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V. I. Dyrda[1], M. I. Lysytsia[1], V. A. Lapin[2], H. M. Ahaltsov[1],
Ye. V. Kalhankov[3], O. V. Tolstenko[3], O. A. Chernii[3]

[1]Institute of Geotechnical Mechanics named by N. Poljakov
of National Academy of Sciences of Ukraine, Dnipro, Ukraine;
[2]Kazakh Research and Design Institute of Construction and Architecture, Almaty, Kazakhstan;
[3]Dnipro State Agrarian and Economic University, Dnipro, Ukraine.
E-mail: vita.igtm@gmail.com, lisitsa.n.i@gmail.com, lapin_1956@list.ru, ag.gena@gmail.com,
kalhankov.ye.v@dsau.dp.ua, info@dsau.dp.ua, sanek20.1984@gmail.com

DYNAMICS OF HEAVY VIBRATING MACHINES TAKING INTO ACCOUNT INSTABILITY IN TIME OF THEIR PARAMETERS

Abstract. Underground mining of uranium ores consists of several technological processes, one of the most important of which is the release of broken rock from the working excavation zone and loading it into transportation vehicles. The issue of increasing the intensity of production requires a simultaneous increase in the productivity of all production processes, including the production of mineral raw materials. At the same time, it is necessary to create both a high-performance and a safe process. This problem is successfully solved by the use of vibration machines with elastic links made of elastomeric materials, which, along with an increase in productivity, can reduce energy consumption and the number of freezes. An integrated approach was used, which includes analytical studies and results of industrial tests of vibratory feeders for underground mining and delivery of uranium ores and building materials. On the basis of the developed algorithm and synergistic model of fatigue microfracture of rubber links in vibratory feeder, mathematical equations were obtained, which made it possible to describe dynamics of feeders with time-depending parameters; when solving the integro-differential equation of the oscillatory system, the dependence of the amplitude characteristics of the feeder on the time of its operation is obtained. An original algorithm and synergistic model were developed, and on their basis, a mathematical apparatus was created, which allowed determining change of amplitude of vibratory feeder oscillations during its operation. On the basis of analytical calculations, a method was developed and introduced for predicting changes of parameters change of oscillation amplitudes of vibratory feeder used for underground mining and feeding of uranium ores.
Key words: vibratory feeder, vibrations, synergetic model, fatigue failure.

Introduction. During the long-term operation of mining machines, the physical and mechanical properties of elastic links based on elastomeric materials do not remain constant, but change significantly due to aging of the material from a long cyclic load or the action of an active external environment, for example, radiation fluxes. This leads to a change in the parameters of the machines themselves and the disruption of technological processes [1-5].

The presence of experimental data on changes in the basic mechanical properties of elastic links over time, such as shear modulus G and dissipation coefficient ψ for given loading conditions, significantly simplifies the calculation of vibratory machines. However, such experimental information is in most cases absent since to obtain it requires a variety of and fairly lengthy studies. Below we consider an algorithm that allows one to determine the mechanical characteristics with a minimum of experimental data, taking into account the microdestruction that develops in elastic links.

The purpose of the work is the development of a synergetic model and algorithm for calculating vibration feeders taking into account the instability in time of their parameters; confirmation of the analytical model by the results of industrial tests.

Method. In this paper, we consider the dynamics of heavy mountain vibrating feeders of the VOF type (vibrating ore feeders) working under the rubble for the production and delivery of uranium ores. Structurally, VOF vibrating feeders are a single-mass oscillatory system; prismatic rubber elements of the RMB type (rubber-metal blocks) serve as elastic links. During operation, such elements experience simple shear deformations; their physical and mechanical parameters are unstable in time: the shear modulus increases, and the dissipation coefficient decreases. Such a change is mainly associated with aging processes inherent in all elasto-hereditary materials, which include rubber [6-10].

The calculation algorithm described below uses the Walpole method developed for composite materials [11,12], which consists in the fact that the characteristics of the material are determined averaged by the characteristics of the main material, the characteristics of the material of the inclusions and depending on the concentration of these inclusions.

In our case, the main material is intact rubber, and the inclusion material is the microdestruction that develops in the main material.

It was previously shown [13] that for cases when instantaneous modulus $\hat{G}'_0$ of initially homogeneous material and elastic modulus of inclusions $\hat{G}'_1$ do not depend on time, and when inclusions in material are only of one type, then instantaneous value of effective moduli $\hat{G}'_{ef}$ of non-uniform material, i.e. material with different inclusions, can be represented as:

$$\hat{G}'_{ef} = \hat{G}'_1 + (1-p)\left(\hat{G}'_0 - \hat{G}'_1\right) : \left[\hat{I} + p\left(\hat{\overline{G'_0}} + \hat{G}'_1\right)^{-1} : \left(\hat{G}'_0 - \hat{G}'_1\right)\right]^{-1}, \text{ Pa}, \quad (1)$$

where $\hat{G}'_1$ is tensor of inclusion elastic modulus, Pa; $\hat{\overline{G}}'_0$ is isotropic tensor, which is connected with the tensor of the moduli $\hat{G}'_0$ of the material basic matrix by the known ratio [14], Pa; p is total concentration of inclusions in typical volume of material; $\hat{I}$ is identity tensor.

Hence, value of $\hat{G}'_{ef}$ can be obtained after determining $\hat{G}'_1$ and $\hat{G}'_0$, and performing appropriate mathematical operations.

With the help of physical model of rubber fracturing [15] under the action of cyclic loading, we obtain ratio for effective modulus of the rubber in question, whose mechanical properties change significantly as a result of structuring processes: shear modulus increases, and dissipation factor decreases. It should be noted that in this paper, only one macroscopic characteristic of rubber is considered, namely, effective shear modulus. Despite availability of experimental data, it is impossible to take into account dependence of dissipative properties on developing fracture directly in the general algorithm because of absence of well-developed mathematical apparatus.

With taking into account experimental information mentioned above [15], let's accept the following synergistic model of fatigue fracture of rubber elements. Sample is a set of material points, each of them features the same properties as the source material. Process of accumulation and development of microfractures is interpreted as formation, in the initially homogeneous and isotropic material, of some areas with inclusions (areas containing fractures) with new properties, though identical in all areas.

When calculating the effective modulus, a number of assumptions is made; rubber in the initial state is homogeneous and isotropic; the modulus of the resulting inclusions is n times larger than the modulus of the base material; developing inclusions are mathematically characterized by a matrix of elastic moduli similar to the matrix of elastic moduli of the base material; the elastic modulus of the material inclusions is independent of time.

Taking into account the proposals made, and presenting the independent components of stress tensor in the form of a six-dimensional column matrix [16], matrix of elastic moduli $\hat{G}'_0$ can be written in the following way

$$\hat{G}'_0 = \begin{Vmatrix} 2E/3 & 0 & 0 & 0 & 0 & 0 \\ 0 & 2E/3 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2E/3 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2E/3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2E/3 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2E/3 \end{Vmatrix}, \text{ Pa}, \quad (2)$$

matrix of elastic moduli of microdamages can be written as

$$\hat{G}'_1 = \begin{Vmatrix} 2En/3 & 0 & 0 & 0 & 0 & 0 \\ 0 & 2En/3 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2En/3 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2En/3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2En/3 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2En/3 \end{Vmatrix}, \text{ Pa}, \quad (3)$$

where E is elastic modulus of medium, Pa.

To obtain the values of the moduli $\hat{G}'_{ef}$ by the formula (1), it is necessary to determine all the tensor quantities included in this expression and perform the corresponding mathematical operations with them. So, the components of the tensor $\hat{G}'_0$ are presented in the form

$$G_{0ijkl} = \frac{\mu(\lambda + 6\mu)}{3\lambda + 8\mu}\delta_{ij}\delta_{kl} + \frac{\mu(9\lambda + 14\mu)}{2(3\lambda + 8\mu)}\left(\delta_{il}\delta_{ik} + \delta_{jl}\delta_{ik}\right), \text{ Pa}, \quad (4)$$

and tensor itself has the following form

$$\hat{G}'_0 = \begin{Vmatrix} 10E/9 & E/9 & E/9 & 0 & 0 & 0 \\ E/9 & 10E/9 & E/9 & 0 & 0 & 0 \\ E/9 & E/9 & 10E/9 & 0 & 0 & 0 \\ 0 & 0 & 0 & E & 0 & 0 \\ 0 & 0 & 0 & 0 & E & 0 \\ 0 & 0 & 0 & 0 & 0 & E \end{Vmatrix}, \text{ Pa}, \quad (5)$$

where λ and μ are the Lame coefficients for basic medium, s^{-1}; δ are the Kronecker symbols; i, j, k, l = 1, 2, 3.

Tensor operations: sum of tensors, inverse tensor and convolution of tensors are performed according to the known formulas for tensor analysis [16]. Finally, we get the following expression for

$$\hat{G}'_{ef} = \begin{Vmatrix} A & 0 & 0 & 0 & 0 & 0 \\ 0 & A & 0 & 0 & 0 & 0 \\ 0 & 0 & A & 0 & 0 & 0 \\ 0 & 0 & 0 & B & 0 & 0 \\ 0 & 0 & 0 & 0 & B & 0 \\ 0 & 0 & 0 & 0 & 0 & B \end{Vmatrix}, \text{ Pa}. \quad (6)$$

Here, the following expressions are accepted

$$A = \frac{2E}{3}\left[n + \frac{(1-p)(1-n)\Delta}{\Delta + p\Delta_1(1-\Delta)}\right], \text{ Pa}; \qquad B = \frac{2E}{3}\left[n + \frac{(1-n)(1-p)\left(n + \frac{3}{2}\right)}{\left(n + \frac{3}{2}\right) + p(1-n)}\right], \text{ Pa};$$

$$\Delta = \left[4\left(n + \frac{5}{3}\right)^3 - \frac{1}{3}\left(n + \frac{5}{3}\right) + \frac{1}{9}\right]; \qquad \Delta_1 = 4\left(n + \frac{5}{3}\right)^2 - \frac{1}{9}. \quad (7)$$

When $n = 0$, i.e. in the absence of any fractures, effective modulus coincides with the modulus of the source material; when $n = 1$, effective modulus coincides with the modulus of microdamages. These conclusions are natural as they follow from the very statement of the problem and validate correctness of the made calculations.

In this way, dependences of stresses and strains on the magnitude of microfractures, which are developing in the material, can be obtained. And relation between the deformation γ and stress τ in this case is expressed as

$$\tau = \hat{G}'_{ef} \cdot \gamma \text{, Pa,} \tag{8}$$

where

$$\hat{G}'_{ef} = G_{in}\left[n + \frac{(1-n)(1-p)\left(n+\frac{3}{2}\right)}{\left(n+\frac{3}{2}\right)+p(1-n)}\right]\text{, Pa.} \tag{9}$$

Here, G_{in} is initial value of the source material modulus, Pa.

Results and discussion. Let's use the obtained results for calculation of effective modulus of RMB type elements made of 2959-type rubber (on the basis of natural caoutchouc with filling of 45 mass parts of black carbon), for which initial value of rubber dynamic is $G_{in} = 1.60$ MPa (at an oscillation angular frequency $\omega = 60$-80 rad/s). Let's use the previously obtained in [6, 8-10] experimental results on time-dependent change of the shear modulus for elements made of rubber 2959, and let's assume that $n = 1.2$.

Let's consider a concrete example. Let it be necessary to predict a change of oscillation amplitude in ore vibratory feeder of the VPR-4m type, elastic links of which are made in the form of shift elements of the RMB type. Parameters of vibratory feeder are as follows: mass of vibrating elements is $m = 3770$ kg; oscillation angular frequency is $\omega = 101.5$ rad/s; initial value of instantaneous shear modulus for rubber is $G_{in} = 1.76$ MPa; and dissipation coefficient is $\psi = 0.31$.

Equation for the vibrating elements movements in the vibratory feeder is

$$m\ddot{x} + C_t x = P\sin\omega t\text{ ,} \tag{10}$$

where m is mass of the work member, kg; C_t is reduced stiffness of the main elastic links, N/m; P is exciting power, N; ω is loading angular frequency, rad/s; t is time, s.

The solution of equation (10) is expressed as

$$x = a\sin(\omega t - \varphi), \tag{11}$$

where x is coordinate, m; φ is phase, rad.

Express the dependence of the amplitude of the conveyor oscillations as follows

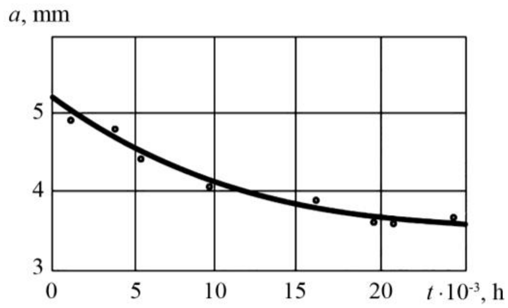
$$a = \frac{Q}{m\sqrt{\left\{\omega_0^2\left[1 - A_1(\omega)\right] - \omega^2\right\}^2 + B_1^2(\omega)\omega_0^4}}\text{ .} \tag{12}$$

Here a is amplitude of oscillations, m; Q is the force of inertia, N; ω_0 is natural vibration angular frequency of an ideally elastic system, rad/s; $A_1(\omega)$ and $B_1(\omega)$ are rheological characteristics of rubber (cosine and sine Fourier transform of a fractional exponential function) [6].

Values for effective modulus were determined from the dependence $G_{ef} \sim p/p_{kr}$ by the formula (9), rate of critical fracture $p_{kr} = 5{,}6$ was taken according to the experimental data obtained in [6], and kinetic curve $p(t)$ was also obtained experimentally on model samples with long-term cyclic loading.

Time dependence of vibratory feeder amplitude calculated in this way is shown in figure and, as it is seen, satisfactorily coincides with experimental data [6]. This coincidence confirms the suitability of the proposed method for calculating mechanical characteristics of vibration machines, the elastic links of which change their parameters over time. As it is seen, oscillation amplitude decreased from 5.2 mm to 3.7 mm after 24,000 hours and led to degradation of vibratory feeder productivity.

It should be noted that in engineering practice, change of oscillation amplitude in vibratory machines during their long-term operation is quite frequent phenomenon. In practice, this undesirable phenomenon is usually eliminated by changing frequency of drive oscillations or, in case of excessive stiffness, by replacing elements in the elastic suspension.



Change of oscillation amplitude of the VPR-4m vibratory feeder
at long-term operation: the points is experimental data, the line is calculated curve

Conclusions. 1. A synergistic model and algorithm were developed for calculating vibratory feeders for drawing and feeding uranium ores with taking into account time-dependent instability of elastic suspension parameters.

2. When solving the integro-differential equation of the oscillatory system and taking into account the unstable in time rheological parameters of the rubber elements of the elastic suspension of the feeder, the dependence of its oscillation amplitude on the operating time is obtained; calculation results satisfactorily coincide with the data of industrial tests.

В. И. Дырда[1], Н. И. Лисица[1], В. А. Лапин[2], Г. Н. Агальцов[1], Е. В. Калганков[3], А. В. Толстенко[3], А. А. Черний[3]

[1]Поляков атындағы Украина ұлттық ғылым академиясының геотехникалық механика институты, Днепр, Украина;
[2]«Қазақ құрылыс және сәулет ғылыми-зерттеу және жобалау институты» АҚ, Алматы, Қазақстан;
[3]Днепр мемлекеттік аграрлық-экономикалық университеті, Днепр, Украина

ПАРАМЕТРЛЕРІ УАҚЫТЫНДАҒЫ ТҰРАҚСЫЗДЫҚТЫ ЕСКЕРЕТІН АУЫР ДІРІЛ МАШИНАЛАРЫНЫҢ ДИНАМИКАСЫ

Аннотация. Уран кенін жерасты өндіру бірнеше технологиялық үдерістерден тұрады, олардың ең маңыздысының бірі – сынған тау жыныстарын тазарту кеңістігінен шығару және оны көлік құралдарына тиеу. Өндіріс қарқындылығын арттыру мәселесі барлық өндірістік үдерістердің, оның ішінде минералды шикізат өндірісінің өнімділігін бір уақытта арттыруды талап етеді. Сонымен бірге жоғары тиімділікті де, қауіпсіз үдерісті де құру қажет. Бұл мәселе эластомерлік материалдардан жасалған серпімді байланысы бар діріл машиналарын қолдану арқылы сәтті шешіледі, бұл жағдай өнімділіктің жоғарылауымен бірге энергия шығынын және қатып қалу санын азайтуға мүмкіндік береді.

Әртүрлі технологиялық мақсат үшін діріл технологиясын жасаудың әлемдік тәжірибесін зерттеу оның негізінен минералды бетінде өңдеу үшін қолданылатындығын көрсетті. Жерасты жағдайында діріл технологиясын қолдану әлемдік тәжірибеде іс жүзінде жоқ, сонымен қатар бұл мәселе бойынша ғылыми әдебиеттер де кездеспейді.

Жұмыста уран кенін өндіру және жеткізуде блокада астында жұмыс істейтін VPR типтегі ауыр діріл беретін фидерлер (діріл кенін беру) динамикасын қарастырамыз. Құрылымдық тұрғыдан алғанда, VPR дірілдеткіштері – біртекті массалы тербеліс жүйесі; BRM типтегі призмалық резеңке элементтер (резеңке-металл блоктар) серпімді буын ретінде қызмет етеді. Жұмыс кезінде мұндай элементтер қарапайым ығысу деформацияларына ұшырайды; олардың физикалық және механикалық параметрлері уақыт бойынша тұрақсыз: ығысу модулі жоғарылайды, ал ыдырау коэффициенті төмендейді. Мұндай өзгеріс негізінен резеңке кіретін барлық эласто-тұқым қуалайтын материалдарға тән қартаю үдерісіне байланысты болып келеді.

Аналитикалық зерттеулерді және уран кенін, құрылыс материалдарын жерасты қазып шығаруда және дірілді өнеркәсіптік сынау нәтижелерін қосқанда кешенді тәсіл қолданылды. Әзірленген алгоритмге және тербелмелі бергіштің резеңке байланыстары микрокрекингінің синергетикалық моделіне сүйене отырып, уақытты тұрақсыз параметрлермен қоректендіргіштер динамикасын сипаттауға мүмкіндік беретін математикалық теңдеулер алынды; тербелмелі жүйенің интегро-дифференциалдық теңдеуін шешкенде фидердің амплитуда сипаттамаларының жұмыс уақытына тәуелділігі алынады. Түпнұсқа алгоритм және синергетикалық модель жасалды және олардың негізінде математикалық аппарат құрылды, ол жұмыс кезінде діріл бергіштің тербеліс амплитудасының өзгеруін анықтауға мүмкіндік береді. Аналитикалық есептеу негізінде діріл бергіштің тербеліс амплитудасы параметрлерінің өзгеруін болжау әдісі жасалды және енгізілді. Бұл әдіс уранды шахтада жұмыс істеп тұрған VPR-4 м діріл бергішінің тербеліс амплитудасының өзгеруін есептеу үшін руданы төгу және арбаларға тиеу кезінде пайдаланылды. Мұндай фидерлердің жұмыс мерзімі шамамен 2-3 жыл. Үш вибраторлы фидер жұмысының бүкіл кезеңінде (шамамен 30 мың сағат) жұмыс органдары тербелістерінің амплитудасы мен жиілігін өлшеу бойынша эксперименттік зерттеулер жүргізілді. Алынған есептеу нәтижелері өндірістік сынақ нәтижелері бойынша қанағаттанарлық деңгейде.

Түйін сөздер: діріл бергіш, діріл, синергетикалық модель, шаршау.

В. И. Дырда[1], Н. И. Лисица[1], В. А. Лапин[2], Г. Н. Агальцов[1], Е. В. Калганков[3], А. В. Толстенко[3], А. А. Черний[3]

[1]Институт геотехнической механики им. Н. С. Полякова
Национальной академии наук Украины, Днепр, Украина;
[2]АО «Казахский научно-исследовательский и проектный институт
строительства и архитектуры», Алматы, Казахстан;
[3]Днепровский государственный аграрно-экономический университет, Днепр, Украина

ДИНАМИКА ТЯЖЁЛЫХ ВИБРАЦИОННЫХ МАШИН С УЧЁТОМ НЕСТАБИЛЬНОСТИ ВО ВРЕМЕНИ ИХ ПАРАМЕТРОВ

Аннотация. Подземная разработка урановых руд состоит из нескольких технологических процессов, одним из наиболее важных из которых является выпуск отбитой горной массы из очистного пространства и погрузка её в средства транспортировки. Вопрос повышения интенсивности добычи требует синхронного повышения производительности всех процессов добычи, в том числе и выпуск минерального сырья. При этом необходимо создавать как высокопроизводительный, так и безопасный процесс. Эта проблема успешно решается применением вибрационных машин с упругими звеньями из эластомерных материалов, которые наряду с увеличением производительности позволяют снизить энергоёмкость и количество зависаний.

Изучение мирового опыта создания вибрационной техники различного технологического назначения показало, что преимущественно она используется для переработки минерального на поверхности. Применение вибрационной техники в стеснённых подземных условиях в мировой практике практически отсутствует, а также отсутствует и научная литература по данному вопросу.

В статье рассматривается динамика тяжёлых горных вибрационных питателей типа ВПР (вибрационные питатели рудные), работающих под завалом на выпуске и доставке урановых руд. Конструктивно вибропитатели ВПР представляют собой одномассную колебательную систему; упругими звеньями служат призматические резиновые элементы типа БРМ (блоки резинометаллические). При эксплуатации такие элементы испытывают деформации простого сдвига; их физико-механические параметры во времени нестабильны: модуль сдвига увеличивается, а коэффициент диссипации уменьшается. Такое изменение связано в основном с процессами старения, присущими всем упруго-наследственным материалам, к которым относится и резина.

Использован комплексный подход, включающий аналитические исследования и результаты промышленных испытаний вибропитателей при подземной добыче и доставке урановых руд и строительных материалов. На основе разработанных алгоритма и синергетической модели усталостного микроразрушения резиновых звеньев вибропитателя получены математические уравнения, позволяющие описать динамику питателей с нестабильными во времени параметрами; при решении интегро-дифференциального уравнения колебательной системы получена зависимость амплитудной характеристики питателя от времени его эксплуатации. Разработан оригинальный алгоритм и синергетическая модель и на их основе создан математический аппарат, позволяющий определить изменение амплитуды колебаний вибропитателя в течение его эксплуатации. На основе аналитических расчётов разработан и внедрён метод прогнозирования изменения параметров амплитуды колебаний вибропитателя. Этот метод использован для расчёта изменения амплитуды колебаний вибрационного питателя типа ВПР-4м, работающего в урановом руднике под завалом при выпуске руды и погрузке её в вагонетки. Длительность эксплуатации таких питателей примерно 2-3 года. На протяжении всего времени эксплуатации трёх вибропитателей (около 30 тысяч часов) проводились экспериментальные исследования по замеру амплитуды и частоты колебаний их рабочих органов. Полученные результаты расчёта удовлетворительно совпадают с результатами промышленных испытаний.

Ключевые слова: вибропитатель, колебания, синергетическая модель, усталостное разрушение.

Information about authors:

Dyrda Vitaly Illarionovich, Doctor of Technical Sciences (D. Sc.), Professor, Head of Department of Elastomeric Component Mechanics in Mining Machines, Institute of Geotechnical Mechanics named by N. Poljakov NAS of Ukraine (IGTM, NASU), Dnipro, Ukraine; vita.igtm@gmail.com; https://orcid.org/0000-0002-2113-816X

Lysytsia Mykola Ivanovych, Candidate of Technical Sciences (Ph. D.), Senior Researcher, Senior Researcher in Department of Elastomeric Component Mechanics in Mining Machines, Institute of Geotechnical Mechanics named by N. Poljakov NAS of Ukraine (IGTM NASU), Dnipro, Ukraine; lisitsa.n.i@gmail.com; https://orcid.org/0000-0001-6364-8937

Lapin Vladimir Alekseevich, Ph.D. in Engineering Science, Director of Center for Scientific Research in Building Industry, Corresponding Member of International Engineering Academy and National Engineering Academy of the Republic of Kazakhstan, «KazRDICA» JSC, Almaty, Kazakhstan; lapin_1956@list.ru; https://orcid.org/0000-0002-1669-5332

Ahaltsov Hennadii Mykolaiovych, Master of Science, Junior Researcher of Department of Elastomeric Component Mechanics in Mining Machines, Institute of Geotechnical Mechanics named by N. Poljakov NAS of Ukraine (IGTM NASU), Dnipro, Ukraine; ag.gena@gmail.com; https://orcid.org/0000-0001-6296-7573

Kalhankov Yevhen Vasylovych, Master of Science, Senior Lecturer of Department «Reliability and repair of machinery», Dnipro State Agrarian and Economic University (DSAEU), Dnipro, Ukraine; kalhankov.ye.v@dsau.dp.ua; https://orcid.org/0000-0002-4759-6687

Tolstenko Oleksandr Vasylovych, Candidate of Technical Science (Ph. D.), Associate Professor of Department «Reliability and repair of machinery», Dnipro State Agrarian and Economic University (DSAEU), Dnipro, Ukraine, info@dsau.dp.ua; https://orcid.org/0000-0003-4752-5704

Chernii Oleksandr Anatoliiovych, Master of Science, Senior Lecturer of Department «Reliability and repair of machinery», Dnipro State Agrarian and Economic University (DSAEU), Dnipro, Ukraine; sanek20.1984@gmail.com; https://orcid.org/0000-0003-0691-5829

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