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Original Study Article

Mathematical model of the cross-section of wheat grain

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ABSTRACT

BACKGROUND: When studying the optimal length of the holes in the lattice bottom of the inclined chamber of a combine harvester, which ensures preliminary separation of the combed grain heap, the cross section of wheat grain was modeled in the shape of a separate ball or a cut cylinder. This is due to the fact that the description of the technological process is significantly simplified with this shape of grain. However, such models of the grain cross-section are very far from the real shape of the object, since the dorsal side of the grains is convex, and there is a longitudinal groove on the ventral side. The kind of surface closest to the real shape of the grain is the Pascal's snail mathematical model. For this model, the centroid coordinates are determined, and equations are obtained for calculating its cross-sectional area and moments of inertia for each coordinate axis. Verification of the obtained equations in the KOMPAS-3D software showed that the discrepancy between the real and theoretically predicted values of the centroid coordinates is about 13%, which reduces the adequacy of the calculations and requires their refinement.

AIM: Refinement of the mathematical model of the cross-section of wheat grain shaped as the Pascal's snail.

METHODS: The object of the study is a cross section of wheat grain shaped as the Pascal's snail. When determining the centroid coordinates, methods of theoretical mechanics were used, and the resulting expressions were verified in the KOMPAS-3D three-dimensional modeling software.

RESULTS: Mathematical expressions for analytical calculation of the centroid coordinates are obtained for different versions of the Pascal's snail: $a = b$ (cardioid), $a < b$ (the Pascal's snail without an internal loop), $a > b$ (the Pascal's snail with an internal loop). Verification of the obtained expressions proves their adequacy, since the convergence of theoretical and experimental data is 100%.

CONCLUSIONS: The use of refined mathematical models of the cross-section of wheat grain can significantly simplify the modeling of the separation process of combed heaps, as well as to increase the accuracy of calculations. To simplify the description of this process, it is advisable to use the KOMPAS-3D three-dimensional modeling software.

Keywords: cross-section of wheat grain; Pascal's snail; cardioid; centroid coordinates; cross-sectional area of grain.

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Оригинальное исследование

Математическая модель поперечного сечения зерна пшеницы

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АННОТАЦИЯ

Обоснование. При исследовании оптимальной длины отверстий решетчатого днища наклонной камеры зерноуборочного комбайна, обеспечивающей предварительную сепарацию очесанного зернового вороха, поперечное сечение зерна пшеницы моделируется отдельно взятым шаром или конечным цилиндром. Последнее обстоятельство обусловлено формой зерновки, которая существенным образом упрощает описание технологического процесса. Однако, подобные модели поперечного сечения зерна весьма далеки от реальной формы объекта, поскольку спинная сторона зерновок выпуклая, а на брюшной стороне имеется продольная бороздка. Наиболее близкой поверхностью к реальной форме зерновки является математическая модель, представляющая собой улитку Паскаля. Для указанной модели определены координаты центра тяжести фигуры и получены уравнения для расчета площади ее поперечного сечения и моментов инерции для каждой из осей координат. Проверка полученных уравнений в программе «КОМПАС-3D» показала, что расхождение между реальными и теоретически предсказанными значениями координат центра тяжести фигуры составляет порядка 13%, что снижает адекватность расчетов и требует их уточнения.

Цель исследований — уточнение математической модели поперечного сечения зерна пшеницы, учитывающей геометрические свойства улитки Паскаля.

Материалы и методы. Объектом исследования является поперечное сечение зерна пшеницы, моделируемое улиткой Паскаля. При определении координат центра тяжести фигуры использовали методы теоретической механики, а проверку полученных выражений осуществляли в системе трехмерного моделирования «КОМПАС-3D».

Результаты. Получены математические выражения для аналитического нахождения координат центров тяжести для различных вариантов улитки Паскаля: $a = b$ (кардиоида), $a < b$ (улитка Паскаля без внутренней петли), $a > b$ (улитка Паскаля содержит внутреннюю петлю). Проверка полученных выражений свидетельствует об их адекватности, поскольку сходимость теоретических и экспериментальных данных составляет 100%.

Заключение. Использование уточненных математических моделей поперечного сечения зерна пшеницы позволяет существенным образом упростить моделирование процесса сепарации очесанного вороха, а также повысить точность расчетов. Для упрощения описания этого процесса целесообразно использовать систему трехмерного моделирования «КОМПАС-3D».

Ключевые слова: поперечное сечение зерна пшеницы; улитка Паскаля; кардиоида; координаты центра тяжести; площадь поперечного сечения зерна.

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BACKGROUND

The requirement for the implementation of new progressive technologies in the harvesting process in the Russian Federation is driven by the constant increase in the production of grain crops in the country. For example, the Ministry of Agriculture predicts that Russia will maintain its leadership in wheat production in 2024 and increase exports to 50 million tons of grain. However, addressing the challenges of reducing labor intensity and energy costs and improving the quality of grain and seeds to the required parameters is currently impossible using traditional combine technologies [1, 2]. The high consumption of fuels and lubricants (up to 7 liters per ton of harvested grain), the rising cost of production (up to 12,000 rubles per ton of grain), and direct and indirect grain losses of up to 30%–50% [3, 4] of the entire harvest require the adoption of modern farming methods.

Numerous studies and production experiences have indicated the possibility of increasing the productivity and energy efficiency of combine harvesters and reducing direct and indirect grain losses through combine combing. A comparative study indicated that using a stripper header instead of a straight-flow header resulted in notable fuel savings (up to 40%) per hectare and an increase in productivity by a factor of 1.3 [5]. However, one of the challenges of this harvesting technology is that the combed heap contains up to 85% free grain, which, when entering the threshing gap, leads to increased crushing (up to 8%) by the working parts of the threshing drum and a decrease in quality indicators [6].

To avoid this issue, it is advisable to perform preliminary separation of the combed heap to remove free grain and directly send the latter for cleaning, bypassing the threshing device. With the current design of a combine harvester, an additional separating device can be placed in the inclined chamber [7, 8]. Theoretical studies exploring the optimal length of the holes in the lattice bottom of a combine harvester's inclined chamber, designed to aid in the preliminary separation of the combed grain heap, modeled the cross section of the wheat grain either as a separate ball or a truncated cylinder [9–11]. This representation of caryopsides considerably simplifies the description of the separation process. However, these models are quite far from the real shape of the grain, as the dorsal side of the caryopsides is convex, and there is a longitudinal groove on the ventral side. Consequently, the difference in the rate of separation of free grain between theoretical and experimental data was found as ~30% [12].

The surface closest to the actual cross-sectional shape of the grain is represented by the mathematical model developed by I.A. Mayatskaya, which is Pascal's snail (Fig. 1) [13, 14]. For these models, the author determined the coordinates of the center of gravity of the figure and derived equations for calculating its cross-sectional area and moments of inertia for each coordinate axis.

Models of the grain cross section were constructed in the KOMPAS-3D program, and the discrepancy between the real and theoretically predicted values of the coordinates of the figure center of gravity was ~13% [12], which reduces the accuracy of the calculations and necessitates further refinement.

STUDY AIM

The study aimed to present the mathematical model of the cross section of a wheat grain, represented in the form of Pascal's snail.

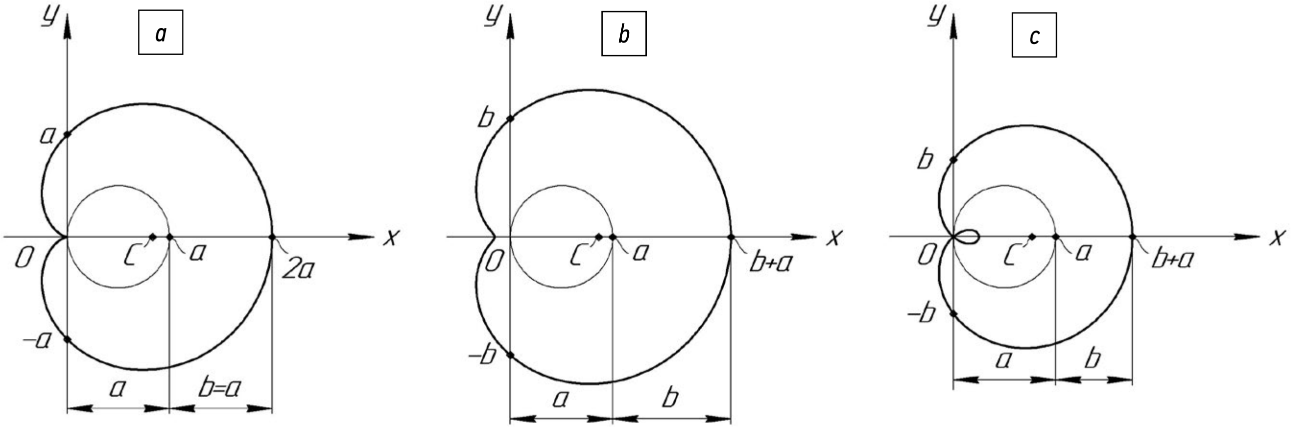


Fig. 1. Special cases of the cross-section of wheat grain shaped as the Pascal's snail: *a*) a = b (cardioid); *b*) a < b (the Pascal's snail without an internal loop); *c*) a > b (the Pascal's snail with an internal loop).

Рис. 1. Частные случаи поперечного сечения зерна пшеницы выполненной в виде улитки Паскаля: *a*) a = b (кардиоида); *b*) a < b (улитка Паскаля без внутренней петли); *c*) a > b (улитка Паскаля содержит внутреннюю петлю).

MATERIALS AND METHODS

The study focused on a cross section of a wheat grain represented in the form of Pascal's snail. The coordinates of the figure center of gravity were determined using methods from theoretical mechanics, and the resulting equations were validated in the three-dimensional modeling system KOMPAS-3D.

RESULTS AND DISCUSSION

Запишем уравнение улитки Паскаля в прямоугольной системе координатах в общем виде [7]

$$(x^2+y^2-a\cdot x)^2-b^2\cdot(x^2+y^2)=0, \qquad (1)$$

where a and b are the geometric parameters of the figure (Fig. 1), and x and y are Cartesian coordinates.

If $a = b$, then Pascal's snail becomes a cardioid. The Pascal's snail equation in polar coordinates (φ; r) ($-\pi \le \varphi \le \pi$) can be represented as follows:

$$r=a\cdot(1+\cos\varphi)\,, \qquad (2)$$

where φ is the polar angle of the radius vector of the current point of the curve..

The center of gravity of the figure bounded by the cardioids, denoted as point C (x_c; y_c) (см. рис. 1, *a*).), is determined (Fig. 1*a*). Owing to the symmetry of the cardioid, $y_c = 0$, only x_c as the abscissa of point C needs to be determined:

$$x_c=\frac{M_y}{S}\,, \qquad (3)$$

where S is the area bounded by the cardioid, and M_y is the static moment of the body bounded by the cardioid relative to the y-axis.

The square S of the figure bounded by the cardioid is determined as follows:

$$\begin{gathered} S=\frac{1}{2}\int_0^{2\cdot\pi} r^2(\varphi)\,d\varphi= \\ =\frac{1}{2}\int_0^{2\cdot\pi}\left[a\cdot(1+\cos\varphi)\right]^2 d\varphi=\frac{3\cdot\pi\cdot a^2}{2}. \end{gathered} \qquad (4)$$

According to its definition, the static moment of a figure is as follows [15]:

$$M_y=\iint\limits_S x\,dx\,dy\,. \qquad (5)$$

The static moment is calculated by transitioning to polar coordinates for the points ($x;\ y$) of the indicated figure

$$\begin{gathered} x=\rho\cos\varphi;\quad y=\rho\sin\varphi;\quad dxdy=\rho\, d\rho d\varphi; \\ -\pi\le\varphi\le\pi;\quad 0\le\rho\le a(1+\cos\varphi). \end{gathered} \qquad (6)$$

Then

$$\begin{gathered} M_y=\iint\limits_S x\,dx\,dy=\iint\limits_S \rho\cos\varphi\cdot\rho\, d\rho d\varphi= \\ =\int_{-\pi}^{\pi}\cos\varphi\, d\varphi\int_0^{a(1+\cos\varphi)}\rho^2 d\rho=\int_{-\pi}^{\pi}\cos\varphi\, d\varphi\cdot\frac{1}{3}\rho^3\Big|_0^{a(1+\cos\varphi)}= \\ =\frac{a^3}{3}\int_{-\pi}^{\pi}(1+\cos\varphi)^3\cos\varphi\, d\varphi=\frac{5\pi}{4}a^3. \end{gathered} \qquad (7)$$

According to Eq. (4) and Eq. (7), from Eq. (3) we obtain:

$$x_c=\frac{5}{6}a\,. \qquad (8)$$

Consider an example in which the diameter of the initial circle a is 20 mm. Then, according to Eq. (8), the center of gravity of the cardioid is located at a distance x_c of 16.67 mm from the origin.

To validate the theoretical studies, a cardioid was constructed using the KOMPAS-3D program (Fig. 2), and the abscissa of the center of gravity of the figure was determined as x_c = 16.67 mm, with its cross-sectional area S = 1884.95 mm^2. The construction results demonstrate the accuracy of the derived equations (4) and (8), as there is 100% agreement between theoretical and experimental data.

By analogy with the cardioid, we determine the position of the center of gravity of the figure bounded by Pascal's snail for the case when $0 < a < b$ (Fig. 1*b*).

The Pascal's snail equation in polar coordinates (φ; r) ($-\pi \le \varphi \le \pi$) has the following form [7]:

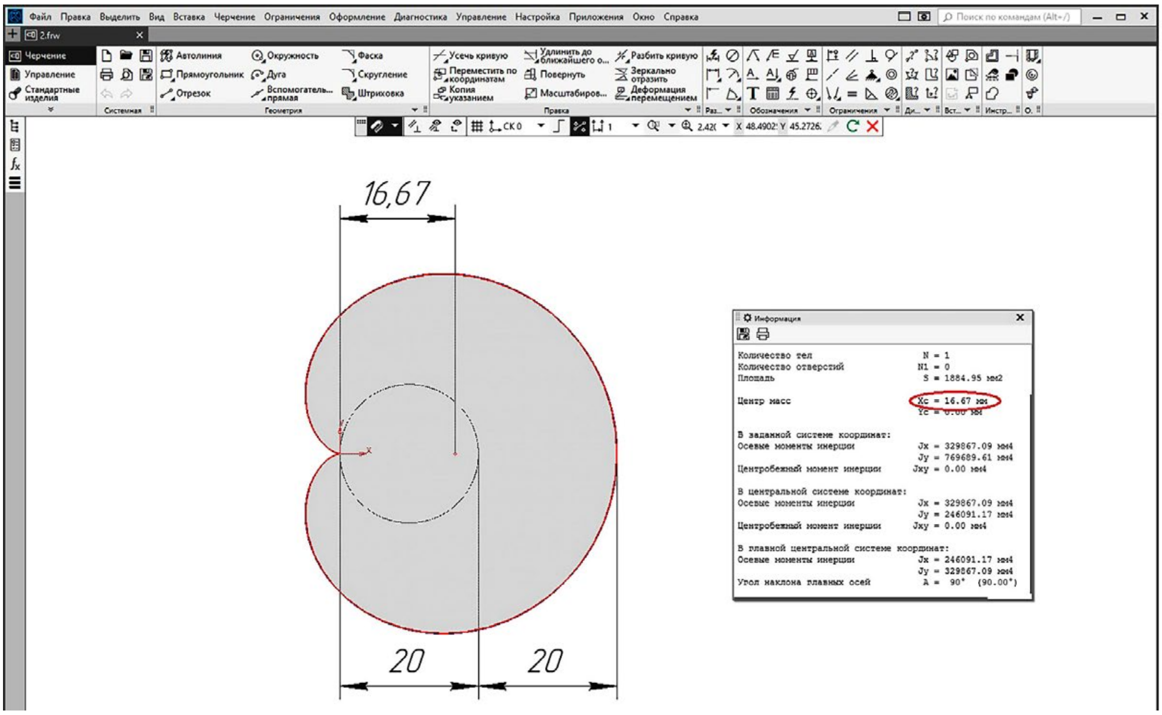
$$r=a\cdot\cos\varphi+b\,. \qquad (9)$$

The area S bounded by Pascal's snail is as follows:

$$\begin{gathered} S=\frac{1}{2}\int_0^{2\cdot\pi} r^2(\varphi)\,d\varphi= \\ =\frac{1}{2}\int_0^{2\cdot\pi}(a\cdot\cos\varphi+b)^2\, d\varphi=\frac{\pi\cdot a^2}{2}+\pi\cdot b^2. \end{gathered} \qquad (10)$$

The static moment of the figure is calculated by transitioning to polar coordinates for the points ($x;\ y$) of the specified figure.

$$\begin{gathered} x=\rho\cos\varphi;\quad y=\rho\sin\varphi;\quad dxdy=\rho\, d\rho d\varphi; \\ -\pi\le\varphi\le\pi;\quad 0\le\rho\le a\cdot\cos\varphi+b. \end{gathered} \qquad (11)$$



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Количество тел                  N = 1
Количество отверстий           N1 = 0
Площадь                         S = 1884.95 мм2

Центр масс                     Xc = 16.67 мм
                               Yc = 0.00 мм

В заданной системе координат:
Осевые моменты инерции         Jx = 329867.09 мм4
                               Jy = 769689.61 мм4
Центробежный момент инерции   Jxy = 0.00 мм4

В центральной системе координат:
Осевые моменты инерции         Jx = 329867.09 мм4
                               Jy = 246091.17 мм4
Центробежный момент инерции   Jxy = 0.00 мм4

В главной центральной системе координат:
Осевые моменты инерции         Jx = 246091.17 мм4
                               Jy = 329867.09 мм4
Угол наклона главных осей       A =  90°  (90.00°)
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Fig. 2. Screenshot of the working window of the KOMPAS-3D software when determining the centroid of the cardioid ($a = b = 20$ mm).
Рис. 2. Скриншот рабочего окна программы «КОМПАС-3D» при определении центра тяжести кардиоиды $a = b = 20$ мм.

Then

$$M_y = \iint\limits_S x dx dy = \iint\limits_S \rho\cos\varphi \cdot \rho\, d\rho d\varphi = \int\limits_{-\pi}^{\pi} \cos\varphi\, d\varphi \int\limits_{0}^{a\cdot\cos\varphi+b} \rho^2 d\rho = \int\limits_{-\pi}^{\pi} \cos\varphi\, d\varphi \cdot \frac{1}{3}\rho^3 \Big|_0^{a\cdot\cos\varphi+b} = \\ = \frac{1}{3}\int\limits_{-\pi}^{\pi} (a\cdot\cos\varphi+b)^3 \cos\varphi\, d\varphi = \frac{\pi\cdot a\cdot(a^2+4\cdot b^2)}{4}. \qquad (12)$$

According to Eq. (10) and Eq. (11), from Eq. (3) we obtain the following:

$$x_c = \frac{a\cdot(a^2+4\cdot b^2)}{2\cdot(a^2+2\cdot b^2)}. \qquad (13)$$

Consider an example in which the studied version of Pascal's snail has the initial parameters of $a = 20$ mm, $b = 30$ mm. Then, according to Eq. (13), the center of gravity of the figure is located at a distance from the origin of coordinates $x_c = 18.18$ mm.

With the same data, Pascal's snail was constructed using the KOMPAS-3D program, and the actual coordinate of the figure center of gravity was determined as $x_c = 18.18$ mm (Fig. 3). The construction results affirm the accuracy of the derived equation (13), with 100% agreement between theoretical and experimental data.

Consider the special case 3, where $0 < b < a$, and Pascal's snail contains an internal loop as illustrated in Fig. 4.

The Pascal's snail equation is presented in polar coordinates (φ; r) [7]:

$$x = r\cdot\cos\varphi, \quad y = r\cdot\sin\varphi. \qquad (14)$$

Then Eq. (1) takes the form:

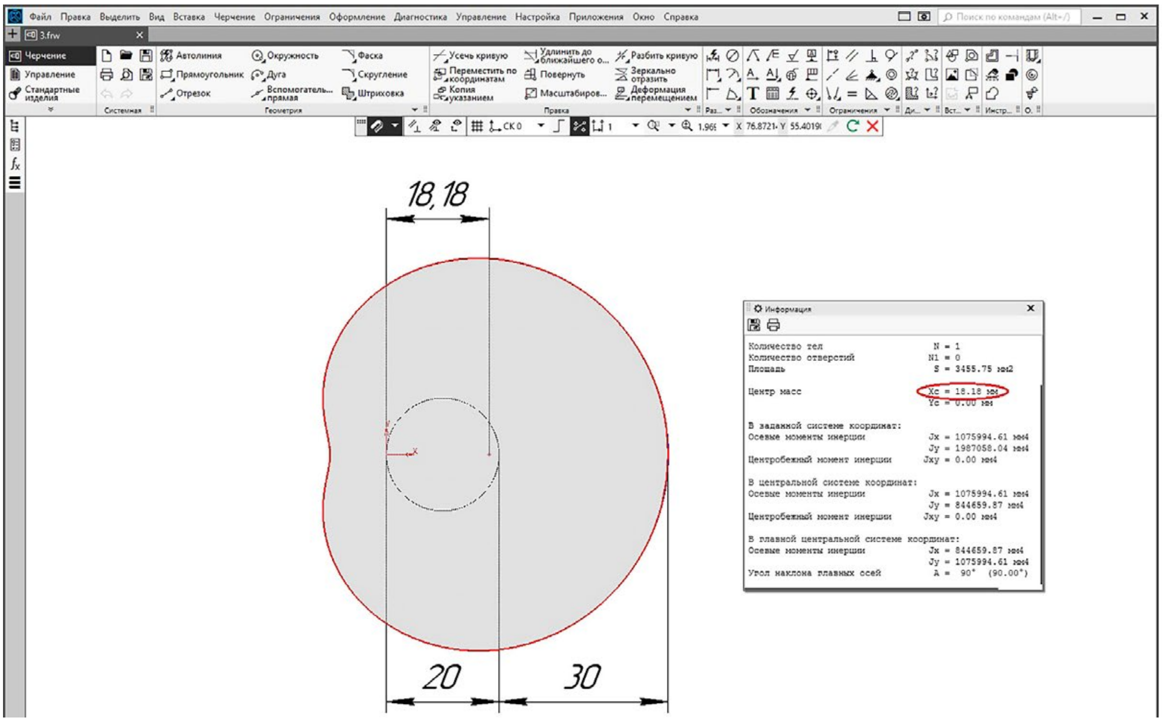
$$(r^2 - a\cdot r\cdot\cos\varphi)^2 - b^2\cdot r^2 = 0, \Rightarrow \\ \Rightarrow \quad r = a\cdot\cos\varphi \pm b. \qquad (15)$$

This equation is analyzed for different signs in front of b. With the (–) sign we obtain the following:

$$r = a\cdot\cos\varphi - b. \qquad (16)$$

With the condition $r \geq 0$, we obtain the following:

$$a\cdot\cos\varphi - b \geq 0 \quad\Rightarrow\quad \cos\varphi \geq \frac{b}{a} \quad\Rightarrow \\ \Rightarrow \quad -\alpha \leq \varphi \leq \alpha, \quad \text{где} \quad \alpha = \arccos\frac{b}{a}. \qquad (17)$$



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Информация
Количество тел                    N = 1
Количество отверстий             N1 = 0
Площадь                           S = 3455.75 мм2

Центр масс                       Xc = 18.18 мм
                                 Yc = 0.00 мм

В заданной системе координат:
Осевые моменты инерции           Jx = 1075994.61 мм4
                                 Jy = 1987058.04 мм4
Центробежный момент инерции     Jxy = 0.00 мм4

В центральной системе координат:
Осевые моменты инерции           Jx = 1075994.61 мм4
                                 Jy = 844659.87 мм4
Центробежный момент инерции     Jxy = 0.00 мм4

В главной центральной системе координат:
Осевые моменты инерции           Jx = 844659.87 мм4
                                 Jy = 1075994.61 мм4
Угол наклона главных осей         A =  90°  (90.00°)
```

Fig. 3. Screenshot of the working window of the KOMPAS-3D software when determining the centroid of the Pascal's snail at $a = 20$ mm and $b = 30$ mm.

Рис. 3. Скриншот рабочего окна программы «КОМПАС-3D» при определении центра тяжести улитки Паскаля при $a = 20$ мм и $b = 30$ мм.

This results in the following:

$$r = a \cdot \cos\varphi - b \quad \left(-\alpha \le \varphi \le \alpha; \quad \alpha = \arccos\frac{b}{a}\right). \tag{18}$$

The equation of the loop in polar coordinates (i.e., Eq. 18) corresponds to Fig. 4.

With the (+) sign in Eq. (15), we obtain (again, subject to $r \ge 0$):

$$r = a \cdot \cos\varphi + b \quad \left(-(\pi - \alpha) \le \varphi \le \pi - \alpha\right). \tag{19}$$

Equation (19) represents the external line of Pascal's snail in polar coordinates.

According to Eqs. (18) and (19), we determine the center of gravity of Pascal's snail. For this purpose, we calculate the area bounded by the figure in the absence of an internal loop:

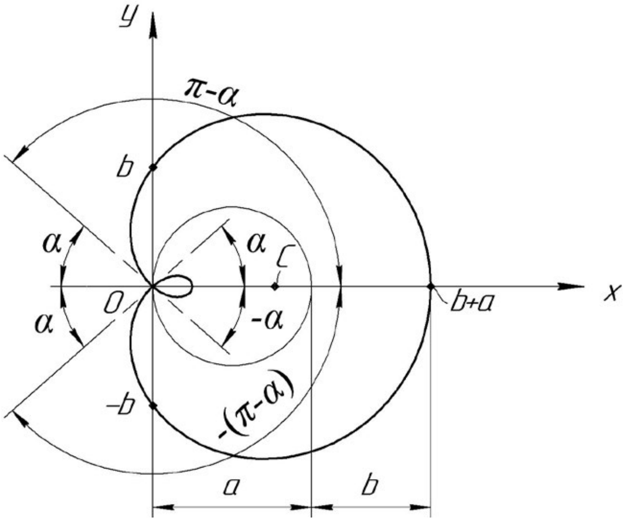


Fig. 4. The Pascal's snail with an internal loop.

Рис. 4. Улитка Паскаля с внутренней петлей.

$$S = \int_{-(\pi-\alpha)}^{\pi-\alpha} d\varphi \int_0^{a\cdot\cos\varphi + b} \rho d\rho = \frac{1}{2}\int_{-(\pi-\alpha)}^{\pi-\alpha} (a \cdot \cos\varphi + b)^2\, d\varphi = \int_0^{\pi-\alpha} (a \cdot \cos\varphi + b)^2\, d\varphi = \left|\alpha = \arccos\frac{b}{a}\right| = \\ = \left(\frac{a^2}{2} + b^2\right) \cdot (\pi - \alpha) + \frac{3}{2} \cdot b \cdot \sqrt{a^2 - b^2}. \tag{20}$$

The static moment is calculated by converting to polar coordinates for the points $(x;\ y)$ of the given figure:

$$x = \rho\cos\varphi; \quad y = \rho\sin\varphi; \quad dxdy = \rho\, d\rho d\varphi; \quad -\pi \le \varphi \le \pi; \quad 0 \le \rho \le a \cdot \cos\varphi + b. \tag{21}$$

Then,

$$M_y=\iint\limits_S xdxdy=\iint\limits_S \rho\cos\varphi\cdot\rho\, d\rho d\varphi=\int\limits_{-(\pi-\alpha)}^{\pi-\alpha}\cos\varphi\, d\varphi\int\limits_0^{a\cdot\cos\varphi+b}\rho^2 d\rho=\int\limits_{-(\pi-\alpha)}^{\pi-\alpha}\cos\varphi\, d\varphi\cdot\frac{1}{3}\rho^3\Bigg|_0^{a\cdot\cos\varphi+b}=$$

$$=\frac{2}{3}\int\limits_0^{\pi-\alpha}(a\cdot\cos\varphi+b)^3\cos\varphi\, d\varphi=\left|\alpha=\arccos\frac{b}{a}\right|=\frac{1}{4}\cdot a\left(a^2+4\cdot b^2\right)(\pi-\alpha)+\frac{1}{12}\cdot\frac{\sqrt{a^2-b^2}}{a}\cdot b\cdot\left(13\cdot a^2+2\cdot b^2\right). \tag{22}$$

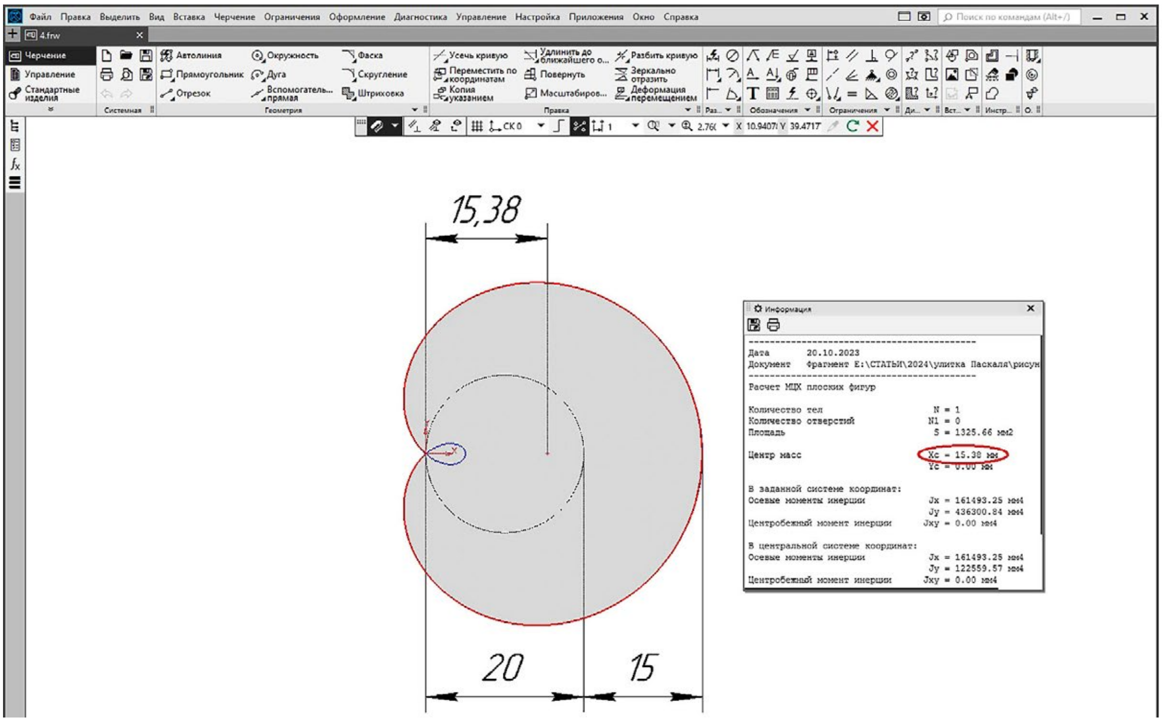
According to Eq. (20) and Eq. (22), from Eq. (3) we obtain:

$$x_c=\frac{\frac{1}{4}\cdot a\left(a^2+4\cdot b^2\right)(\pi-\alpha)+\frac{1}{12}\cdot\frac{\sqrt{a^2-b^2}}{a}\cdot b\cdot\left(13\cdot a^2+2\cdot b^2\right)}{\left(\frac{a^2}{2}+b^2\right)\cdot(\pi-\alpha)+\frac{3}{2}\cdot b\cdot\sqrt{a^2-b^2}}. \tag{23}$$

Consider an example in which the studied version of Pascal's snail has the initial parameters of $a = 20$ mm, $b = 15$ mm. According to Equation (23), the center of gravity of the figure is positioned at a distance of $x_c = 15{,}38$ mm from the origin of the coordinates.

The same version of Pascal's snail is constructed. Using the application package in the KOMPAS-3D three-dimensional modeling system, the actual value of the coordinate of the figure center of gravity was determined as $x_c = 15.38$ mm (Fig. 5). The construction results indicate the accuracy of the derived Eq. (23), with 100% agreement between theoretical and experimental data.

Thus, the utilization of refined mathematical models of the cross section of wheat grain enables increased accuracy in calculating the process of separating combed heaps on the lattice bottom of the inclined chamber of a combine harvester. Moreover, to simplify the description of this process, employing the KOMPAS-3D three-dimensional modeling system is recommended.



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Дата        20.10.2023
Документ    Фрагмент E:\СТАТЬИ\2024\улитка Паскаля\рисун
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Расчет МЦХ плоских фигур

Количество тел                    N = 1
Количество отверстий             N1 = 0
Площадь                           S = 1325.66 мм2

Центр масс                       Xc = 15.38 мм
                                 Yc = 0.00 мм

В заданной системе координат:
Осевые моменты инерции           Jx = 161493.25 мм4
                                 Jy = 436300.84 мм4
Центробежный момент инерции     Jxy = 0.00 мм4

В центральной системе координат:
Осевые моменты инерции           Jx = 161493.25 мм4
                                 Jy = 122559.57 мм4
Центробежный момент инерции     Jxy = 0.00 мм4
```

Fig. 5. Screenshot of the working window of the KOMPAS-3D software when determining the centroid of the Pascal's snail at $a = 20$ mm and $b = 15$ mm.

Рис. 5. Скриншот рабочего окна программы «КОМПАС-3D» при определении центра тяжести улитки Паскаля при $a = 20$ мм и $b = 15$ мм.

CONCLUSIONS

1. During theoretical studies on separation, it is advisable to model the cross section of a wheat grain in the form of Pascal's snail.
2. Mathematical equations are derived for analytically determining the coordinates of the center of gravity for different versions of Pascal's snail: $a = b$ (cardioid), $a < b$ (Pascal's snail without an internal loop), and $a > b$ (Pascal's snail contains an internal loop). The accuracy of the derived equations is demonstrated by the 100% agreement between theoretical and experimental data.
3. The utilization of refined mathematical models of the cross section of wheat grain enables increased accuracy in calculating the separation process of the combed heap on the lattice bottom of a grain combine harvester's inclined chamber. The KOMPAS-3D three-dimensional modeling system should be employed to simplify the description of this process.

ADDITIONAL INFORMATION

Authors' contribution. V.V. Nikitin — analysis of publications on the research topic, writing the text of the manuscript; V.N. Ozhereliev — expert opinion, editing the text of the manuscript, approval of the final version of the manuscript; N.V. Sinyaya — creating figures, editing the text of the manuscript. All authors made a substantial contribution to the conception of the work, acquisition, analysis, interpretation of data for the work, drafting and revising the work, final approval of the version to be published and agree to be accountable for all aspects of the work.

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Вклад авторов. В.В. Никитин — поиск публикаций по теме статьи, написание текста рукописи; В.Н. Ожерельев — экспертная оценка, редактирование текста рукописи, утверждение финальной версии; Н.В. Синяя — создание изображений, редактирование текста рукописи. Авторы подтверждают соответствие своего авторства международным критериям *ICMJE* (все авторы внесли существенный вклад в разработку концепции, проведение исследования и подготовку статьи, прочли и одобрили финальную версию перед публикацией).

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