STUDY OF INFLUENCE OF FINGER WORKING ELEMENT CONFIGURATION ON PROCESS OF CAPTURING STEM MATERIAL

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Abstract. The article presents a methodological approach to revealing the physical essence of the phenomena that occur on the fingers when gripping large piles of hay and straw material, for example, stackers, pile drivers, hay carriers, etc. The finger working elements actually move between the stem material and the field surface along a curved trajectory. To reduce the resistance to movement, they should be manufactured with a certain curvature, which is measured by the bending arrow *h*. Moreover, the bend of the finger axis line should coincide with the arc of a circle described by the end of the rotary lever. A finger with a bending arrow 0.055 m experiences the least resistance, since during the time of its penetration under the stem material the angle of inclination is minimal. The determination of the indicators of the process was carried out on a laboratory installation using measuring and recording equipment. The resistance to finger penetration under material was determined by synchronous registration of measurements with a rheostat sensor. The resistance was measured taking into account the angle of rotation of the fork grip lever. The signals from the sensor were transmitted through the matching unit to the recording device N-388-4. Calibration of the sensor spring was carried out using a sample dynamometer. The instrument system worked on the principle of converting physical quantities into electrical signals. This allowed the use synchronization of parameter measurements, and recording on the recorder tape. Experimental studies confirmed theoretical calculations. The force of resistance to movement of fingers with a diameter of 0.06 m and a sharpening angle of 30 ° was 0.4-1.0 kN. The smallest values of this force were obtained with a bending arrow of the finger axis h_f = 0.05 m. The resistance to penetration of a finger with such curvature under the stem material was 1.2 times lower compared to the straight configuration.

Keywords: stem materials, fork gripper, finger element, process, parameter measurement.

Introduction

Straw of cereals, legumes and similar crops is a by-product of agricultural production. Straw materials are traditionally used in animal husbandry [1-6], in bioenergetics as biofuel [1; 5-11], in crop production to protect the soil from erosion, at enterprises for the production of fruits and vegetables, mushrooms, protein-vitamin yeast, cellulose, methanol, lignin etc. [1; 2; 12].

The collection and storage of thatch materials require up to 70% of labour costs and funds for the collection of the entire biological harvest. To increase the efficiency, it is necessary to improve the methods of collecting straw materials and to develop effective means of mechanization [5; 7].

For rational storage and transportation of straw, rectangular and roll bales with a density of 90-150 $kg \cdot (m^3)^{-1}$ are pressed, formed into a large pile with a density of 40-80 $kg \cdot (m^3)^{-1}$ [2; 3; 5-7]. Such structures are characterized by heterogeneity of the structure and physical and mechanical properties of stem particles. To carry out studies of the processes of interaction of the fork working elements of machines with a set of stems, it is advisable to idealize the structure of these materials. The model will adequately describe the real object with its technological properties. This methodological approach contributes to the reduction of the influence of random factors, the rational determination of the regularities of the course of rheological processes in straw materials [8; 9; 12]. The process of handling a mass of hay and straw material involves penetration of the finger working elements of a fork-type gripping device under the material, followed by lifting it for loading or transportation [6; 9; 12].

The article presents a methodological approach, analysis, and research results regarding the influence of the configuration parameters of the finger working elements, specifically the tip sharpening angle and the bending arrow (height) along the longitudinal axis. Fork-type gripping devices are incorporated into the designs of stackers, pile carriers, hay carriers, and similar equipment. Such technical solutions perform the tasks of gripping, loading, and transporting large masses of loose or compressed hay and straw material [5; 6; 9].

Gripping stacks of stem material by the simultaneous penetration of the fork fingers from the longitudinal sides is the most effective method for self-loading these machines, as it minimizes the risk of displacement or destruction of the stem mass. Comparatively short gripping fingers allow penetration under the stack with reduced resistance, which contributes to a simpler and more efficient design of the technical equipment compared to other devices with similar functions [3; 5; 6; 9; 10].

Materials and methods

Theoretical studies on penetration of finger working elements under a stack of hay and straw material were carried out using the following methods: structural analysis and synthesis of the process; analogies based on the identity of equations describing different phenomena; abstraction of secondary factors; and mathematical modeling. The tasks included minimizing the force required for the working element to penetrate the material by optimizing parameters such as the tip sharpening angle and the longitudinal configuration (curvature) of the finger.

It is known [3; 9], that the condition for material displacement (straw and field surface) along the finger tip can be expressed as:

$$\Omega \leq k_v \left[\frac{\pi}{2} - \max\left(\varphi_s, \varphi_{fs}\right) \right], \tag{1}$$

where Ω – sharpening angle of the tip (cone), in degrees;
k_v – coefficient accounting for the resistance of the tip and the inertia of the straw mass;
max (φ_s, φ_{fs}) – maximum angles of friction of straw and field surface along the finger material, in degrees.

The tip sharpening must ensure reliable operation, minimizing the likelihood of the cone tip wrapping or clogging during penetration. However, condition (1) does not reveal the relationship between the angles Ω, φ_s and φ_{fs} and is unidirectional in nature [6; 9].

The resistance of the finger during penetration under the material was determined by synchronous measurement using a rheostat sensor. Resistance was measured taking into account the rotation angle of the fork grip lever. Signals from the sensor were transmitted through a matching unit to the recording device N-388-4. The spring of the sensor was calibrated using a standard dynamometer. The instrument system operated on the principle of converting non-electrical quantities into electrical signals, which allowed synchronized measurement and recording in the recorder tape.

During the experiments, the resistance of the finger penetrating straw material was determined by synchronous registration of direct repeated measurements with the rheostat sensor (Fig. 1).

a)

b)

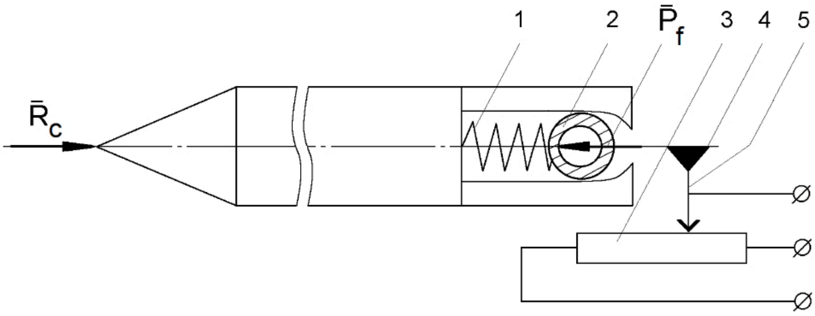

Fig. 1. **Methods for studying the influence of the longitudinal configuration of the finger working element:** a – general view of the curved finger with sensor; b – schematic of the rheostat sensor; 1 – spring, the compression of which corresponds to the resistance force; 2 – bushing of the finger's hinge connection with the drive; 3 – rheostat; 4 – rheostat rod; 5 – rheostat slider

The pre-compressed spring (1) was compressed proportionally to the resistance. One end of the spring was fixed to the finger element, while the other end was connected to a bushing that moved as an intermediate link with the grip beam. A rod (4) attached to the bushing actuated the slider (5) of the variable resistor (rheostat) (3). Resistance was measured taking into account the rotation angle *Q* of the fork grip lever (Fig. 1). Signals from the rheostat sensor were transmitted through the matching unit to the recording device N-388-4 with a measurement error of 0.02 [13].

The measuring and recording instruments (sensors, matching unit, AGAT power supply unit, TOPAZ-3 strain gauge amplifier, N-388-4 recorder) are shown in Fig. 1. Together, they form a system for acquiring, processing, and outputting measurement results. The system operated on the principle of electrical measurement of non-electrical quantities, where different physical quantities were converted into electrically uniform signals [9; 13]. This approach allowed for remote control, synchronization of parameter measurements with an error of 0.05 at various points of the setup, and recording of their variations in the recorder tape.

Results and discussion

A schematic of the movement of the gripping finger with a conical tip at the interface between the straw stack and the field surface was developed (Fig. 2) The criterion for rational design was taken as the minimization of the force R_{cn}, which represents the sum of resistance forces acting on the finger tip from the material.

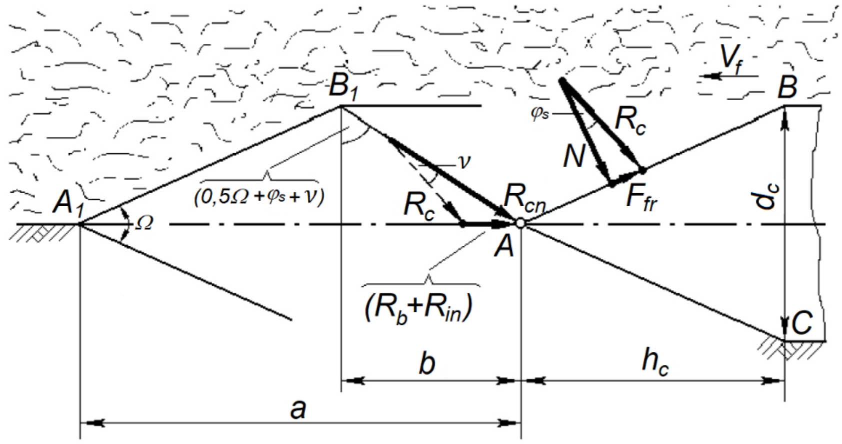

Fig. 2. **Calculation scheme for determining the sharpening angle of the finger tip**

It is assumed that the velocity V_f of the movement of the finger tip *BAC* is constant. In this case, the straw material from point *A* will move along the generatrix *AB* of the cone, as along a lift. The direction of the force R_{cn}, which coincides with the line AB_1 represents the vector sum of the resistance forces, namely: *N* – the normal pressure force, and F_{fr} – the friction force, which together form the resultant force R_c; R_b – the resistance of the tip sharpening; R_{in} – the inertia of the straw mass.

As can be seen from the scheme (Fig. 2), the angle, by its physical nature, determines the coefficient k_ν in condition (1) and characterizes the parameters of the tip sharpening. Additionally, the magnitude of the angle ν accounts for the finger's movement velocity V_f, and the physico-technical properties of the straw material.

During the time of the finger tip *BAC* movement along the path $a = b + h_c$ (Fig. 2), all the material located in front of the cone (triangle BAB_1), will be lifted and compacted above the gripping finger beyond point B_1. At this moment, the straw located in the projection of the triangle AA_1B_1, will move along the generatrix A_1B_1. By determining the parameters of the path $a = b + h_c$ and assuming that the material density is uniform along the entire path of the finger tip, the equation for the resultant force R_c is obtained:

$$R_c = \frac{\pi q_s d_c^2 \cos\dfrac{\Omega}{2}}{2\cos\varphi_s}\left(\mathrm{tg}\left(\frac{\Omega}{2}+\varphi_s\right)+\mathrm{ctg}\frac{\Omega}{2}\right), \tag{2}$$

where q_s – specific pressure of the straw stack on the field surface, N·(m^2)$^{-1}$;
d_c – diameter of the cone base, m.

For the calculation of the force R_{cn}, which is the sum of the forces R_c, R_b, R_{in}, a justified simplification was adopted replacing the effect of the coefficient k_ν with the angle ν. Thus, we have:

$$R_{cn}\frac{\pi q_s d_c^2 \cos\frac{\Omega}{2}}{2\cos(\varphi_s+\nu)}\left(\mathrm{tg}\left(\frac{\Omega}{2}+\varphi_s+\nu\right)+\mathrm{ctg}\frac{\Omega}{2}\right). \quad (3)$$

The function $R_{cn} = f(\Omega)$ has a minimum, which was determined by setting its derivative equal to zero.

Taking into account the likelihood of successful operation at the maximum values of the angles φ_s and ν, as well as the field surface friction angle φ_{fs} along the steel, which varies from 14 ° to 65 ° [8; 9], the final condition for determining the optimal sharpening angle of the finger tip was obtained:

$$\Omega_0 \le \frac{\pi}{2} - \max(\varphi_s, \varphi_{fs}) - \max\nu\,. \quad (4)$$

Based on formulas (3) and (4), the graph $R_{cn} = f(\Omega)$ was constructed, shown in Fig. 3. The following input data were used: q_s = 1,3 kN·(m^2)$^{-1}$; d_c = 0,06 m [9]; φ_s = 25-35 ° [2; 9; 10]; ν = 15 °-25 ° [2; 9; 10]. From the graph, it can be seen that the minimum value of the force R_{cn} is 37 N (curve 1) at φ_s = 25 ° and ν = 15 °, Ω = 55 °. However, according to condition (4), the optimal sharpening angle of the finger tip is determined at the maximum values of the angles φ_s, φ_{fs} and ν. This corresponds to operation under challenging conditions: increased moisture ($W \ge 25\%$) and material density ($\rho \ge 50$ kg·(m³)$^{-1}$); intertwined straw; "heavy" soil, and similar factors. In this case, the dependence is represented by curve 3, where the minimum value of Ω is 31 °. Based on the obtained results, the sharpening angle of the finger tip is taken as Ω = 30 °.

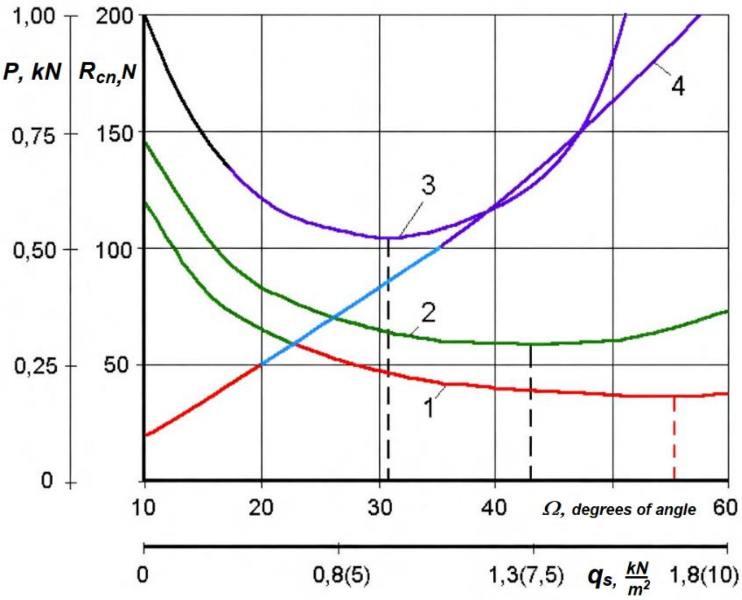

Fig. 3. **Graphical dependencies of the resistance force to the movement of the finger tip $R_{cn} = f(\Omega)$:** 1 – φ_s = 25 °; ν = 15 °; 2 – φ_s = 30 °; ν = 20 °; 3 – φ_s = 35 °; ν = 25 ° and the force P_f required to push the finger, determined from the specific pressure of the stack q_s and the specific resistance of the field surface p_{fs} (4)

For penetration of the finger under the straw stack, the force P_f must exceed the sum of the resistance forces:

$$P_f > R_{cn}^{s} + R_{ci}^{s} + R_{cn}^{fs} + R_{cl}^{fs}\,, \quad (5)$$

where R_{cn}^{s} and R_{cl}^{s} – resistance forces to the movement of the finger tip and the cylindrical (lateral) part of the finger in the straw material, respectively, in newtons, N;
R_{cn}^{fs} and R_{cl}^{fs} – resistance forces to the movement of the cone and cylindrical part of the finger in the soil layer, respectively, in newtons, N.

For the function $P_f = f(q_s, p_f)$ typical input data for field operation conditions of the fork-type gripping device were used: $q_s = (0.8\text{-}1.8)$ kN·(m^2)$^{-1}$; $p_{fs} = (5\text{-}15)$ kN·(m^2)$^{-1}$ [2; 8; 9; 10]. The graph in Fig. 3 (curve 4) shows that the magnitude of the force P_f required to push the finger working element under the stack under typical operating conditions is 0,4-0,8 kN. Under challenging operating conditions, the force P_f exceeds 1 kN. Determining this force allows for a justified selection of the hydraulic drive size and other parameters of the fork-type gripping device.

The movement of the fork grip is carried out using pivoting levers (Fig. 4a), which move along a circular trajectory with the radius R_1. Consequently, the finger working elements also move under the straw stack along a curved trajectory [9].

If the gripping finger is straight, at the initial moment of penetration under the stack, it forms an angle ξ_{max} with the horizontal. As the finger moves forward, the angle ξ decreases, reaching $\xi = 0$ at the end of the process. In Fig. 4b, the penetration of the finger under the straw stack from position CD to position C_1D_1 is shown.

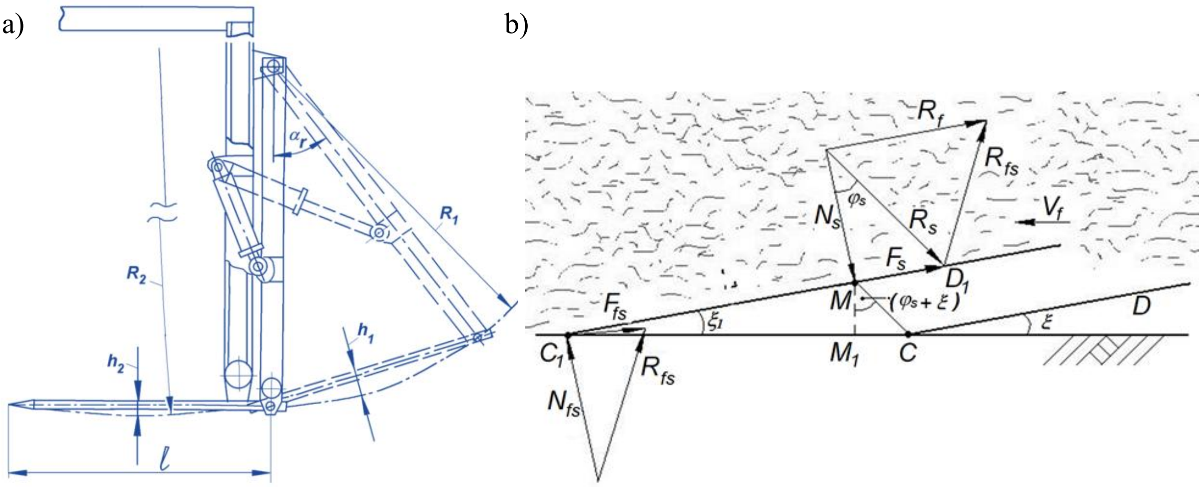

Fig. 4. **Determination of the longitudinal configuration (curvature) of the fork grip finger:**
a – schematic of the technological process of the fork-type gripping device;
b – schematic of the forces acting on the finger working element

The material located at point C, is lifted to point M along the line C_1M (denoted as – c). The distance $CM = m$ can be determined from the triangle CC_1M as:

$$m = \frac{c \cdot \sin \xi_1}{\cos(\xi + \varphi_s)}, \tag{6}$$

where ξ – inclination angle of the finger in position CD, in degrees;
ξ_1 – inclination angle of the finger after it has moved a distance CC_1, in degrees;
φ_s – friction angle of the straw along the finger material (steel), in degrees.

Under the action of the normal pressure force N_s and the friction force F_s the finger experiences a resistance equal to the resultant force R_s (Fig. 4b). As can be seen from the scheme and from expression (6), the larger the angle ξ, the greater the distance m, over which the finger lifts the straw mass, and consequently, the greater the resistance from the stack.

In addition to the straw material, the finger also encounters resistance from the field surface. At point C_1 the forces N_{fs} and F_{fs} act on the finger, with their resultant R_{fs} opposing the finger's movement and tending to lift it. After transferring the vector of the force R_{fs} to point D_1 the resultant resistance force for the penetration of the finger working element under the straw material R_s is obtained.

Based on the analysis, it was determined that to reduce the resistance during penetration under straw material, the finger should have a specific curvature, measured by the bending arrow h. If the bend of the finger's axis line coincides with the arc of the circle described by the pivoting lever R_1 (Fig. 4a), then the height of the segment (bending arrow) is determined by the formula:

$$h = \frac{l_f}{2} \cdot \mathrm{tg}\frac{\alpha_r}{4}, \quad (7)$$

where l_f – length of the finger, in meters;
α_r – rotation angle of the lever, in degrees.

According to calculations (7), it was established that a bending arrow of h_1 = 0.12 m (Fig. 4a) for r_1 = 2.1 m, l_f = 1.6 m, α_r = 35 ° [2; 9; 10] is too large for normal operation during the stack gripping process. With such curvature, the front half of the finger at the end of its penetration under the stack rises above the soil surface by up to 18 °, which increases the resistance force at the end of the process.

Based on subsequent calculations, it was determined that the most acceptable design is a finger whose axis line coincides with the arc of a circle with radius R_2 = 6 m (Fig. 4a). In this case, the bending arrow is h_2 = 0,055 m. A finger with this curvature experiences the least resistance, as the inclination angle ξ remains minimal for the majority of the penetration process under the straw stack.

A four-factor experiment matrix was compiled for laboratory research $P_f = f(q_s, h_f, t_f, W)$. Statistical analysis and calculation of regression coefficients were performed using the computer program "Statistics" [13; 14].

The regression equations describing the change in resistance or P_f force required to push the gripping finger under the straw pile are as follows:

$$P_f = 0.503 - 7.024X_1 + 0.043X_2 + 0.305X_3 + 63.648X_1^2 + 2.341X_1X_4, \quad (8)$$

where X_1, X_2, X_3, X_4 are coded values of factors, respectively:
q_s – specific load on the base of the straw pile, kN·(m^2)$^{-1}$;
h_f – finger con figuration, characterized by the bending arrow, m;
t_f – finger penetration time under the straw, s;
W – material humidity, %.

As can be seen from the graph (Fig. 5), the lowest values of the P_f force occur when the finger bending radius h_f is from 0.045 to 0.065 m.

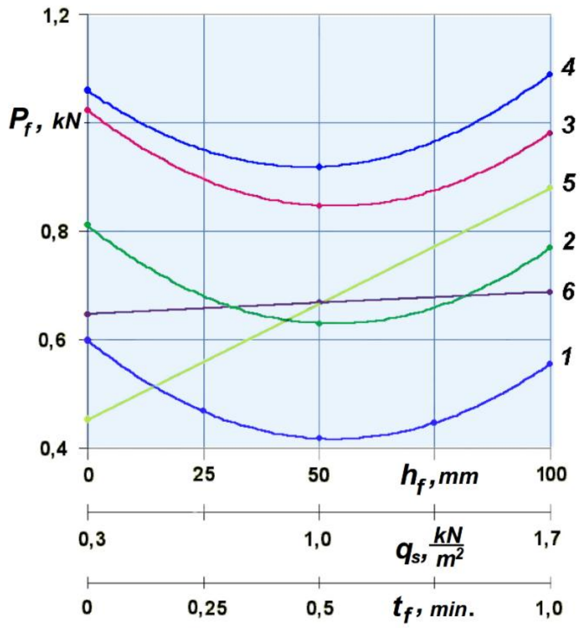

Fig. 5. **Dependence of the force of P_f, necessary for penetration of the gripping finger under the stack, on the bending arrow h_f (1, 2, 3, 4), the specific pressure on the base of the stack q_s (5), the time of movement of the finger under the stack t_f (6)**

Comparison of coefficients with linear factors shows that the change in the resistance force is most influenced by the finger bending h_f (X_1) and the specific pressure on the base of the stack q_s (X_3). The humidity of the straw material as a separate factor (X_4) has little effect on the finger penetration resistance. However, when the "humidity" factor interacts with the "finger bending" factor, increasing the bending leads to a more significant increase in resistance. The significant effects of the interaction of factors X_1X_4 indicate that to determine the resistance when changing one of the factors, the other must be taken into account.

Substituting the values of the secondary factors X_2 (t = 6 s) and X_4 (W = 0.25%) into equation (8), we have:

$$P_f = 0.565 - 7.024X_1 + 0.305X_3 + 63.648X_1^2. \tag{9}$$

The results of the research show that the greatest axial force required to push the finger under the stack in difficult production conditions reaches 1.3 kN. Determining this force allows for a reasonable selection of the power hydraulic cylinder and other mechanisms for driving the fork gripper.

Conclusions

1. Based on the results of theoretical and experimental studies of the straw material gripping process, the significant influence of the configuration parameters of the finger working elements has been demonstrated. The resistance force during the penetration of fingers with a diameter of 0.06 m and an optimal tip sharpening angle of 30 ° ranged from 0.4 to 1.0 kN. The minimum values of this force were obtained with a bending arrow of the finger's longitudinal axis equal to 0,055 m. The resistance to penetration of such a finger under a stack was 1.2 times lower compared to a straight longitudinal configuration and 1.3 times lower compared to a more curved finger (bending arrow - 0.1 m). The finger curvature does not negatively affect the qualitative parameters of the process (losses of straw material).
2. The resistance force of the finger working element penetrating under the straw stack was verified using the strain gauge method. The measured values correspond well with the theoretical data with a confidence level of 0.95 and amount to 0.4-0.8 kN under typical operating conditions and 0.8-1.2 kN under challenging conditions.
3. The obtained values of the force required to insert the gripping finger under a pile of hay and straw material allow us to reasonably determine the kinematic and structural parameters of the fork gripping device.

Author contributions

Conceptualization, O.Y.; methodology, O.Y., MV. and M.T.; software, M.V. and M.T.; validation, O.Y., M.V. and O.T.; formal analysis, M.V., I.A. and S.T.; investigation, O.Y., M.T. and O.T.; data curation, O.Y., M.V., I.A., and M.T.; writing-original draft preparation, M.T.,I.A., O.T. and S.T.; writing-review and editing, M.V., I.A. and S.T.; visualization, O.Y., M.V., O.T. and S.T.; project administration, O.Y. All authors have read and agreed to the published version of the manuscript.

References

[1] Гелетуха Г., Драгнєв С., Кучерук П., Матвєєв Ю. Практичний посібник з використання біомаси в якості палива у муніципальному секторі України (Practical guide to the use of biomass as fuel in the municipal sector of Ukraine). Kyiv: 2017. 72 p. (In Ukrainian). [online] [11.02.2026] Available at: https://uabio.org/wp-content/uploads/2018/01/biofin.pdf
[2] Хайліс Г. А., Федорусь Ю. В. Механіка рослинних матеріалів: навчальний посібник (Mechanics of Plant Materials: A Study Guide). Lutsk: Lutsk State Technical University. 2004. 302 p. (In Ukrainian).
[3] Гайденко О. Технічні рішення для заготівлі соломи (Technical solutions for straw harvesting). Агробізнес Сьогодні. No. 5. 2014. pp. 12-15. (In Ukrainian). https://agro-business.com.ua/agro/mekhanizatsiia-apk/item/1068-tekhnichni-rishennia-dlia-zahotivli-solomy.html
[4] Geletukha G.G., Zhelezna T.A., Drozdova O.I. Comprehensive analysis of energy production technologies from solid biomass in Ukraine. Part 1. Straw. Industrial heat engineering. Volume 35,

No. 3. 2012, pp. 56-63. [online] [11.02.2026] Available at:https://uabio.org/wp-content/uploads/2013/06/complex-analysis-article-zheliezna.pdf

[5] Машини для збирання зернових та технічних культур: посібник (Grain and industrial crop harvesting machines: a guide). Edited by Kravchuk, V.I., Melnyk, Y.F. Research: Pohorily UkrNDIPVT. 2009. 296 p. (In Ukrainian). Available at: http://vthntusg.at.ua/_ld/0/18_zernovi_disk.pdf

[6] Войтюк Д.Г., Гаврилюк Г.Р. Сільськогосподарські машини: підручник (Agricultural machinery: a textbook). Kyiv: Karavela, 2023. 552 p. (In Ukrainian).

[7] Томчук В.В. Управління пожнивними рештками і мульчею (Management of stubble remains and mulch). The scientific heritage. No. 46. P. 2. 2020, pp. 35-45. (In Ukrainian). [online] [11.02.2026] Available at: https://repository.vsau.org/getfile.php/24742.pdf

[8] Piskunova L.E., Yeremenko O.I., Zubok T.O., Serbeniuk H.A., Korzh Z.V. Scientific and methodological aspects of solid biofuel production processes in compliance with labor protection and environmental safety measures. Polityka energetyczna – energy policy Journal. Volume 25. Issue 1. 2022, pp. 143-154. DOI: 10.33223/epj/144008.

[9] Dubrovin V., Yeremenko O., Vygovsky S. Research of process of capture of the stem materials by a forked mechanism. MOTROL Commission of Motorization and Energetics in Agriculture. Lublin. Vol. 15, No. 3, 2013, pp. 20-28.

[10] Yeremenko O., Polishchuk V., Voitiuk V., Tarasenko S., Antypov Ie., Zubok T., Valiev T. Determination of optimum apex angle of cone-shaped part of matrix hole of pelletizer by means of simulating biomass granulation process. Proceedings of 24nd International Scientific Conference “Engineering for Rural Development”, May 21-23, 2025, Jelgava, Latvia, pp. 550-556. DOI: 10.22616/ERDev.2025.24.TF153.

[11] Polishchuk V.M., Shvorov S.A., Zablodskiy M.M., Kucheruk P.P., Davidenko T.S., Dvornyk Ye.O. Effectiveness of Adding Extruded Wheat Straw to Poultry Manure to Increase the Rate of Biogas Yield. Problemele Energeticii regionale. 3 (51)., 2021, pp. 111-124. DOI: 10.52254/1857-0070.2021.3-51.10.

[12] Garfí M., Ferrer M.L., Velo E., Ferrer I. Evaluating benefits of low-cost household digesters for rural Andean communities. Renewable and sustainable energy reviews. Vol. 16. 2012, pp. 575-581. DOI: 10.1016/j.rser.2011.08.023.

[13] Данілов В.Я. Статистична обробка даних: навчальний посібник (Statistical data processing: a tutorial). Kyiv: Taras Shevchenko National University of Kyiv, 2019. 196 p. (In Ukrainian).

[14] Долішня Н.Б., Піндус Н.М. Порівняльний аналіз теоретичних методів статистичної обробки експериментальних даних (Comparative analysis of theoretical methods for statistical processing of experimental data). Mathematical modeling. № 1 (26). Dnipro State Technical University. 2012, pp. 62-65. (In Ukrainian). [online] [11.02.2026] Available at: https://www.dstu.dp.ua/Portal/Data/74/80/15st62-65.pdf