}{T_\Phi}\times$$
$$\times\left[\frac{1}{2}\sum_{q=1}^{Q_1}\sum_{m=1}^{M}G_{1qm}(\omega)D_q-\sum_{q=1}^{Q_2}\sum_{m=1}^{M}G_{2qm}(\omega)D_q+G_3(\omega;\ \omega_\Phi)+\right.$$
$$+\sum_{r=1}^{R}\left(F_1(r;\ m_q)+\frac{1}{2}\sum_{q=1}^{Q_2}\left[\frac{\partial^2F_2(r;\ P)}{\partial P_q^2}\right]_{m}D_q\right)\times \tag{4}$$
$$\left.\times\sum_{m=1}^{M}\sum_{l=1}^{M}\exp\left[-jr(\varphi_m-\varphi_l)\right]\text{A}_{ml}(r)\frac{\omega}{r^2}W\left(\frac{\omega}{r}\right)\right].$$

We introduced the following notations in expression (4):

$$T_\Phi=\frac{2\pi}{\int_{-\infty}^{\infty}\omega_\Phi W(\omega_\Phi)d\omega_\Phi};$$

$$G_{1qm}(\omega)=\int_{-\infty}^{\infty}\left[\frac{\partial^2F_1(\omega;\ \omega_\Phi)}{\partial P_q^2}\right]_m\text{A}_m(\omega;\ \omega_\Phi)W(\omega_\Phi)d\omega_\Phi;$$

$$G_{2qm}(\omega)=\int_{-\infty}^{\infty}\left[\frac{\partial^2F_2(\omega;\ \omega_\Phi)}{\partial P_q^2}\right]_m\text{A}_m(\omega;\ \omega_\Phi)W(\omega_\Phi)d\omega_\Phi;$$

$$G_3(\omega)=\int_{-\infty}^{\infty}\Psi(\omega;\ \omega_\Phi)W(\omega_\Phi)d\omega_\Phi.$$

With no errors in positioning cutting elements, i.e. for an “ideal” operating device, taking into account the random change of the cutter angular velocity, we obtain the dependence for the moment spectral density, which is presented in [5, 9].

Expressions (4) give the possibility, at the stage of designing, to assess the influence of errors of cutting elements positioning on the cutter body on the moment spectral density. It presents the input data for analysis of dynamic loads in structural members of a milling unit [5, 14], calculation of reliability indicators [16, 17], and selection of optimal operating parameters and modes.

Analysis of research findings

As an example, let us consider the effect of blade positioning errors on the characteristics of the moment on executive body of a MTP-42 deep milling machine [2]. It is trailed to a T-130B tractor, includes a milling cutter, a drive system, a frame with an impact plate, rear and front rollers [2].

Taking into account that the deep milling machine has an impact plate, which rests on a peat deposit surface [2] and provides a constant milling depth, as well as considering the correlation relations for homogeneous pulse parameters only, we can obtain for spectral density from (4):

$$S_M(\omega)=\frac{4}{T_\Phi}\left[\frac{1}{2}\sum_{m=1}^{M}G_{1qm}(\omega)+G_3(\omega;\ \omega_\Phi)+\right.$$
$$+m_A^2\sum_{r=1}^{R}\left|S_e(r;\ m_q)\right|^2\times$$
$$\left.\times\sum_{m=1}^{M}\sum_{l=1}^{M}\exp\left[-jr(\varphi_m-\varphi_l)\right]\text{A}_{ml}(r)\frac{\omega}{r^2}W\left(\frac{\omega}{r}\right)\right],$$

where:

$$G_{1qm}(\omega)=\int_{-\infty}^{\infty}\left|S_e(j\omega;\ \omega_\Phi)\right|^2D_A(\omega_\Phi)\text{A}_m(\omega;\ \omega_\Phi)W(\omega_\Phi)d\omega_\Phi;$$

$$G_3(\omega)=\int_{-\infty}^{\infty}\Psi(\omega;\ \omega_\Phi)W(\omega_\Phi)d\omega_\Phi,$$

where m_A, $D_A(\omega_\Phi)$ – are mathematical expectation and variance of the pulse amplitudes [9]:

$$m_A=R_\Phi bc\left(m_\tau\frac{C_T}{\delta^{0,4}}+m_\gamma\frac{m_{\omega_\Phi}^2R_\Phi^2}{2\cdot10^3}\right);$$

$$D_A(\omega_\Phi)=R_\Phi^2b^2c^2\left[D_\tau\left(\frac{C_T}{\delta^{0,4}}\right)^2+\frac{D_\gamma\omega_\Phi^4R_\Phi^4}{4\cdot10^6}\right],$$

where b – is the width of blade interacting with peat; C_T – is coefficient depending on the type of operating device [2]; δ – is average thickness of a chip [2]; m_τ, m_γ, D_γ, D_τ – are mathematical expectations and variances of the yield point τ and density γ of peat; m_{ω_Φ} – is mathematical expectation of the cutter angular speed;

$$\Psi(\omega;\ \omega_\Phi)=\left|S_e(j\omega;\ \omega_\Phi)\right|^2\times$$
$$\times\sum_{m=1}^{M}\sum_{\substack{l=1\\m\neq l}}^{M}\exp\left[-j\frac{\omega}{\omega_\Phi}(\varphi_m-\varphi_l)\right]K_{qgml}\text{A}_{ml}(\omega;\ \omega_\Phi)+$$
$$+2\left|S_e(j\omega;\ \omega_\Phi)\right|^2\sum_{m=1}^{M}\sum_{l=1}^{M}\text{A}_{ml}(\omega;\ \omega_\Phi)\sum_{p=1}^{\infty}K_{qgmlp}\times$$
$$\times\exp\left[-j\frac{\omega}{\omega_\Phi}(\varphi_m-\varphi_l)\right]\cos\left(\frac{\omega}{\omega_\Phi}2\pi p\right),$$

where $K_{Aml}(\omega_\Phi)$, $K_{Amlp}(\omega_\Phi)$ – are correlation moments of the pulse amplitudes,

$$K_{Aml}(\omega_\Phi) = R_\Phi^2 b^2 c^2 \times$$
$$\times \left[D_\tau K_{\tau\perp}\left[(m-l)h\right]\left(\frac{C_T}{\delta^{0,4}}\right)^2 + D_\gamma K_{\gamma\perp}\left[(m-l)h\right]\frac{\omega_\Phi^4 R_\Phi^4}{4\cdot 10^6}\right];$$

$$K_{Amlp}(\omega_\Phi) = R_\Phi^2 b^2 c^2 \times$$
$$\times \left[D_\tau K_\tau\left[(m-l);p\right]\left(\frac{C_T}{\delta^{0,4}}\right)^2 + D_\gamma K_\gamma\left[(m-l);p\right]\frac{\omega_\Phi^4 R_\Phi^4}{4\cdot 10^6}\right],$$

where $K_{\tau\perp}[(m-l)h]$, $K_{\gamma\perp}[(m-l)h]$ – are normalized correlation functions of variation of the yield point τ and density γ of peat in a direction transverse to the milling unit movement; $K_\tau[(m-l); p]$, $K_\gamma[(m-l); p]$ – are normalized correlation functions of the spatial variation (both in the movement direction and in the direction transverse to the movement) of the yield point τ and density γ of peat; $S_e(j\omega; \omega_\Phi)$ – is spectrum of a function describing section moment of unit amplitude on a blade.

The squared absolute value $S_e(j\omega; \omega_\Phi)$ is [9]:

$$\left|S_e(j\omega;\,\omega_\Phi)\right|^2 =$$
$$= \frac{1}{4}\left\{ \left|U(\omega-\omega_\Phi;\,\omega_\Phi)\right|^2 + \left|U(\omega+\omega_\Phi;\,\omega_\Phi)\right|^2 - \right.$$
$$\left. -2U(\omega-\omega_\Phi;\,\omega_\Phi)\times U(\omega+\omega_\Phi;\,\omega_\Phi)\cos\varphi_k \right\},$$

where:

$$U(j\omega;\,\omega_\Phi) = \frac{2}{\omega}\sin\frac{\omega\varphi_k}{2\omega_\Phi}.$$

The density of the cutter angular velocity distribution can be calculated using the approaches presented in [5].

MTP-42 has the following design parameters and modes of operation. The cutter diameter is 0.8 m. Its width is 1.7 m. Total number of cutting planes is 29, in each of which four blades are positioned. Dish-shaped blades are mounted on the operating device surface in blade holders [2]. Diameter of a cutting element (blade) is equal to 0.078 m.

The calculation was performed at average milling depth of 0.4 m, yield point of 26 kPa [2], peat density of 890 kg/m^3 [2] (their coefficients of variation were accepted at 10%), milling cutter angular speed of 32.5 s^{-1} having normal distribution density with coefficient of variation of 3%. The unit speed of advance is 0.089 m/s.

The distribution of blade positioning errors relative to the “ideal” positions on the cutter body is shown in Fig. 2.

Fig. 3 shows the moment spectral density without taking into account the blade positioning error (“ideal” operating device), calculated using the expressions obtained in [5, 9]. Fig. 4 presents the moment spectral density taking into account the blade positioning errors.

In Fig. 4, the frequency zones (A and B) lying between the peaks multiples of blades interaction frequencies in the cutting plane are highlighted and presented in separate graphs to show these areas in more detail.

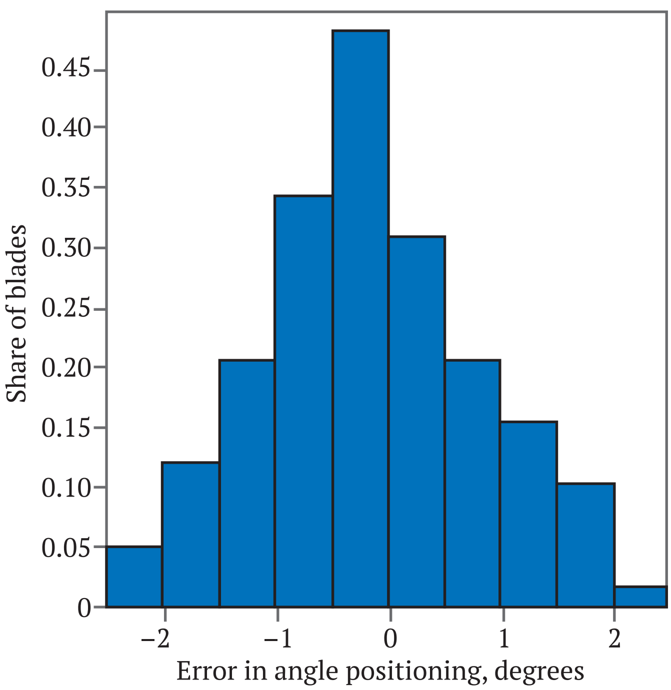

Fig. 2. Distribution of errors of blade positioning on the operating device (X axis – Error in angle positioning; Y axis – Share of blades)

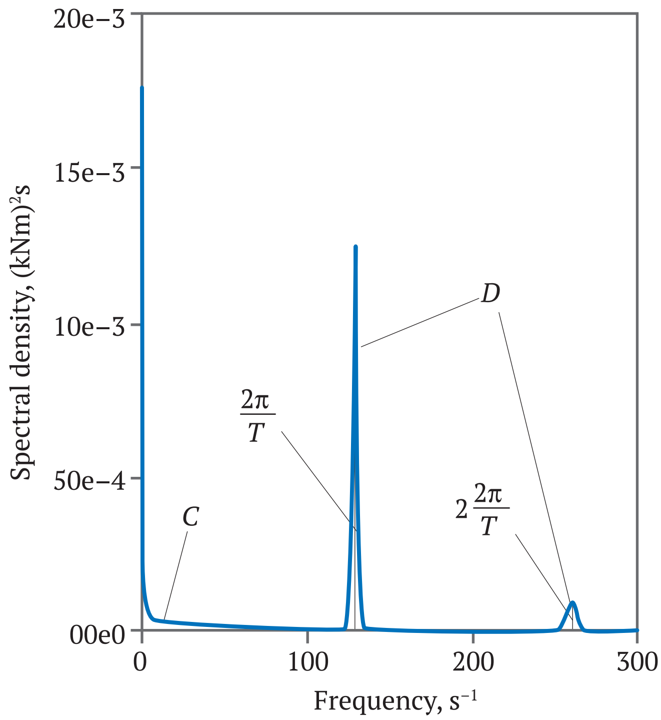

Fig. 3. Moment spectral density for “ideal” operating device

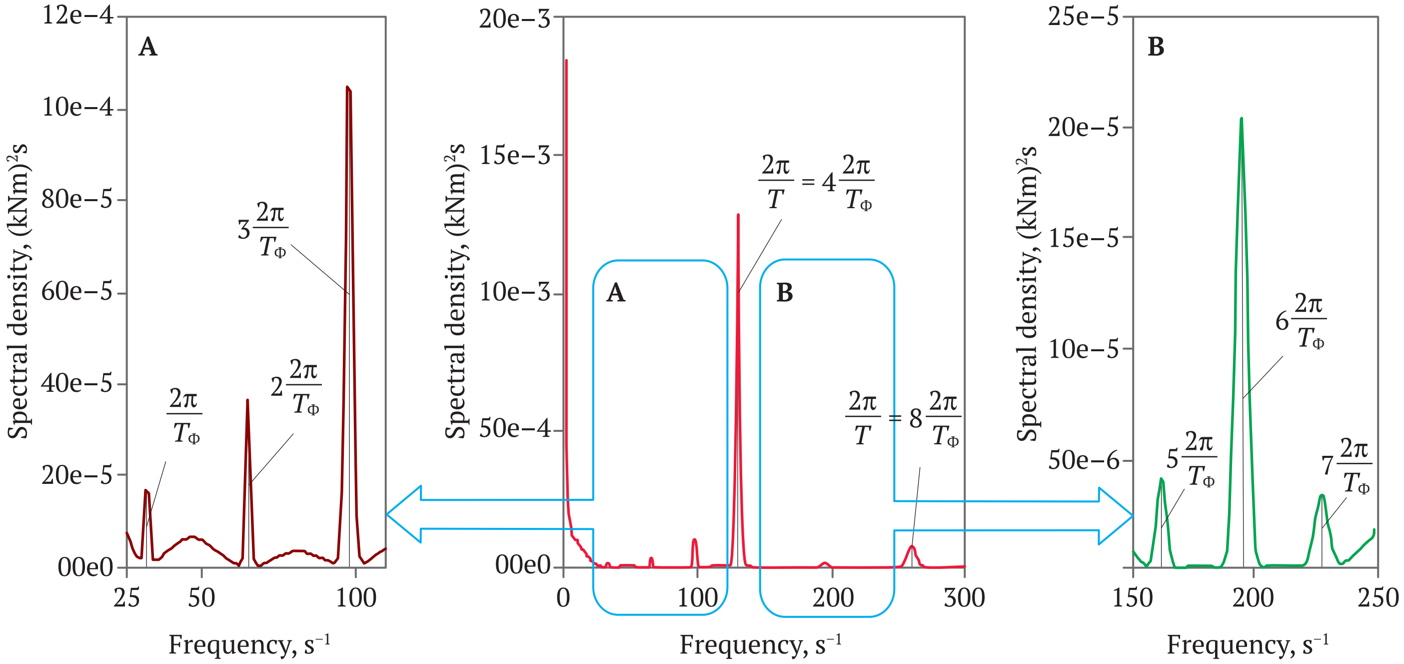

Fig. 4. Section moment (on cutter) spectral density taking into account blade positioning errors

The obtained expressions and calculation results make it possible to highlight some characteristic features of the section moment on a milling cutter.

For the "ideal" operating device, two components can be distinguished in the spectral density (Fig. 3). The first one, the continuous one, is proportional to the variances of the pulse parameters and to the squared absolute value of the section moment spectrum on a blade (*C* in Fig. 3).

Its appearance is defined by correlation functions of pulses parameters, the spectrum of the moment on a blade $S_e(j\omega;\ \omega_\Phi;\ P)$ and the function depending on the arrangement of blades on a cutter [5]:

$$Z(\omega)=\sum_{m=1}^{M}\sum_{l=1}^{M}\exp\left[-j\frac{\omega}{\omega_\Phi}(\varphi_m-\varphi_l)\right].$$

The second part of the spectral density (*D* in Fig. 3) is related to the periodic interaction of blades with peat (kinematic component) [5].

It represents a sequence of peaks, the form of which is determined by a kind of angular velocity distribution density of an operating device, belonging to frequencies $\omega_r = 2\pi r / T$, where $r = 1, 2, 3\ldots$, multiple of the period of blades interaction with a peat deposit. Its value is proportional to the squared mean values of the pulse parameters, spectrum $S_e(j\omega;\ P)$ and depends on the blade arrangement.

Errors in positioning cutting elements on a cutter body lead to changes in value and nature of load, its frequency content (Fig. 4), including appearance of additional components at frequencies multiple of cutter angular speed $\omega_r = 2\pi r / T_\Phi$, where $r = 1, 2, 3\ldots$, enriching load spectrum and increasing its variance. Then the spectral density is proportional to:

$$\sum_{m=1}^{M}\sum_{l=1}^{M}\sum_{k=1}^{K}\sum_{i=1}^{K}\left[1+\frac{\Delta\delta_{mk}}{\varphi_T}\right]\left[1+\frac{\Delta\delta_{li}}{\varphi_T}\right]\exp\left[-j\frac{\omega}{\omega_\Phi}(\delta_{mk}-\delta_{li})\right].$$

Despite its relatively small value, these features should be taken into account if an operating device has a large number of blades and uses fine feeds.

The effect of these additional loads is greatest when the natural frequencies of a unit drive members are equal or multiple to the milling cutter angular speed, because this can lead to resonance phenomena which can increase the dynamic loads in the unit drive members.

Conclusion

Probabilistic models of section moment at an operating device of a milling unit were suggested in the paper, and on their basis analytical expressions for calculating spectral density of the moment, taking into account the impact of errors of blade positioning on the milling cutter body, were obtained. They can be connected with installation and manufacturing errors, deterioration of cutting elements design parameters due to their wear or irreversible deformations during operation.

Errors in positioning cutting elements on a cutter body lead to changes in the magnitude and nature of load and its frequency content. In this case, new, additional components appear at frequencies multiple of the cutter's angular velocity, enriching the load spectrum and increasing its variance. Their magnitude is determined by the nature and cumulative value of the errors.

These facts should be taken into account in the calculation of dynamic loads in designing structural members of milling units, especially if their operating devices have a large number of blades, use fine feeds, and when the natural frequencies of the structural members are equal to or multiple of the angular speed of a milling cutter.

The research findings serve as a basis for the development of methods for dynamic analysis of milling unit structural members, as well as the corresponding mathematical support and software for their computer-aided design systems. Application of CAD will increase the efficiency of new machinery development, reduce the design time, and allow providing recommendations to reduce loads and improve the reliability of structural members of existing units.

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Information about the author

Konstantin V. Fomin – Dr. Sci. (Eng.), Associate Professor, the Head of the Department of Mechanization of Environmental management and Repair of Machines, Tver State Technical University, Tver, Russian Federation; ORCID 0000-0002-8153-1115, Scopus ID 57202900121; e-mail fomin_tver@mail.ru

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