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# Study of performance of vibration treatment of mechanical equipment details

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**ABSTRACT**

Finishing and cleaning treatments of surface of details (for the purpose of cleaning details), removal of burrs, rounding off sharp edges, are preparing surfaces for coatings by grinding and polishing are used in all branches of industry, especially widely in mechanical engineering and instrument making. The essence of volumetric vibro-abrasive treatment is that details to be machined with abrasive bodies are placed in a container that is imparted with oscillatory motion at a certain frequency. Microparticles of metal are removed from treated surfaces due to the relative movement and pressure between abrasive granules and details caused by container vibrations. Factors that influence the intensity of processing are shown. Equations for the relative motion of loading granules and the working medium have been compiled. Dynamic equations for the relative motion of loading elements are obtained. Influence of the container shape on the process of vibration treatment of small flat details was investigated. Features of the dynamics of boundary elements of the loading mass are considered. The influence of vertical and horizontal movement of the container on the details is considered.

**KEYWORDS**

container shape • vibration treatment • container • granule • transfer inertial force • relative motion equations of container motion

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## Introduction

Wide technological possibilities of vibration treatment create favorable conditions for industrial use. The essence of vibration processing consists of the sequential application of a large number of micro-impacts to the surfaces of details being processed by granules of a grinding material under the action of directed vibrations transmitted to the working chamber. Metal removal is achieved through mechanical or mechanochemical dispersion of the smallest particles of metal and its oxides from the surface being treated by abrasive granules.

The relevance of this research is confirmed by the works of a large number of scientists, namely: in [1], it was worked on improving methodology for designing technological processes for treatment details with free abrasives; Mordovtsev A.A. [2] were engaged assessment of reliability of technological process of vibro-abrasive machining in digital production conditions; Zhailaubaev D.T. et al. [3] developed determination of influence of vibrations of cutting tools on accuracy of processing; Asaev A.S. et al. [4] investigated process of finishing abrasive treatment of internal surfaces using effect of vibration cavitation; Rechenko D. et al. [5] scrutinized problem

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designs of grinding wheels for ultra-high-speed grinding. Allagulov V.R. and Shkalikov E. A. [6] studied the dependence of roughness on cutting conditions. As Volosova M.A. et al. [7] scrutinized the problem of the influence of the state of the surface layer of ceramic inserts $Al_2O_3$+TiC on the quality of applied coatings and reliability during milling of hardened steel. In [8,9], it was developed the effect of loading on tribotechnical characteristics of antifriction diamond-bearing mineral ceramics. Kutin A.A. et al. [10] studied global trends in the machine tool industry. In [11], the treatment of small flat details in U-shaped containers of vibration machines was studied. Burlakova G.Yu. et al. [12] explored the adhesion of small flat details. Mitsyk V.Ya. [13] was engaged in the intensification of the processing of details in vibrating tanks. Provolotsky A.E. et al. [14] investigated the formation of developed microreliefs of surfaces. Babichev A.P. et al. [15,16] worked on the fundamentals of vibration technology, application of vibration technologies in finishing and cleaning operations of details: cleaning, washing, removal of flash and burrs, edge processing. Serga G.V. et al. [17] carried out increasing productivity of technological systems for finishing, cleaning and hardening processing of details based on screw rotors. Babichev A.P. et al. [18–20] were engaged in vibration mechanochemistry in the process of finishing and hardening coatings of details using vibration technologies. Asayev A.S. [21] analyzed finishing treatment of blade surfaces with free abrasive using the vortex cavitation effect. Nguyen T. et al. [22] considered computer modeling and experimental research of the process of processing components in a centrifugal-rotary installation. Tarasovskii V.P. [23] conducted research on the processing surface of corundum ceramic details with free abrasive. Melnikova E.P. and Prokopets G.A. [24] investigated the influence of the concentration of abrasive filler granules on the intensity of the vibration treatment process. Shchetinin V.S. and Sablin P.A. [25] analyzed the relation between spatial vibrations and roughness of machined surface using turning as an example. In [26], the dependence of surface roughness on cutting conditions was studied. Golobokov A.V. et al. [27] worked on simulation modeling of the grinding process of instrument bearing blanks made of special corrosion-resistant steels. Tamarkin M.A. et al. [28] conducted research on the vibration treatment of external and internal surfaces of details in preparation for coating application. Asaev A.S. [29] studied of the wear resistance of thread rolling dies subjected to finishing treatment with free abrasive using intensifying cavitation action. Piedra-Cascón W. et al. [30] analyzed printing parameters, support structures, slicing and post-processing procedures in additive manufacturing technologies using vanilla polymers. Wang G. et al. [31] developed profile formation in an abrasive environment.

## Material and Methods

During vibro-abrasive treatment, as a result of the action of the vibration force, metal removal is carried out due to the simultaneous action of three mechanisms, namely, chipping, abrasion and micro-cutting. Chipping occurs when individual projections of abrasive grains collide with a detail; abrasion occurs during the mutual, almost parallel movement of details and filler; micro-cutting is accompanied by the removal of the finest chips from details [11,12]. The micro-cutting accounts for the largest volume of metal

removed of all metal removal mechanisms mentioned above. Thus, the basis of vibro-abrasive treatment should be the micro-cutting process, which is carried out by cutting protrusions of abrasive grains, which provides a significant increase in productivity [13,14].

Process parameters that determine the kinetic energy of the abrasive tool's impact on workpieces and the conditions of movement of the working medium significantly affect the productivity of vibro-centrifugal machining and its labor intensity. This is due to the fact that when processing loose details, in order to create the greatest kinetic energy of abrasive's impact on detail, following conditions must be met, namely, good mixing of details, intense abrasive action while imparting a sufficient level of kinetic energy to abrasive tool to remove metal from surface of the details and creating maximum possible difference in speed between abrasive particles and the details being processed. Laboratory installation, the description and operating principle of which are detailed in [32], was designed based on the above given information and also taking into account the advantages and disadvantages of installations described in works [15–18].

To describe movement of working medium in containers of various shapes it is necessary to create a mathematical model for studying influence of speeds and accelerations of elements of working medium in different zones of container using equations of dynamics of container movement, modeling movement of loading elements taking into account configuration of the container and, consequently, change in pressure in mass of loading, predicting dependence of metal removal on physical and mechanical parameters of processing [19,20].

## Results and Discussion

During vibration treatment, metal is removed from the workpiece by abrasive granules as a result of the relative motion of the granules and the workpiece depending on the vibration forces acting vertically and horizontally: $F_y^{(\mathrm{pos})} = m_\mathrm{d}\omega^2 e\sin(\omega t)$; $F_z^{(\mathrm{pos})} = m_\mathrm{d}\ \omega^2 e\cos(\omega t)$.

According to practice, intensity and result of treatment are influenced by: relative sliding velocities of granules; size of contact area of workpiece with processing environment; compaction of working environment because it changes viscosity and friction coefficients; container shape; frequency-amplitude parameters of container vibrations; ratio of sizes, number of workpieces and abrasive grains.

Dynamic equations for the relative motion of loading elements considering the absolute motion of a granule as a synthesis of two motions [1,10,21] can be obtained: relative to the container (when the observer is attached to the container); portable together with the loaded container (when the granule conditionally belongs to the container).

It can be designated: $\vec{V}_\mathrm{rel}$, $\vec{a}_\mathrm{rel}$ are relative velocity and relative acceleration of the granule; $\vec{V}_\mathrm{trans}$, $\vec{\mathrm{a}}_\mathrm{trans}$ are transfer velocity and transfer acceleration of the granule; $m_\mathrm{g}$ is the granule mass. The dynamic equation of the relative motion of a granule in vector form has the following form [22,23]:

$$m_\mathrm{g}\vec{a}_\mathrm{rel} = m_\mathrm{g}\vec{g} + \vec{N} + \vec{F}_\mathrm{fr} + \vec{F}_\mathrm{trans}^\mathrm{in}, \quad (1)$$

where $m_\mathrm{g}\vec{g}$ is the gravity of the granule, $g$ = 9.81 m/s$^2$, $\vec{N}$ is the resulting reaction of bonds imposed on the granule by other loading elements and the container walls, $\vec{F}_\mathrm{fr} = f\vec{N}$ is

the frictional force applied to the granule, $f$ is the coefficient of friction depending on materials and state of contacting bodies, $\vec{F}^{\text{in}}_{\text{trans}}$ is the transfer force of inertia:

$$\vec{F}^{\text{in}}_{\text{trans}} = -m_{\text{g}}\vec{\text{a}}_{\text{trans}}. \quad (2)$$

Magnitude and direction of transfer acceleration are dictated by equations of motion of the container and are determined by Eqs. (1) and (2) [12]. Acceleration components are equal to the second derivatives with respect to time of coordinates *Y*(*t*) and *Z*(*t*):

$$a_{\text{trans}_Y} = \ddot{Y} = -\omega^2 A_Y \sin(\omega t + \delta_1), \quad (3)$$

$$a_{\text{trans}_Z} = \ddot{Z} = -\omega^2 A_Z \cos(\omega t + \delta_2), \quad (4)$$

where $A_Y$ and $A_Z$ are amplitudes along axes *Y* and *Z*.

Differential equations for the relative motion of a granule located anywhere in the container can be obtained by projecting vector equation (1) onto the coordinate axes. The influence of container shape on the process of vibration machining of small flat details can be investigated. The issue of the shape influence of vertical walls and the shape of the cross-section of the container on the treatment of details (metal removal) near its walls is relevant, as well as a comparative analysis of a polygonal cross-section and a circular cross-section from the point of view of possible contact of loading elements with the walls of the container. Therefore, it is advisable to select in cross-section (section view from *Z* axis shown on Figs. 1 and 2) so-called natural coordinate axes which are movable (move together with the granule located in position *M*).

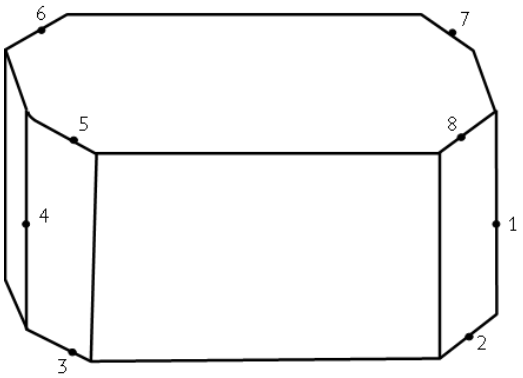



**Fig. 1.** Location of loading elements being examined in the container

$M\tau$ is tangent to the trajectory of relative motion, directed along $\vec{V}_{\text{rel}}$. $Mn$ is along a normal to the trajectory directed inside the container (towards the center of the circular section radius of which is equal to *R*). In this case, only horizontal components of the transfer inertial force will be projected onto the axes [7,24] $\text{M}_{\tau n}$. It can be obtained:

$$\begin{cases} m_{\text{g}}\dfrac{dV_{\text{rel}}}{dt} = \text{pr}_{\tau}\vec{N} + \text{pr}_{\tau}\vec{F}^{\text{in}}_{\text{trans}_Y}, & (5) \\ m_{\text{g}}\dfrac{V^2_{\text{rel}}}{R} = \text{pr}_{n}\vec{N} + \text{pr}_{n}\vec{F}^{\text{in}}_{\text{trans}_Y}. & (6) \end{cases}$$

To investigate the influence of the container shape (view from *OX* axis, refer to Fig. 1), in differential equations of motion, both vertical and horizontal components of transfer inertial force, depending on the position of unbalance, can be taken into account.

$$\begin{cases} m_{\mathrm{g}} \dfrac{dV_{\mathrm{rel}}}{dt} = \mathrm{pr}_{\tau}\, \overrightarrow{mg} + \mathrm{pr}_{\tau}\vec{N} + \mathrm{pr}_{\tau}\vec{F}^{\mathrm{in}}_{\mathrm{trans}_Z} + \mathrm{pr}_{\tau}\vec{F}^{\mathrm{in}}_{\mathrm{trans}_Y}, & (7) \\ m_{\mathrm{g}} \dfrac{V^2_{\mathrm{rel}}}{R} = \mathrm{pr}_{n}\, \overrightarrow{mg} + \mathrm{pr}_{n}\vec{N} + \mathrm{pr}_{n}\vec{F}^{\mathrm{in}}_{\mathrm{trans}_Y} + \mathrm{pr}_{\tau}\vec{F}^{\mathrm{in}}_{\mathrm{trans}_Z}. & (8) \end{cases}$$

Numbers can be given to granules located near the walls of the container for the convenience of theoretical calculations shown on Fig. 1. The features of the dynamics of boundary elements of the loading mass can be considered for which the influence of the horizontal movement of the container on the granules located near the walls of the container can be analyzed [3,5].

Figure 2 shows the top view of the container for the proposed section of the vibration machine. This issue is being explored in two directions: whether there is contact between the granule and the wall if the cross-section is a polygon; whether there is contact between the granule and the wall if cross-section is round. Interest is made by those positions of the container in which imbalance occupies extreme positions, namely, the extreme right and the extreme left.

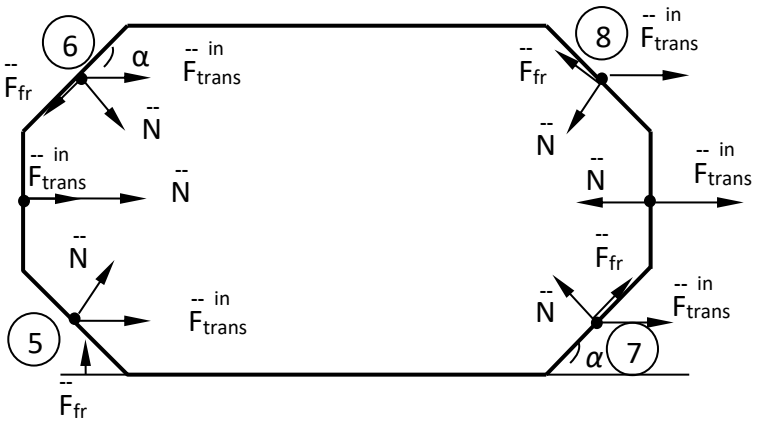



**Fig. 2.** Diagram of forces in the extreme right position of unbalance
where $\alpha$ is the angle characterizing the cross-sectional shape of the container

The transfer force of inertia for the loading element is directed to the right at the extreme right position of the imbalance. It is assumed that the granules in their relative motion slide along the walls of the container clockwise (Fig. 2).

Reaction from the wall to the granule can be represented with two components, namely, *N* is the normal component and $\vec{F}_{\mathrm{fr}}$ is the frictional force that consists of frictional forces in horizontal and vertical planes ($\vec{F}_{\mathrm{fr}} = \vec{F}_{\mathrm{fr}_{\mathrm{hor}}} + \vec{F}_{\mathrm{fr}_{\mathrm{ver}}}$) if a point is pressed against a wall and slides having components of relative velocity in these planes. The translational force of inertia in this position is equal in magnitude to

$$F^{\mathrm{in}}_{\mathrm{trans}} = m_{\mathrm{g}}|\ddot{Y}| = m_{\mathrm{g}} \frac{m_{\mathrm{d}} \omega^2 \mathrm{e}}{\mathrm{M}}, \quad (9)$$

and it is directed to the right.

Applying the differential equation of motion (8), it can be obtained that if the granule tries to remain in the horizontal plane and move with speed $V_{\mathrm{rel}_{\mathrm{hor}}}$ then for a U-shaped container section:

in points 7 and 8, $\frac{m_g V_{rel}^2}{R} = N_7 - F_{trans}^{in}\sin\alpha,\ N_7 = N_8 = F_{trans}^{in}\sin\alpha + \frac{m_g V_{rel}^2}{R},$ (10)

in points 5 and 6, $\frac{m_g V_{rel}^2}{R} = N_6 - F_{trans}^{in}\sin\alpha, N_5 = N_6 = -F_{trans}^{in}\sin\alpha + \frac{m_g V_{rel}^2}{R}.$ (11)

For the cross-section of the container with broken the walls in form of a polygon on inclined sides:

in points 7 and 8, $N_7 = N_8 = F_{trans}^{in}\sin\alpha,$ (12)

in points 5 and 6, $N_5 = N_6 = -F_{trans}^{in}\sin\alpha.$ (13)

After analysis of Eqs. (10) and (11), it can be concluded that loading elements located near points 7 and 8 will experience normal pressure from the container walls and this pressure is less for the polygonal section. It depends on the angle $\alpha$; for larger angles $\alpha$, the pressure is greater.

Analysis of Eqs. (12) and (13) lead to the conclusion that normal and tangential forces of reactions of the left walls do not arise if the walls are straight with an extreme right position of imbalance in the horizontal direction; they can arise if relative movement of detail in the horizontal plane is possible with circular sections.

Considering that in vertical plane all details are subject to their own gravity forces and gravity forces of loading elements located above them, probability of movement of details 5, 6, 7 and 8 in horizontal plane is small which means that details 5 and 6, not having contact with the container wall, will move downwards in direction of *Z* axis while details 7 and 8 can make contact and be processed. If details 5–8 are in positions 1 and 2, 3 and 4, the effect of gravity of adjacent upper details is significant (for these loading elements the coefficient *K* for the gravity of details is introduced). Influence of vertical and horizontal movement of the container on details located near the surface of the container is considered. Figure 3 shows the view of the container from *OX* axis and the points at which the loading elements are located (1, 2, 3, 4).

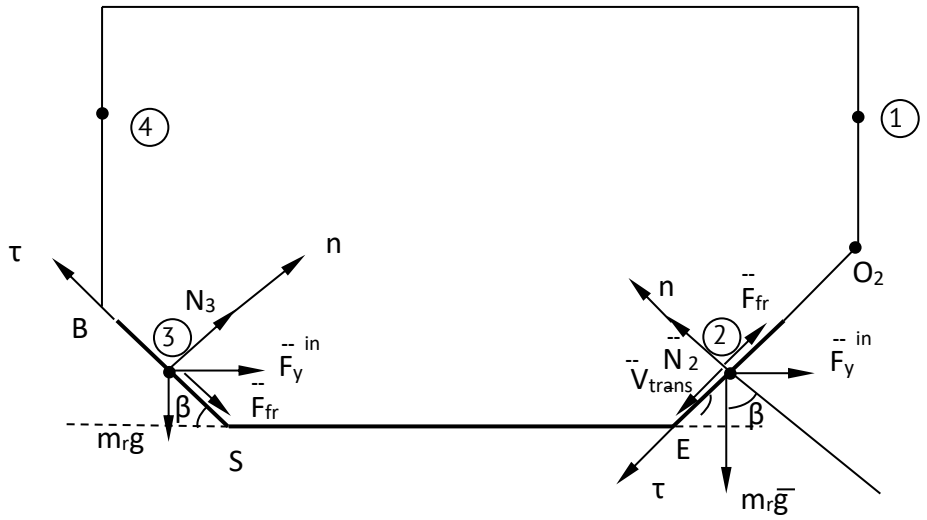



**Fig. 3.** Diagram of forces in extreme right position of imbalance, where β is the angle of inclination of the wall to horizontal

Dynamic equations for the relative motion of details located in position 2 can be composed. Translational inertial force is equal to Eq. (9) and it is directed to the right. According to Eqs. (7) and (8) for a flat wall, the equations shown below can be obtained:

$$N_2 = Km_g g\cos\beta + m_g|\ddot{Y}_c|\sin\beta + \frac{m_g V_{rel}^2}{R},$$
$$\left(|\ddot{Y}_c| = \frac{m_d \omega^2 e}{M} = 8.84\ m/s^2\right), \quad (14)$$
$$m_g \frac{dV_{rel}}{dt} = Km_g g\sin\beta - f\cdot N_2 - m_g \ddot{Y}\cos\beta,$$

or taking into account $N_2$ it can be concluded:

$$a_{rel_\tau} = Kg\sin\beta - fg\cos\beta - f\ddot{Y}_c\sin\beta - f\frac{m_g V_{rel}^2}{R} - \ddot{Y}_c\cos\beta, \quad (15)$$

where *K* is the coefficient that takes into account the fact that, starting from position *O*2, detail 2 is also subjected to the gravitational forces of details located above it. It is can be taken as *K* = 5. To estimate the direction of acceleration of detail 2 it can be assumed that $\beta$ = 45°. It is concluded that $\cos\beta = \sin\beta = \frac{\sqrt{2}}{2}$, $a_{rel_\tau} = \frac{\sqrt{2}}{2}(Kg(1-f) - \ddot{Y}(1+f))$, $a_{rel_\tau} > 0$, which is why details 2 moves downwards with acceleration.

Dynamic equations of relative motion (7) and (8) for a flat wall can be composed in detail in position 3. It can be obtained:

$$N_3 = m_d(Kg\cos\beta - \ddot{Y}\sin\beta),$$
$$\ddot{Y} = 8.84\ m/s^2, \quad (16)$$
$$m_g \frac{dV_{rel}}{dt} = -Km_g g\sin\beta - f\cdot N_3 - m_g\ddot{Y}\cos\beta.$$

Taking into account $N_3$ it can be obtained:

$$a_{rel_\tau} = \frac{dV_{rel}}{dt} = -Kg\sin\beta - \ddot{Y}\cos\beta - fKg\cos\beta + f\ddot{Y}\sin\beta. \quad (17)$$

It can be assumed that $\beta = 45°$, $\cos\beta = \sin\beta = \frac{\sqrt{2}}{2}$. Then $a_{rel_\tau} = \frac{\sqrt{2}}{2}(-Kg(1+f) + +\ddot{Y}(f-1))$.

It is clear that the projection of relative acceleration onto the τ axis is always negative. Friction force in this case is equal to:

$$F_{fr} = fm_g(Kg\cos\beta - \ddot{Y}\sin\beta). \quad (18)$$

If detail in position 2 has traveled a distance *ES* and has a speed at point *S* then it will slowly rise along inclined plane *SB* and come into contact with other details if:

$$Kg\cos\beta > \ddot{Y}\sin\beta, \quad (19)$$

when $\beta = 45°$, $Kg > \ddot{Y}_c$ that in our case is real ($g$ = 9.81, $\ddot{Y} = 8.84$).

Values of normal reactions are equal to each other (Fig. 4) in the extreme upper position of imbalance for points 2 and 3:

$$N_2^{(в)} = N_3^{(в)} = \left(Km_g g - F^{in}\right)\cos\beta. \quad (20)$$

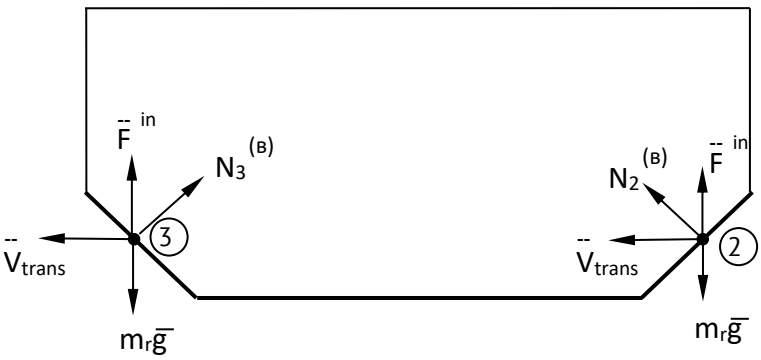



**Fig. 4.** Diagram of forces in the upper position of imbalance

Upward movement is impossible because $Kg > \ddot{Z}$ and transfer velocity is directed to the left. Dynamic equations of relative motion for points 2 and 3 in the extreme lower position of the imbalance can be composed. In this case, the translational inertial force is directed downward. The force diagram is shown on Fig. 5. Equations (8) and (9) for a straight wall near which point 2 is located have the form shown below:

$$N = m_g(Kg + \ddot{Z})\cos\beta, \quad (21)$$

$$a_\tau = (Kg + \ddot{Z})(\sin\beta - f\cos\beta). \quad (22)$$

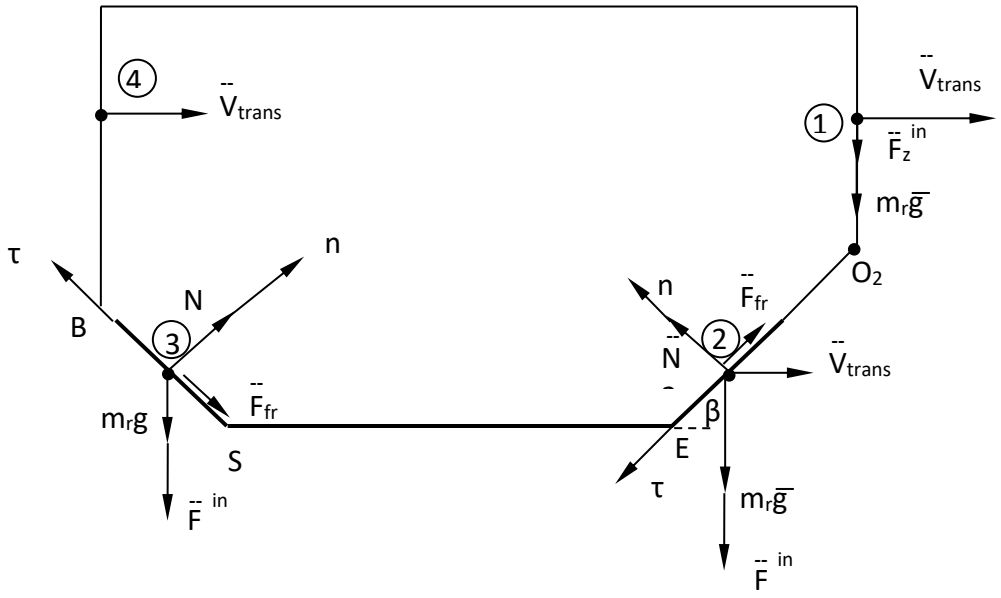



**Fig. 5.** Diagram of forces acting on the loading elements with the unbalance in the lower position

In the vicinity of points located on section *OE,* if transition from the vertical wall to the bottom were rounded, then:

$$N_{o_{round}} = N_{flat} + \frac{m_g V_{rel}^2}{R}, \quad (23)$$

$$a_{\tau_{round}} = a_{\tau flat} - \frac{f V_{rel}^2}{R}. \quad (24)$$

It means that the reaction force from the wall will be bigger and the relative acceleration along the tangent to the circle of radius *R* at each point will be less. For angles $\beta > arc\ tg\ f$ the movement of points 2 is accelerated, because of (22) $a_\tau > 0$ when $\frac{\sin\beta}{\cos\beta} > f$. Friction force is equal to:

for flat wall $F_{fr_{flat}} = f m_g(Kg + \ddot{Z})\cos\beta, \quad (25)$

for a rounded curve $F_{fr_{round}} = f\frac{m_g V_{rel}^2}{R} + F_{fr_{flat}}, \quad (26)$

it means that the rounded curve increases the friction force during the reduction of the radius of curvature.

There are results for points 3 located near the wall *SB* (Fig. 5) obtained from Eqs. (9) and (10): $N_3 = m_g(Kg + \ddot{Z})\cos\beta$. It means that the result is similar to points 2: $a_\tau = -(Kg + \ddot{Z})(\sin\beta + f\cos\beta)$. It means that movement can be slowed down upwards along the wall *SB* if at point *S,* the speed of details along axis *S*τ was not equal to zero.

Direction of transfer speed for points on the right wall promotes pressing of loading elements 2 to the wall and for details on left wall 3 promotes separation of these points

from the container walls. Same conclusion can be made regarding loading elements located on vertical walls of the container in positions 1 and 4.

Situation in extreme left position (Fig. 6) can be found. Normal reaction forces of the walls have changed: $N_{3_{\text{left}}} = N_{2_{\text{right}}}$ and $N_{2_{\text{left}}} = N_{3_{\text{right}}}$. Accelerations have also changed places but in the extreme left, position the container's transfer velocity is directed downwards and the transfer force of inertia is directed to the left:

$$a_{\tau_2} = Kg\sin\beta + \ddot{Y}\cos\beta - f\text{К}g\cos\beta + f\ddot{Y}_c\sin\beta, \quad (27)$$

$$a_{\tau_3} = \ddot{Y}\cos\beta - Kg\sin\beta - f\text{К}g\cos\beta - f\ddot{Y}_c\sin\beta. \quad (28)$$

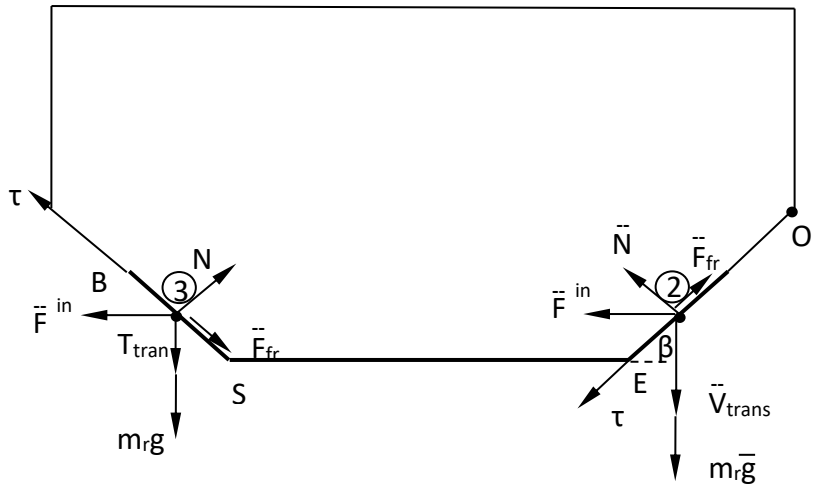



**Fig. 6.** Diagram of forces acting on loading elements with unbalance in left position

Accelerations of details 2 and 3 indicate the following:

1. details located on the right wall are still moving at an accelerated rate because $Kg(\sin\beta - f\cos\beta) + \ddot{Y}_c(\cos\beta + f\sin\beta) > 0$, which is always;
2. details located on the left wall can also move upwards at an accelerated rate only under the following condition: $\ddot{Y}_c > \frac{\text{К}g(\sin\beta + f\cos\beta)}{\cos\beta - f\sin\beta}$, which is unlikely.

In our case, ($\beta = 45°$) $\ddot{Y} < \frac{\text{К}g(1+f)}{1-f}$ but the acceleration of details 3 in this position is less in magnitude than in the right position of the container. The obtained equations of motion of the container loading elements allows us to characterize the movement of details in different sections of the container and, therefore, determine the maximum and minimum productivity of the vibration treatment process.

## Conclusions

Thus, the result of this study was the development of a set of several mathematical models that allow us to consider the dynamics of movement of the environment, taking into account specifics of the object under consideration. It was shown that changing the shape of the container allows for a shift in the direction of flows, thereby increasing the pressure acting on details; it was found that when the flow of loading mass in the container is shifted, adhesion forces are neutralized. It can be used in engineering calculations when predicting metal removal as an indicator of vibration treatment performance, considering that this mathematical model is based on the influence of physical and mechanical parameters on the treatment process.

## CRediT authorship contribution statement

**Viktor I. Bulakov**: conceptualization; **Galina Yu. Burlakova:** conceptualization; **Viktor G. Artiukh**: investigation; **Daria A. Kitaeva**: data curation; **Nikolay V. Korihin**: data curation.

## Conflict of interest

The authors declare that they have no conflict of interest.

## References

1. Tamarkin MA, Tishchenko EE. Improving methodology for designing technological processes for treatment details with free abrasives. *Current Issues in Mechanical Engineering*. 2021;8(1–2): 22–27. (In Russian).
2. Mordovtsev AA. Reliability assessment of the manufacturing process of vibro-abrasive treatment in the conditions of digital production. *Transport Engineering*. 2022;6(6): 21–29.
3. Zhailaubaev DT, Gabbasov EM, Alimuratov AM, Galimov AG. Determination of the effect of oscillations of cutting tools on the accuracy of machining. *Young Scientist*. 2022;12(407): 19–22. (In Russian)
4. Asaev AS, Ivanaysky AV, Averin NV, Volkov DI. Study of finishing abrasive treatment of internal surfaces using the effect of vibration cavitation. *Bulletin of RSATU named after P.A. Solovyov*. 2021;4(59): 57–62. (In Russian)
5. Rechenko D, Kamenov R. Development and Power Calculation of a Grinding Wheel Design for Ultra-High-Speed Grinding. *EPJ Web of Conferences*. 2021;248: 04008.
6. Allagulov VR, Shkalikov EA. Dependence of roughness on cutting modes. *Young Scientist*. 2023;16(463): 12–16. (In Russian)
7. Volosova MA, Stebulyanin MM, Gurin VD, Melnik YA. Influence of Surface Layer Condition of Al2O3+TiC Ceramic Inserts on Quality of Deposited Coatings and Reliability during Hardened Steel Milling. *Coatings*. 2022;12(12): 1801.
8. Krasnitckii SA, Sheinerman AG, Gutkin MYu. Brittle vs ductile fracture behavior in ceramic materials at elevated temperature. *Materials Physics and Mechanics*. 2024;52(2): 82–89.
9. Bolotov AN, Novikova OO, Novikov VV. Effect of loading on tribotechnical characteristics of antifriction diamond-bearing mineral ceramics. *Materials Physics and Mechanics*. 2025;53(2): 104–112.
10. Kutin AA, Kliuev MB, Asaev AS, Averin NV, Kravchenko NYu. Global trends in the machine tool industry. *Russian Engineering Research*. 2023;43(9): 1112–1118.
11. Burlakova GYu, Pichugin NI. Processing of small flat details in U-shaped containers of vibratory machines. In: Babichev AP. (Eds.) *Issues of Vibration Technology*. Rostov-on-Don, Russia: Don State Technical University; 2010. p.141–143. (In Russian)
12. Burlakova GYu, Kozhemyakin VG, Nikolaenko AP. Study of adhesion of small flat details. *Vibrations in Engineering and Technology*. 2010;3(59): 8–15. (In Russian)
13. Mitsik VYa. *Intensification of treatment of details in vibrating tanks with a counter-moving flow of working medium [dissertation]*. Voroshilovgrad; 1986. (In Russian)
14. Provolotsky AE, Lapshin SP, Negrub SL, Laskin VM. Formation of developed microreliefs of surfaces. *Cutting and Tooling in Technological Systems*. 2004;66: 153–162. (In Russian)
15. Babichev AP. (ed.) *Application of vibration technologies in finishing and cleaning operations of details: cleaning, washing, removing flash and burrs, edge processing*. Rostov-on-Don: Publishing Center of DSTU; 2010. (In Russian)
16. Babichev AP. *Fundamentals of Vibration Technology*. 2nd ed., rev. and enl. Rostov-on-Don: Publishing Center of DSTU; 2008. (In Russian)
17. Serga GV, Lebedev VA, Belokur KA, Yakovlev DYa. Improving productivity of technological systems for finishing, cleaning and hardening of details based on screw rotors. *Hardening Technologies and Coatings*. 2016;4(136): 16–19. (In Russian)
18. Babichev AP, Motrenko PD, Ivanov VV. *Vibration mechanochemistry in the process of finishing and hardening coatings of details*. Rostov-on-Don: Publishing Center of DSTU; 2012. (In Russian)
19. Babichev AP, Motrenko PD. *Application of vibration technologies to improve surface quality and performance properties*. Rostov-on-Don: Publishing Center of DSTU; 2006. (In Russian)

20. Babichev AP, Motrenko PD. Vibration technologies in mechanical engineering: application experience and development prospects. In: *Hardening Coatings*. Rostov-on-Don: Publishing Center of DSTU; 2015. p.24–30. (In Russian)
21. Asaev AS, Drozdov PA, Sitnikov IV, Ivanayskiy AV, Averin NV. Finishing treatment of tract surfaces of turboprop blades with free abrasive using vortex cavitation effect. *Mechanical Engineering Technology*. 2024;1: 11–16. (In Russian)
22. Nguyen VT, Tamarkin MA, Solovev AH, Panfilov I. Computer modeling and experimental research of component processing procedure in centrifugal-rotary installation. In: *Advanced Materials: Proceedings of the International Conference on Physics and Mechanics of New Materials and Their Applications, PHENMA 2019*. Cham: Springer; 2020. p.513–528.
23. Tarasovskii VP, Rybal'chenko VV, Kuznetsov VA, Omarov AY, Smirnov AV, Vasin AA, Kornyushin MV, Tomshin VO, Krasnovskii AN, Yurasov SY. Surface machining of corundum-ceramic components by free abrasive. *Russian Engineering Research*. 2020;40(9): 793–796.
24. Melnikova EP, Prokopets GA. Influence of concentration of abrasive filler granules on intensity of vibration treatment process. In: *Promising Directions for Development of Finishing and Hardening Treatment and Vibration Wave Technologies: Collection of papers of a scientific seminar; 28 February 2020;* Rostov-on-Don. Rostov-on-Don: DSTU; 2020. p.124–135. (In Russian)
25. Schetinin VS, Sablin PA. Interaction of spatial oscillation with roughness of surface worked by example of turning. *Bulletin of Bryansk State Technical University*. 2021;1: 4–9.
26. Burlakov VI, Artiukh VG, Kitaeva DA, Korihin NV. Machinability of nitride ceramics with abrasive powders and their addition to diamond powder. *Materials Physics and Mechanics*. 2025;53(4): 99–110.
27. Golobokov AV, Kuznetsov VA, Smirnov AV, Prokopiev AYu. Simulation modeling of the grinding process of instrument bearing blanks made of special corrosion-resistant steels. *STIN*. 2022;S12-2: 28–30. (In Russian)
28. Tamarkin MA, Tishchenko EE, Mordovtsev AA, Kokhanyuk AG. Study of vibration treatment of external and internal surfaces of parts during their preparation for coating. *Strengthening Technologies and Coatings*. 2021;17(1): 22–26.
29. Asaev AS. Study of wear resistance of thread rolling dies subjected to finishing treatment with free abrasive using intensifying cavitation action. *Mechanical Engineering Technology*. 2025;1: 11–15. (In Russian)
30. Piedra-Cascon W, Krishnamurthy VR, Att W, Revilla-Leon M. 3D printing parameters, supporting structures, slicing, and post-processing procedures of vat-polymerization additive manufacturing technologies: A narrative review. *Journal of Dentistry*. 2021;107: 103630.
31. Wang G, Zhou X, Yang X, Zhou H, Chen G. Material removal profile for large mould polishing with coated abrasives. *The International Journal of Advanced Manufacturing Technology*. 2015;80(1–4): 625–635.
32. Burlakova GYu. To solving the problem of processing small automotive parts. *Reporter of the Priazovskyi State Technical University. Section: Technical sciences*. 2013;27: 221–224. (In Russian)