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OPTIMIZATION OF STRUCTURE OF SORTING VIBRATORY SEPARATORS

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Abstract. The problem of substantiation of operational efficiency of vibratory separators designed on the basis of vibratory hopper feeders with electromagnetic vibrations exciters and with conic working bowls is considered in the article. The complex of factors influencing the accuracy and productiveness of separation of coins and disk-shaped products on two or more fractions is overviewed. New models of structures for the effective solution of separation problems are proposed. The design of a highly-efficient and high-performance separator with independent oscillations disturbance is described. The results of experimental investigations of vibratory transportation in elliptical modes of vibrations and of the study of separation efficiency are presented. The recommendations that developers and researchers of such devices may use are given.

Keywords: vibratory separator, sorting, electromagnetic exciter, optimization, bowl, independent disturbance, oscillations, efficiency.

Introduction

During the collection and accounting of coins or counters, it is often necessary to separate their composition into fractions by the face values (diameters). Wide application for this operation was acquired by vibratory separators developed on the basis of vibratory hopper feeders, which are driven by electromagnetic vibrations exciters. These devices may also be used to sort small parts or products in the shape of disks (washers, roundels, etc.). When using such separators for sorting coins, the particular attention is to be paid to the accuracy of sorting.

Problem statement

The existing designs of vibratory devices for sorting disk-shaped parts have low productiveness, as well as a sufficiently large sorting error. In order to improve the process performance and to reduce the sorting error, one needs to change some of the device's elements, and to add new features to their design.

Analysis of modern information sources on the subject of the article

The analysis of literary sources [1; 2; 3] has shown that existing structures of mechanical separators and separators based on vibratory hopper feeders are not able to ensure high accuracy of sorting at high process performance, and also it is impossible to separate a composition consisting of more than two components with a help of them. One of the devices for the separation of such a composition is the device for products sorting [4], which is the vibratory hopper that consists of a vibrations exciter and a bowl, on the lateral surface of which, along the transporting tray, the outlet holes are placed, which have the shape of the parts to be separated. The disadvantages of this device are low performance and low reliability of sorting. The low performance of the device is caused by the fact that the part that moves along the tray of the vibratory feeder should fall through the hole that has the shape of the part. It is possible in this design only at low speeds of transportation (up to 0.1 m/sec). When increasing the speed, the parts of the required sizes do not have enough time to fall through these holes, and are carried forward by the flow of other parts. This leads to the loss of the ability to perform the device's direct function - the sorting of parts. In addition, the parts move along the tray of the vibratory feeder in several layers. This prevents the smaller

parts that are in the upper layer from falling through the holes if there are larger parts that overlap these holes below. This causes the fact that smaller parts are being carried forward by the flow of the parts and have the opportunity to fall through the holes, designed for parts of larger sizes. All this significantly reduces the reliability of the sorting process.

Statement of purpose and problems of research

In order to increase the productivity of the process of sorting the coins composition, to improve the reliability of operation and to enlarge the range of coins sizes, into which the composition of coins is simultaneously divided during sorting, it is necessary to change the design of the bowl of vibratory separator and its separate elements that affect the sorting process. It is also necessary to carry out the work on the improvement of vibratory feeders, which are used for separation.

The main material presentation

One of the most prospective devices for the separation of the composition of coins is a separator made on the basis of a vibratory hopper feeder with an independent drive of the vertical and horizontal oscillations components and with a conic bowl with a helical transporting tray along which the measuring holes of a little bit larger width than the coin of the smallest diameter of the composition are cut. The design diagram of this device is presented in Fig. 1.

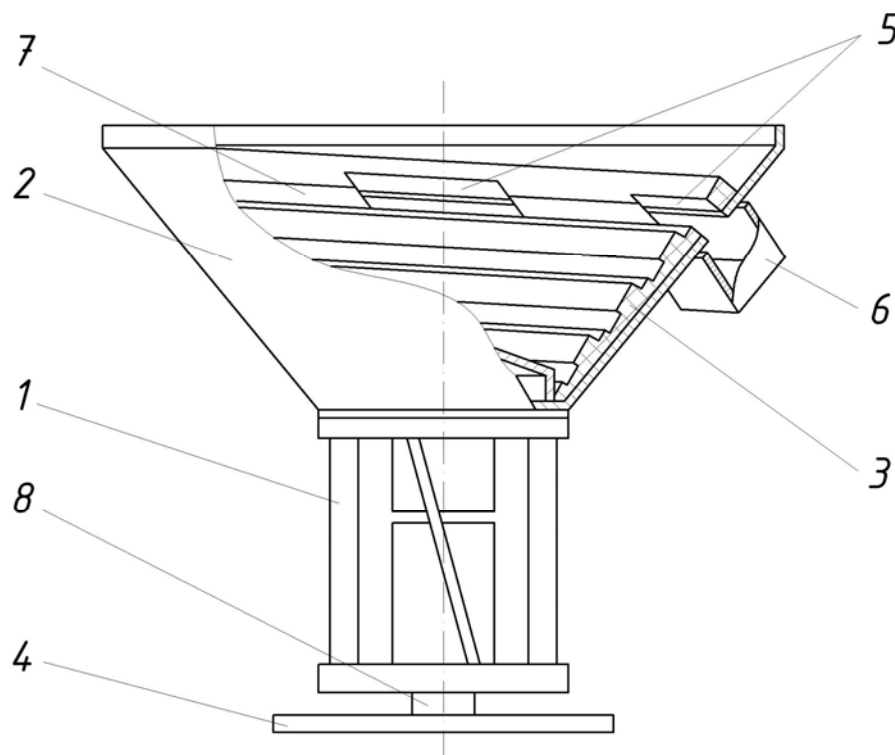


Fig. 1. The design diagram of the vibratory separator

The vibratory separator consists of an electromagnetic drive 1, a conic bowl 2, inside which a rubber working surface 3 is inserted and glued, and of the frame 4. On the surface 3, the helical transporting tray is made. The drive 1 consists of separate independent vibrators excitors of vertical and horizontal components of oscillations. On the lateral surface of the bowl, the measuring holes 5, which are located along the tray, are cut. The number of holes depends on the number of coins face values in the composition. The sidewalls of the holes are made inclined towards the direction of the coins motion. The shape of the measuring holes 5 is shown in Fig. 2. The measuring holes 5 have different height because the lower edge of the holes is lower than the centre of gravity of the smallest coin located on the track and therefore for all windows it is located at the same distance from the support surface of the tray. The upper

edge of each hole, which is intended to drop a certain coin, is made above the top of the coin located on the tray. All holes are arranged along the tray consistently in the course of the coins transportation in the order of increasing the height of their size. From the outside of the bowl 2, in the zone of each of the holes 5, there are discharging trays 6. On the lateral internal surface of the bowl, the hollow 7 equidistant to the supporting surface of the tray is made (Fig. 2). The upper edge of the hollow 7 is made below the upper edge of the smallest coin located on the tray. The shape and location of the hollow 7 is presented in Fig. 4. The drive 1 of the vibratory hopper feeder is placed on the frame 4 using the shock absorber 8 (Fig. 1).

The device operates as follows. When turning on the drive 1 of the vibratory hopper feeder, the cup 2 with the insert 3 is to be oscillating. Due to the directional vibration, the coins of different sizes charged into the cup 2 in bulk are lined up along the tray's surface and are transported upwards along the spiral trajectory. The coins are flatly arranged on the lateral conic surface of the insert 3, and with a help of their edges holds on the supporting plane of the tray. They are arranged on a track in one layer due to the fact that the width of the supporting surface of the tray is made equal to the thickness of the smallest coin. When transporting along the helical tray as the monolayer, the coins pass through the measuring holes 5. After reaching the first hole, the larger coins are to be transported forward, and coins 9 of the smallest diameter fall through the hole 5 of the bowl 2 under the action of gravitational and centrifugal forces and with a help of the corresponding tray 6, are sent to the appropriate container (Fig. 3). Thus, after the first hole on the track, the monolayer of coins of all the following sizes remains unchanged with the exception of the smallest ones. After reaching the coins of the next hole 5, the falling of the next largest fraction of coins takes place. This process is being carried out sequentially in all measuring holes 5, the number of which is equal to the number of fractions of coins to be sorted. Thus, the presented device allows one to sort a composition of coins of different sizes for all the fractions.

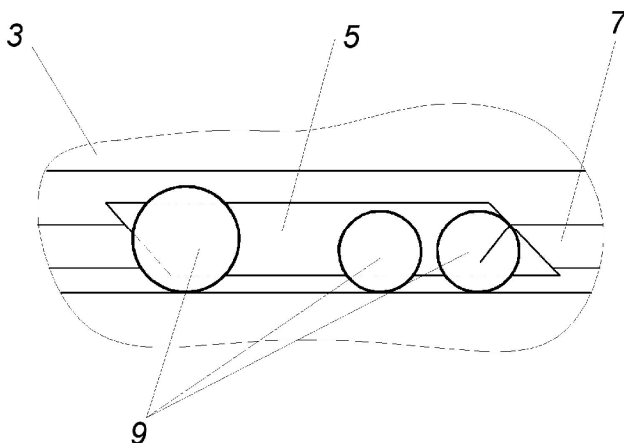


Fig. 2. The configuration of the bowl working surface

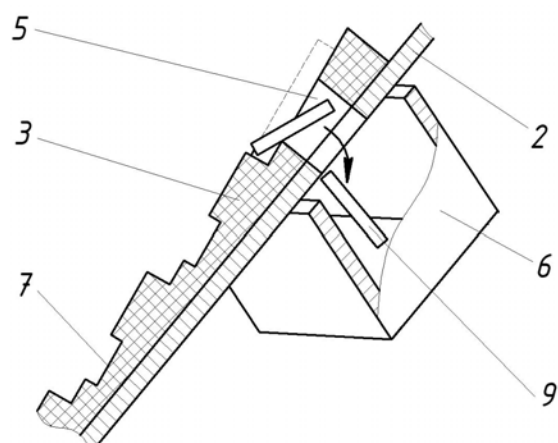


Fig. 3. The diagram of the separation process

Let us consider the position of the coin on the tray of the conic bowl, which does not have a hollow 7 on the lateral surface 3 (Fig. 4, a). The coin is leaning on the helical tray surface by its edge, and the plane of the coin lies on the conic surface of the bowl. Due to the fact that the coin is flat and the surface of the bowl has a certain radius, the surface of the coin can not closely fit to the surface of the bowl. Thus, the coin touches the bowl surface only in two edge points and, therefore, it can rotate around the axis passing through these points at a certain angle, which depends on the distance between the middle of the coin and the surface of the bowl and on the diameter of the coin. Thus, the coin may occupy two utmost positions: the first one (when it is held by the edge points and by the lower edge on the surface of the bowl and, at the same time, by the lower edge on the helical tray) and the second one (when the coin is supported by the edge points and by the upper edge to the surface of the bowl and, at the same time, by the lower edge to the helical tray). Consequently, in the first position, the bottom edge of the coin is closely fit to the surface of the bowl and thus the coin fully rests on the screw tray. This gives a complete guarantee that the coin will not fall from this tray.

In the second position, the upper edge of the coin is closely fit to the surface of the bowl, and the lower edge extends above the surface to a certain value, which may be commensurate with the width of the tray. In this case, this coin runs out of the tray. In the presented device, due to the presence of the hollow 7 (Fig. 4, *b*), the coin 9 is held by its lateral surface on the conic part of the working surface 3 of the bowl 2 in four points. This ensures the coin stability and its unambiguous arrangement in the bowl. This factor contributes to the good filling of the tray with coins, which, in turn, contributes to increasing the productivity of the sorting process. In addition, the stable position of the coin on the surface of the bowl makes it possible to make the width of the supporting bead equal to the thickness of the smallest coin in the composition and to obtain a monolayer row of multi-dimensional products of disc shape on the track. This allows to increase the reliability of the process of coins sorting.

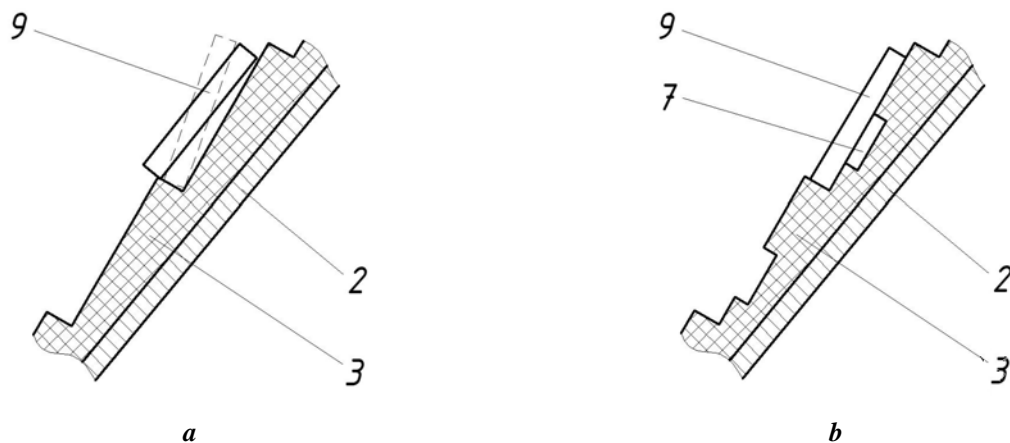


Fig. 4. The possible positions of the coins on the tray

When carrying out the vibratory transportation in the modes with tossing-up, the products do not smoothly move along the tray of the vibratory hopper feeder, but perform the micro-flights relative to the vibratory tray [3]. The magnitude of micro-flights increases with increasing of the amplitude of the vibrations of the tray. Therefore, in order to increase the reliability of coins sorting, the measuring holes have a length that exceeds the value of one micro-flight of the coin to be transported. This eliminates the possibility of overflying of a coin over a measuring hole and ensures the absolute reliability of its falling into the hole designed for this standard size. However, the moment of tearing a coin off the tray and the moment of its touching with the tray are random values. Therefore, there is the possibility of striking of the coin being transported with the lateral wall of the measuring tray at the moment of touching. In this case, in order to make the coin to repulse not chaotically, because of the possibility of its falling into any of the holes and, thus, reducing the reliability of separation, the first in the course of the coins movement wall of the measuring hole is made inclined towards the direction of the coins movement. This gives a guarantee that while touching with this wall, the coin will be thrown down only downward, that is, back to the bowl of the vibratory hopper feeder (Fig. 2), and this allows to obtain a high reliability of the coins sorting.

The working surface of the bowl is made in the form of a conic rubber stocking, inserted into the metal base and fixed with glue. On the working surface, all the elements described earlier are made in order to ensure the coin separation process. During the operation of the device, the internal surface of the bowl gradually wears out due to the friction of the coins that are transported and becomes unfit for further operation. Therefore, the design of the working surface of the bowl with the possibility of removing as a rubber stocking, which is made in a press-mould and is inserted in an all-punched bowl made of sheet material, makes it possible to simplify the design of the device and to increase the durability of its working element.

According to the above-described technology, the vibratory separator with independent oscillation disturbance was developed and manufactured (Fig. 5). The separator consists of the bowl 1 on the internal surface of which the helical tray is made (Fig. 5). The bowl with hoops 3, 5, bottom 4 and barrel 2 form a working mass (m_1), which is attached to the combined elastic system that consists of a central cylindrical

torsion 7, flat springs 6 (forming a torsion "squirrel wheel") and flat compensating springs 14. The intermediate reactive mass 13 (m_2) is attached to the lower part of the torsion 7. In the area of "zero-oscillations" the bulge is made on the central torsion. On this bulge, the hoop 12 for fixing the armatures 8 of the vibrations exciters of horizontal (angular) oscillations with a help of plates 9 is pressed. The plates 9 are attached to the brackets 11, which are the supports for mounting the vibratory feeder on the fixed frame 17 using the rubber dampers 10. The mounting of the feeder with a help of shock absorbers (dampers) and the attachment of the armatures in the area of "zero-oscillations" ensure almost complete vibration isolation of the vibratory feeders, so there is no transfer of vibrations to the frame 17. On the intermediate reactive mass 13, four brackets 23 are mounted, to which four electromagnets 24 of vibrations exciters of horizontal (angular) oscillations are attached. The lower reactive mass 21 is attached to the edges of the flat springs 14, the midpoints of which are fixed to the intermediate mass 13. On the lower reactive mass (m_3), the electromagnet 16 of the vibrations exciter of vertical oscillations is mounted. Its armature 15 is attached to the intermediate mass 13 with a help of bushings 22. The lower reactive mass 21 is mounted on the fixed frame 17 with a help of the rubber damper 20, the stiffness of which may be regulated by the screw. In order to mount the vibratory feeder in a vertical position regulated by the horizontal position of the upper edge of the bowl 1 with a help of the level (gauge), the fixed frame 17 is mounted with a help of supports, the height of which may be regulated by the screws 19.

Thus, the oscillatory system of the separator includes three masses, but, during the operation, for each component of the oscillations only two masses are included. Thus, for horizontal (angular) oscillations, the mass (m_1) is working one, and the reactive mass consists of the lower mass (m_3) and of the intermediate mass (m_2). For the vertical oscillations, the working mass includes the mass (m_1) and the intermediate mass (m_2), and only the lower mass (m_3) is the reactive one. Therefore, the oscillatory system of this vibratory feeder may be considered as two-mass one.

Due to the presence of two independent elastic systems and separate vibrations exciters for vertical and horizontal (angular) oscillations, the vibratory feeder may operate in two modes: in the mode of linear oscillations and in the mode of elliptical oscillation. To operate in the mode of linear oscillations, both vibrations exciters are to be connected to the same phase of the electricity supply network, and in order to ensure elliptical oscillations mode, one vibrations exciter should be connected to the network of "voltage", and the second one should be connected to the network via phase shifter. In addition, due to the fact that horizontal and vertical amplitudes of the oscillations are regulated separately, it is possible to adjust any angles of "throwing" (vibration) and the shape and the inclination of the ellipse on the transporting tray of the bowl.

The vibratory separator operates as follows. When the device is switched on, the armature of the vibrations exciter of vertical oscillations causes the working element to perform vertical oscillations, while the armatures of the vibrations exciter of horizontal (angular) oscillations transmit the impulse forces on the hoop, which forces the central torsion to perform angular oscillations. Due to the kinematic disturbance, the mass m_1 and the reactive masses m_2 and m_3 perform angular antiphase oscillations. When compiling these oscillations, the working element performs helical (spiral) oscillations at a certain angle of "throwing", or elliptical oscillations, if the vibrations exciters are connected via the phase shifter. A composition of parts that are charged into the internal conic bowl are to be transported by the helical tray upwards and, in the holes zones of the bowl, are to be divided into two sizes of standard diameters.

The separator (Fig. 5) was used while carrying out the investigations aimed to determine the optimal parameters of the device operation in elliptical oscillations modes. In the theory of vibratory transportation, the model of transportation of a particle along a rough surface is considered [5]. For a coin moving along the helical path of a hopper feeder, this theory may be also used in the first approximation. The particle of mass m moves along a plane inclined to the horizon at an angle α that performs elliptic oscillations in a fixed coordinate system xyz by the following law:

$$\begin{aligned} x &= A_x \sin(\omega t) ; \\ y &= A_y \sin(\omega t - \epsilon) , \end{aligned} \quad (1)$$

where A_x and A_y are the amplitudes of oscillations in horizontal and vertical planes; e is the angle of phase shift between horizontal (angular) and vertical (normal) oscillations; w is the angular frequency of oscillations ($w = 2\pi n$); n is the number of full oscillations performed per 1 minute; t is time.

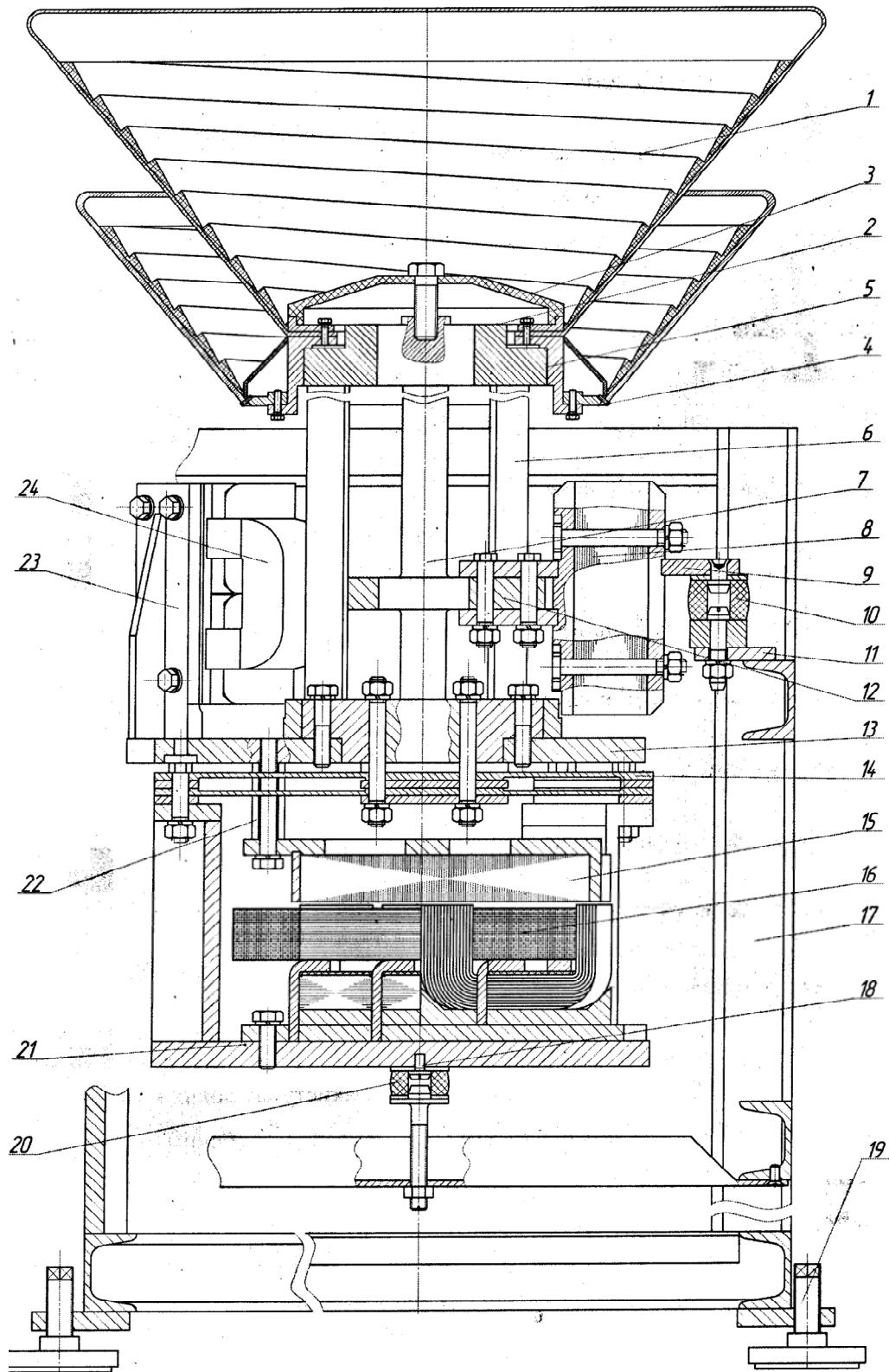


Fig. 5. The general view of the vibratory separator with independent vibrations exciters

Theoretical and practical investigations carried out by researchers and scientists in the works [7; 8] have shown that the parameters, which are expedient to use during high-speed vibratory transportation at frequencies of 25 Hz and 50 Hz, are as follows:

- for 25 Hz: $A_y = 0.35 \dots 0.45$ mm ; $e = 80^\circ \dots 100^\circ$;
- for 50 Hz: $A_y = 0.098 \dots 0.12$ mm ; $e = 75^\circ \dots 95^\circ$.

The amplitude of vertical oscillations in elliptical modes is limited by the mode parameter:

$$W = \frac{A_y \cdot w^2}{g \cdot \cos a}, \quad (2)$$

which shows the ratio between the vertical acceleration of the transporting surface and the free fall acceleration g when there is the inclination of the helical track at an angle a to the horizon.

It is convenient to carry out the research on vibratory transportation of coins in dimensionless quantities. So, let us investigate the dependence of the coefficient of speed k_{uu} while carrying out the vibratory transportation on the parameter of the inclination angle of the helical track k_a , on the vibration angle k_b and on the mode parameter W , taking into account the coefficient of friction f :

$$k_{uu} = \frac{u_{mp}}{A_x \cdot w}; \quad k_a = \frac{tg a}{f}; \quad k_b = \frac{A_x}{A_y \cdot f}. \quad (3)$$

In detachable modes of vibratory transportation for $W \geq 1$, the part (coin) performs flying motion during some period of time. For non-detachable elliptical modes, when $W < 1$, the effective vibratory transportation with significant transporting speeds takes place. Theoretical and experimental investigations are carried out considering that the part and the transporting surface are made of steel and are dry.

In the investigated separators the coin made of brass (duralumin or nickel material) moves on a rubber surface. The coin touches a tray track (groove) and a flat inclined surface of the helical rubber stockings by its ribbed rim (look at description given above). Therefore, the friction significantly affects the optimal parameters of vibratory transportation. These parameters also depends on the state of the coin surface and of the helical rubber stocking.

Considering the works of Krahelskyi I. V. [9], the value of friction coefficient of any frictional couple is usually influenced by a number of parameters (pressure, roughness, surfaces sizes, pollution conditions, etc.), which could not be exactly taken into account. In this regard, the values of friction coefficients presented by different informational sources may be useful only for the partial conditions under which they were obtained. It is clear that the values of the coefficients of friction determined in specific conditions cannot be regarded as unchangeable for a particular frictional couple. Friction constants are difficult to determine, and in most cases it is impossible. The data for coefficients of friction obtained in laboratory conditions widely vary, and therefore their application in the theory of vibratory transportation does not always contribute to obtaining the impartial results.

Taking into account the material presented above, the experimental investigations on coins vibratory transportation with elliptical oscillations of the working element were carried out. On the inclined horizontal plate that could be rotated in a horizontal plane, the conveyor with an independent disturbance of horizontal and vertical components of oscillations was mounted. The amplitudes of oscillations were regulated by the power supply and measured with a help of sensors and double-trace oscilloscope. The phase shift angle was changed with a help of the phase shifter (regulator). The investigated values k_a , k_b and W were ensured by the corresponding values of a , A_y and A_x :

$$a = \arctan(f \cdot k_a), \quad A_y = \frac{W \cdot g \cdot \cos a}{w^2}, \quad A_x = k_b \cdot A_y \cdot f. \quad (4)$$

For the predefined values of k_a , k_b and W , the values of ε were changed from 0° to 180° with a help of the phase shifter and the speed v of coins transportation was measured. The values of speed were

recalculated in dimensionless form k_{uu} . The optimal research results are shown on the diagram of Fig. 6.

The experimental investigations were carried out on the vibratory separator with independent oscillations (Fig. 5) for the composition of coins of various face values. The maximum parameters obtained on the device at frequency $\nu = 50$ Hz and $k_a = 0.03$ are as follows: $e = 86^\circ$, $k_{uu} = 0.68$.

The investigations carried out by Igor Vrublevskiy allow to obtain the dependence for determination of the optimal angle of phase shift, taking into account the coefficient of friction [10]:

$$e = 90^\circ - \frac{50^\circ \cdot A_y}{A_x} \cdot (5 \cdot f - 4 \cdot \tan a). \tag{5}$$

Using the data of the coefficients of friction in the state of rest [11] for brass coins being transported along the rubber tray ($f = 0.7$), for parameters $A_y = 0.1$ mm; $A_x = 3.0$ mm, we obtain the optimal angle of phase shift $e = 86.2^\circ$, which conforms with experimental investigations.

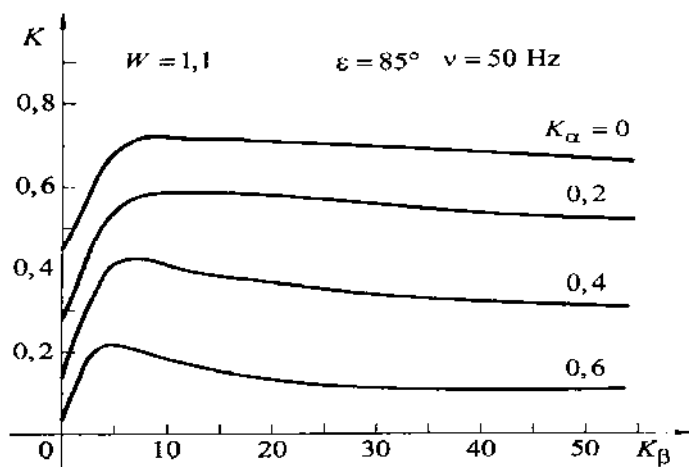


Fig. 6. The plots of investigations of the speed coefficient k_{uu} dependence on the vibration angle b at different values of a

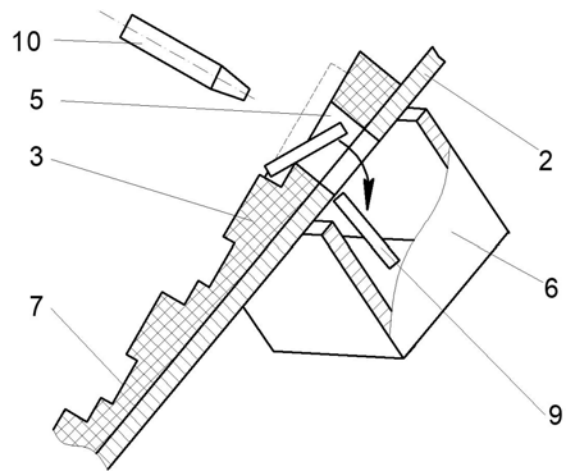


Fig. 7. The improved diagram of the separation process

The authors also carried out experimental studies of the dependence of the separation accuracy on the speed of coins transportation along the tray of the device bowl. The investigations were carried out with two batches of coins, which consist of 1000 coins each. The face values of coins being used during the experiments carrying out were equal to one and two kopecks. Both batches were mixed. The composition of coins was charged into the bowl of the vibratory hopper feeder in bulk, and the separation process was carried out. At the end of the separation process, the number of coins of each face value, which did not fall into their corresponding batches, was determined. Fifty measurements were carried out for each speed of transportation, and the arithmetic mean value of the error index was determined. The results of the investigations are presented in the Table 1.

Analysing the results of the study, it was substantiated that the presented design of the separation device ensures the absolute accuracy of separation at the transportation speed up to 0.5 m/s. The further speed increasing causes the errors of separation. This is due to the fact that coins at such a speed do not have time to fall through the separation holes that have a certain length. Increasing the length of holes leads to reducing of the stiffness of the bowl walls and to the occurrence of parasitic oscillations that worsen the modes of vibratory transportation. In order to improve the process of the coins falling through the separation holes, the pneumatic nozzles 10 were mounted for supplying the compressed air. The location of the nozzle is shown in Fig. 7. Due to the additional aerodynamic forces generated by the action of the airflow upon the coin, the duration of the process of coins falling through the holes is reduced and separation can be carried out at transportation speeds up to 1 m/s. The investigations carried out on such a separator showed that at these speeds, the absolute accuracy of the coins separation was obtained.

Table 1

The results of experimental investigations of coins separation

Speed (m/s)	Number of separated coins of 1-kopeck face value (pieces)	Error of separation of coins of 1-kopeck face value (pieces)	Number of separated coins of 2-kopeck face value (pieces)	Error of separation of coins of 2-kopeck face value (pieces)	Total relative error of separation (%)
0,1	1000	0	1000	0	0
0,2	1000	0	1000	0	0
0,3	1000	0	1000	0	0
0,4	1000	0	1000	0	0
0,5	1000	0	1000	0	0
0,6	999,5	0,5	1000	0	0,05
0,7	999,5	0,5	1000	0	0,05
0,8	999	1	1000	0	0,1
0,9	995	5	1000	0	0,5
1,0	995	5	1000	0	0,5

The scientific and research laboratory (NDL-40) of Lviv Polytechnic National University during a long period of time was carrying out the research in the field of development of highly efficient means of automatic orientation, separation and counting of parts of various types (including coins and disc-shaped parts). The greatest achievement in this field is the development of the complex for automatic processing of coins [12], in many machines of which, the best achievements of the laboratory scientists were applied [13]–[16]. The obtained results and the developed machines are now actual and may be used in various manufactures. In Fig. 8, the photos of the developed equipment for separation of buttons (Fig. 8, *a*) and coins (Fig. 8, *b*) are presented.

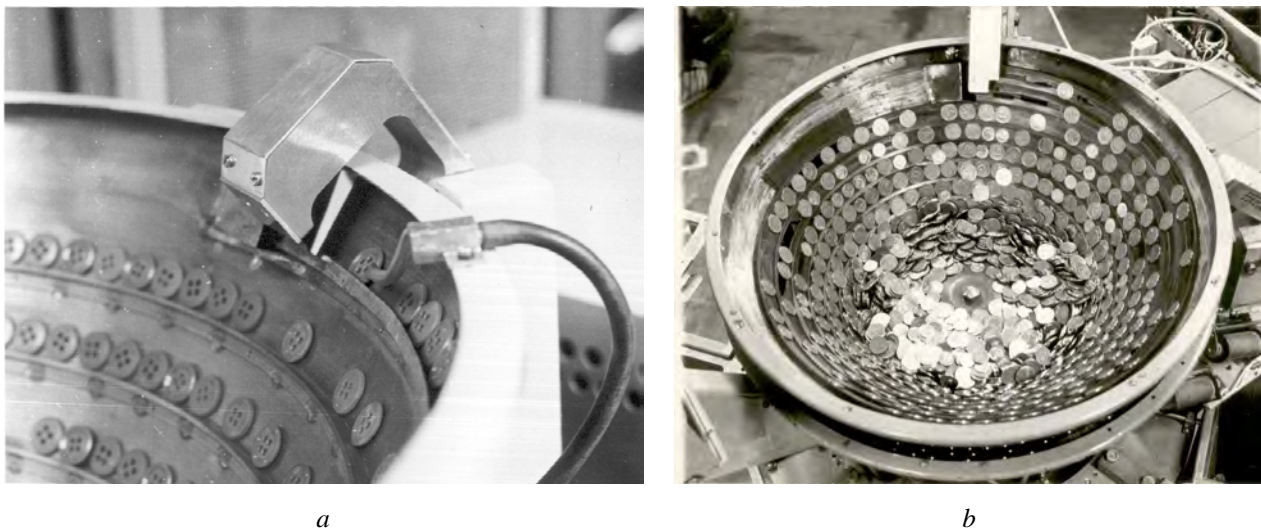


Fig. 8. The photos of the developed equipment for separation of buttons (*a*) and coins (*b*)

Conclusions

Due to the presence of the hollow 7, which is equidistant to the supporting surface having the width equal to the thickness of the smallest coin, on the internal conical surface 3 of the bowl 2 (Fig. 3), the monolayer of coins of various sizes is ensured on the tray. The coins are being transported along the measuring holes 5 and this fact completely excludes the possibility of coins passing past the corresponding measuring holes and thus ensures the absolute accuracy of sorting.

The placement of the measuring holes in order of increasing of their height in the direction of the coins transportation allows to completely separate the composition of coins into all the size fractions, if the

number of holes is equal to the number of the coins fractions sizes.

If there are all the presented above elements in the separating device, it may be used to sort the composition of coins at a linear speed of transportation up to 0.5 m/s ensuring the absolute accuracy of the sorting process. When using the high-speed structures equipped with nozzles for supplying the compressed air, the speed of transportation may be increased up to 1 m/s.

The device with independent vibrations disturbance ensures the high efficiency of separators and may be used both for separation and for counting of products in high-speed modes of transportation (0.5-1 m/s).

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