Model of deformation of a feather quill when rolling with a ribbed roller on the flat surface

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Abstract. Mathematical modeling is an effective and cost-effective alternative to a trial physical experiment in solving problems associated with the development of new technologies and equipment. The paper is devoted to modeling the deformation process of a feather quill when rolling by a ribbed roller on a flat surface to form thorough kneading on its concave side, providing additional bending. The technology is used to enhance the Executive ability (“Fill Power” measure) of feather stock of land birds, which are used for manufacturing down-feather products, as an alternative to increasingly scarce and expensive feathers of waterfowl. This is especially true for products with a short service life, intended for use in the rectifying natural disasters and the consequences of accidents.

The developed mathematical model allows us to investigate the dependence of the resistance force of the roller on the design parameters of the working body: the knurling pitch; the angular size of the flute; the diameter of the riffle vertices.

Stresses arising in the structure of the quill under the action of compressive load, when loading and removing the load in an arbitrary cross-section of a feather quill have different values and are described by the corresponding regression models. The solution of the system of regression equations together with the kinematic equations of motion of the working body allows to determine the strength of resistance and power requirement of the deformation of feather quill of land birds to improve the “Fill Power” of feather stock.

The dependence of the total rolling resistance force for the working body and the chicken feather quill of the given parameters obtained on the model is given.

1. Introduction

Environmental problems of modern civilization make us develop technologies that implement full cycles of processing of raw materials. At the enterprises of the poultry industry and at poultry farms the renewable product is feather raw product. The implementation of various production processes makes it possible to use it in the production of consumer goods, including feather-down products [1-4].

Research in the field of technological advancement of processing of feather-down raw materials and development of equipment for manufacturing feather-down products have been carried out by many scientists: B. N. Nikitin, I. S. Mitrofanov, E. V. Gaevoy, L. A. Bekmurzaev, I.Y. Brink, H. Bauer, E. Benz, R. Gurtler, L. H. Lorch, C. Monjarret, etc.

Down and feather of waterfowl is of higher quality, but more expensive at the same time. Feathers of land birds are cheaper, but its use for products is limited due to low quality indicators.

Recent studies [5-8] have shown that the filling capacity of the feather stock of land birds can be increased by 20% by reducing the radius of the quill. The technology of deformation of the quill with a ribbed roller allows to increase the filling capacity (“Fill Power” measure [9]) of feather stock of
land birds for use in the feather-down products, significantly reducing their cost, instead of more expensive raw of waterfowl (see figure 1).

![Figure 1. Filling capacity “Fill Power” measure for different types of feathers.](image)

This is especially important for products with a short service life, intended for use in the rectifying natural disasters and the consequences of accidents.

Various technical solutions are known to increase the “Fill-Power” measure of the feather stock by mechanical deformation [10-19], including those that implement the process of deformation of the feather quill when rolling with a ribbed roller on a flat surface [14-17]. Increasing the efficiency of such devices is achieved by improving the design and is an urgent task. To this end, the paper considers a model of deformation of a bird feather quill when rolling with a ribbed roller on a flat surface.

Mathematical modeling is an effective and cost-effective alternative to the trial physical experiment in solving problems associated with the development of new technologies and equipment. In this case, the law of motion of the working body, the ribbed roller, is known, it is required to find the strength of the deformation resistance of the feather quill during the rolling. The tasks of this type refer to the inverse [20].

### 2. Research materials and methods

The structure of the feather quill in the place of thorough kneading of the working body determines the magnitude of the deformation resistance force.

The structure of poultry feathers was studied in many works, e.g. [1,2,4,21,22]. As we know, the feather consists of keratin, water and fats. Keratin is a typical representative of the class of fibrous proteins with mechanical strength. Sectional shape of the quill changes from a staff to a web from almost round to elliptical. Figure 2 shows the cross-section of the quill in the feather web area, where the bast layer 1 and the core 2 can be distinguished. The bast layer is formed by keratinized flat epithelial and spindle-shaped cells. The core is formed by keratinized cells of various shapes and sizes. These cells are filled with air, so that the resulting porous structure provides a low weight and heat-shielding properties.

To simplify the model of the feather quill, it is advisable to introduce the concept of conditional diameter of a feather $d_n$, mm Parameters in this case will be the diameter of a staff, the length of the feather quill $L_c$, mm, and the polynomial characterizing the change of conditional quill diameter $d_n$ on the length $l_c$

$$d_n(L_c) = a_1 l_c^2 + b_1 l_c + c_1,$$  \hspace{1cm} (1)
where $a_1, b_1, c_1$ – polynomial coefficients;

$l_c$ – the current value of the length of the feather quill, mm.

Figure 2. Structure of the feather quill.

Figure 3, for example, shows the polynomial dependence of the change in the conditional diameter of the chicken feather quill of the average fraction along the length, which is obtained as a result of experimental studies.

Figure 3. Change of the nominal diameter of the chicken feather quill along the length.

As a working body in the node of mechanical deformation, a ribbed roller acts, which carries out making of thorough kneading on the concave surface of the quill to reduce its radius.
The term groove in the technical literature has two meanings. From one hand, it denotes a notch, flute, rifle on any surface.

From another hand, when describing the structural elements of flax processing equipment, the term “flute” means a tooth, a work tool that causes thorough kneading on the flax stem [23].

Numerous design parameters of ribbed roller and their influence on the deformation process of the quill are considered in [7, 8, 24]. The developed model uses the basic parameters: the diameter of the peaks of the flutes, the pitch of fluting, the width of the tops of the flutes, the angular size of the peaks of the flutes, the angle of fluting.

Deformation of feather quills by rolling with the ribbed roller on a flat surface (it is assumed that the surface and the roller are the rigid bodies) occurs in the gap, the size of which must not exceed the admissible value.

Otherwise, there will be a significant destruction of the fibers of the quill. The size of the minimum allowable gap is determined from the experimental diagram of the deformation of the feather quill under compressive loading. Conditional work area of the flute during rolling of the quill is shown in figure 4a. The range of variation of the angle φ is from minus α to γ.

The ribbed roller when rolling rotates with angular velocity ω, knowing its diameter we can define a circumferential speed Vr. The projection of the circumferential speed Vry on the Y-axis characterizes the rate of deformation of the feather quill, and the projection of Vrx on the X-axis characterizes the speed of displacement of the quill on a horizontal surface (see figure 4b). The strain rate of the quill in the process of rolling changes from the maximum value at the point of contact of the quill with the flute of the working body, to zero when an acceptable gap hadd, and depends on frequency of rotation of the roller, its design parameters, dimensions of a feather quill.

Figure 4. The kinematic scheme of rolling a quill:
- a) to determine the degree of deformation;
- b) to determine the rate of deformation

Its value will determine the quality of the process of formation of thorough kneading with local structure disturbance on the concave surface of the feather quill.

The dependence of the gap h, mm, from the angle of rotation of the ribbed roller is determined by the expression

\[ h = \frac{D}{2} \left( 1 + \frac{2h_{add}}{D} - \cos \phi \right), \]  

where \( h_{add} \) - minimum allowable clearance during rolling, mm; \( D \) - diameter of the peaks of the flutes of the roller, mm; \( \phi \) - angle of rotation of the ribbed roller, rad.

The degree of deformation of the quill corresponding to the gap
\[ \varepsilon(\phi) = \frac{d_n - d_{n-1}}{d_n} \left( 1 + \frac{2h_{\text{add}}}{D} \cos \phi \right), \]

The strength of the deformation resistance when rolling the quill for one flute \( F, H \), is determined in accordance with figure 3 by the expression

\[ F = N(\phi)(1 + f) = (1 + f) \frac{n(\phi)S_n}{cosp}, \]

where \( N \) is the normal pressure force of one flute, N;
\( f \) - coefficient of friction of the stem sliding along the surface;
\( n(\phi) \) - normal pressure on the quill when rolling, H/m²;
\( S_n = \frac{d_n}{2} D \int \frac{1}{2} - \frac{1}{2} d\theta - \) the area of the deformation of the flute, mm²;
\( \lambda \) - angular size of the peak of the flute, rad;
\( \theta \) - the current value of the angular size of the peak of the flute, glad.

The normal pressure on the quill of one flute of the roller during rolling \( n(\phi) \) is distributed over the contact surface, the position of which depends on the angle \( \phi \). Assuming that the structure of the quill is uniform, when rolling on a surface, it is possible to accept

\[ n(\phi) = \begin{cases} 
K_\sigma_n(\varepsilon, d_n), & \text{if } -\alpha \leq \phi \leq 0; \\
K_\sigma_n(\varepsilon, d_n), & \text{if } 0 < \phi \leq \gamma; \\
0, & \text{if } \gamma \leq \phi \leq (2\pi - \alpha), 
\end{cases} \]

where \( \sigma_n \) - the stress in the structure of the chicken feather quill under compression, MPa;
\( \varepsilon \) - degree of deformation of the chicken feather quill;
\( \alpha \) - the angle of grasping a feather, rad;
\( \sigma_p \) - voltage in the structure of the feather quill with decreasing compression load, MPa;
\( \gamma \) - the angular size of the zone to reduce the forces of resistance, rad;
\( K \) - the correlation coefficient between static and dynamic stress states during deformation.

The angle of grasping feathers \( \alpha \), rad, depends on the size of the feather quill and is defined by the following expression

\[ \alpha = \frac{\pi}{180} \cdot \arccos \left( 1 + \frac{2(h_{\text{add}} - d_n)}{D} \right). \]

The angular size of the zone of decreasing the resistance of deformation \( \gamma \), rad (see figure 4a) is determined from the experimental dependence of residual deformation of the quill \( \delta \) from the nominal size of the feather in contact with a flute [25] from the expression

\[ \gamma = \frac{\pi}{180} \cdot \arccos \left( 1 + \frac{2(h_{\text{add}} - d_n(1 - \delta))}{D} \right). \]

A feather quill of medium fraction has a length \( L_c \) from 27 to 75 mm. Therefore, for roller of diameter from 30 to 90 mm with a pitch of corrugations from 2 to 4 mm rolling of feathers will be less than one turn. The number of flutes of the roller \( M \) involved in the rolling process of one quill determines its length

\[ M = \frac{2L_c}{D \cdot \psi}, \]

where \( \psi \) is the angular pitch of the rolling of the roller, rad.

The rolling resistance force for each of the \( M \) flutes \( F_i \), H, can be calculated using the expression (3-7) and the parameters of the model of the feather quill can be calculated by piecewise linear approximation.

The resulting rolling resistance force \( \Sigma F, H \), is defined as the sum of the resistance forces of each flute taking into account their shift by the corresponding angle multiple of the rolling step \( \psi \)

\[ \Sigma F = \sum_{i=1}^{M} F_i. \]

This approach allows us to investigate the process of rolling of a feather quill with a known law of change in the conditional diameter along the length without the use of specialized software.

Figure 5 shows the dependence of total force of resistance to the rolling from the angle of the ribbed roller constructed by the graphic-analytical method using a standard package of computer
programs. As a model of the feather quill we used with polynomial dependence (1) characterizing the change of the conditional diameter of the stem along the length, the coefficients: $a_1=0.0002; b_1=-0.04; c_1=1.8231$.

![Figure 5. Dependence of the resultant resistance force on the angle of rotation of the roller](image)

Figure 5. Dependence of the resultant resistance force on the angle of rotation of the roller

The following design parameters of the roller were taken: $D=30$ mm; $\lambda = 0.02$ rad; $\psi = 0.195$ rad. To determine the stresses in the structure of the chicken feather quill under compression and reduction of the compressive load, the experimental dependences given in [25] were used.

3. Conclusion

The mathematical model of deformation of a feather quill when rolling with a ribbed roller on the surface allows to study the dependence of the resistance force to rolling from structural parameters of the working body; knurling pitch, the angular size of the flutes; the diameter of the peaks of flutes. Stresses arising in the structure of a quill under the action of compressive load, under loading and unloading in an arbitrary section of a quill have different values and are described by the corresponding regression models. The solution of the system of regression equations together with the kinematic equations of motion of the working body allows to determine the resistance force and the required deformation power of a quill of a land bird to increase the index of “Fill Power” of the feather stock.

In the framework of further studies of the problem discussed in the paper, it is planned to improve:
- the methodology for the analysis of the stress state of the feather quill of land birds, to clarify the correlation between the stresses of the deformed structure of static and dynamic nature;
- the model of the feather quill.

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