Advance of spindle drum and frontality of active spindle surface

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Abstract. Harvesting machines of modern cotton pickers are equipped with spindle drums, making rotational movements against the direction of machine motion. To ensure the natural position of the bushes with bolls in the working area of the vertical spindle apparatus, the linear speeds of the spindle centers on the drums advance the speed of the machine. The aim of the paper is to develop a methodology for calculating the lead coefficient depending on the parameters of the drum, spindle, its activity, and frontal location, where the active surface of the spindle should be located opposite the cotton plant. Specific recommendations are given for calculating the operating modes of a cotton picker.

1. Introduction
The bulk of the ripened cotton crop is currently harvested with spindle cotton pickers. Depending on the design of the harvesters, the technology of mechanized cotton picking from open cotton bolls is carried out by overhung spindles horizontally located in the cassettes (volumetric processing of bushes) [1-10] or by vertical spindles located on the periphery of a cylindrical drum (flat processing from the side of the bushes) [10-18]. Spindle drums are vertically mounted, attached to the frame of the harvester, and rotate in conjunction with vertical spindles or cassettes with horizontal spindles. The drum rotation is directed against the motion of the cotton picker along the rows of cotton. The movements of machine and drums with spindles are closely interconnected, and for horizontally spindle units they are synchronized with each other [10,11]. In pickers with vertical-spindle harvesting units, the spindle drums must be ahead of the machine in order not to damage the cotton plant. The leading is characterized by the following ratio [13-20]:

\[ k = \frac{U}{V} \]  

(1)

Where: \( k \) is the lead coefficient; \( U \) is the linear speed of the point on the drum along the circumference of spindle arrangement, defined as \( U = R\omega \), m/s (\( R \) is the radius of the circumference of the drum at the centers of spindles, \( \omega \) is the frequency of drum rotation of the drum, s⁻¹); \( V \) is the speed of the cotton picker, m/s.

The simplicity of design, low material consumption and labor coefficient in manufacturing, ease of use, and energy efficiency (when compared to horizontal spindle machines) made possible wide manufacture of machines with vertical spindle units, as well as to conduct the detailed studies to substantiate their parameters. The influence of drum lead on the kinematics and dynamics of the
cotton-picking process has been studied in [13, 17, 18, 19, 20, 21, 22, 23]. Here we dwell on those studies in which the kinematics of the motion of spindles, drums, and the machine is studied in detail from the point of view of optimizing the cotton-picking technology.

In modern vertical-spindle semi-hinged cotton pickers of MX-1.8, MX-2.4 type due to the rigid kinematic connection between the tractor and the cotton picker, the choice of a necessary lead of spindle drums remains an urgent task in agro-technical and technical-economic areas.

In this direction, the research conducted in our republic is in great demand. The studies on vertical spindle machines in recent years have been carried out in Russia, Turkey, Argentina [16].

2. Methods
The kinematics of the rotary and planetary mechanism on a mobile basis is the basis for theoretical research for determining the coefficient of the drum of the cotton-harvesting machine. The technology of cotton assembly from open boxes dictated the determination of instantaneous centers of rotation of the drum spindle in the cotton collection zone and the development of generalized methods for calculating the outrunning coefficient.

3. Results and discussion
M.V.Sablikov was the first who used high-speed filming to study fast-moving technological processes in horizontal and vertical-spindle harvesting machines and came to the conclusion that only within certain limits of change in absolute velocity vector of the spindle tooth apex it is possible to capture cotton from a cotton boll [13]. As a result, he formulated the so-called “theory of activity” - the coincidence in direction of the wedge-shaped tooth of the spindle and the vector of absolute speed of its vertex within certain angles (β1, β2) related to the tooth geometry and the cotton friction between its faces. Having plotted the diagrams of active parts of the spindles surfaces on a drum, he found out that: “... the magnitude of the active part of spindle surface in a particular working (harvesting) unit depends only on the magnitude of the speed W equal to the geometrical sum of the peripheral speed of the drum and the speed of machine; with a decrease in W the active part of the surface increases”. He determined this speed as follows [13]:

$$W = V_{zp} \sqrt{k^2 - 2k \sin \omega t + 1}$$  \hspace{1cm} (2)

where $W$ - is the absolute peripheral speed of the spindle center on the drum, m/s;

$k$ - is the drum lead coefficient determined from expression (1);

$\omega t$ - is the angle of drum rotation in the working area of the unit or the angle between the longitudinal axis of the cotton row and the radius indicating the spindle position on the drum, degrees;

$t$ - current time, s.

Summarizing theoretical and well-known experimental studies, he has recommended choosing in the future investigations the lead in the processes equal to $k = 1.2 ... 1.5$.

However, the proposed methodology for determining “k” does not include the geometry of the spindle teeth and their location in the area of pressing against the cotton bolls in the harvester.

In the studies carried out by I.Kh.Fayziev and O.S.Jabbar this problem was solved by determining the instantaneous centers of rotation of the drum and spindles based on the known methods of mechanics [19, 20].

So, O.S.Jabbar, when determining the drum lead coefficient and machine speed, has proposed two approaches [20]. In the first approach, at a given position of the spindle center in the working chamber of the harvesting unit, the lead coefficient is calculated by the formula

$$k \geq \frac{2R}{L - B}$$  \hspace{1cm} (3)

where $L$ is the distance between the centers of rotation axes of the paired drums, m; $B$ is the width of the input part of the harvesting unit, m.

The latter is defined as
\[ B = L - 2R \cos \theta \] (4)

Where: \( \theta \) is the angle of entry of the spindle into the working area (at a steady-state rotation of the spindle in the working chamber), i.e. the angle between the radius of the drum, determining the entry of the spindle into the working area and the axis perpendicular to the cotton row axis. Calculation of the angle \( \theta \) is based on the perpendicular direction of the velocity vector \( \mathbf{W} \) (its module determined by the formula (2)), to the axis of cotton sowing. According to the design of harvesting unit and the physical process of entering the working area, the angles \( \theta \) according to formula (4) and \( \varphi_b \) (and according to O.Jabbar \( \theta=90^\circ - \varphi_b \)) have different values; besides, when calculating "B" in [20] a significant error was made - the distance between the spindle center on the drum and the axis of cotton plants sowing was not taken into account (this is the spindle radius and the width of the working gap).

The second approach proposed by O.Jabbar is associated with determining the position of the instantaneous center of rotation (ICR) of the spindle in absolute motion, determined [20] as:

\[ \rho = \frac{\omega R}{\omega_b + \omega} \sqrt{1 + \frac{1}{k^2} - \frac{2 \cos \alpha_b}{k}} \] (5)

where \( \omega_b \) is the spindle speed around its axis, s-1;
the “+” sign for an epicycle spindle drive, “-” for a hypo cyclic spindle drive; \( \alpha_b \) is the angle of drum rotation relative to the axis perpendicular to the sowing cotton axis or \( \alpha_b = 90^\circ - \varphi_b \) in formula (2), degree.

Based on the studies by M.V.Sablikov [13], to ensure the frontal location of the active part of the spindle surface in the working area of the harvesting unit, O.S.Jabbar proposed the conditions [20]:

\[ \rho_1 \leq r \sin \beta_1 \] (6)
\[ \rho_2 \leq r \sin \beta_2 \] (7)

where \( r \) is the spindle radius, m;
\( \beta_1 \) is the angle between the tangent to the circumference of the spindle section at the tooth top and the line characterizing external boundaries of activity, \( \beta_1 = 90^\circ - \varphi t \), degree;
\( \beta_2 \) is the angle between the inner face of the tooth and the line characterizing the internal boundaries of the spindle activity, \( \beta_2 = 90^\circ - (\alpha_3 + \varphi t) \), degree;
\( \varphi t \) is the angle of friction of cotton with the tooth material, \( \varphi t = \arctg f \), \( f \) is the coefficient of friction), degree.

According to the theory of activity, the sum of the angle \( \beta_1 \) and \( \beta_2 \) is

\[ \beta_1 + \beta_2 = 2\delta \] (8)

where \( 2\delta \) is the angle of tooth activity (the angle between the external and internal boundaries of tooth activity).

A more simplified expression for calculating the ICR is given by I.Kh.Fayziev [19]:

\[ OC = \frac{r_n}{k} \sqrt{k^2 + 1 - 2k \cos \alpha_b} \] (9)

where \( OC \) is the distance between the geometrical center of the spindle and the instantaneous center of rotation of the spindle at absolute motion, m;
\( r_n \) is the rolling radius of the roller along the drive belt, m.

Here, as was said above, \( \alpha_b = 90^\circ - \varphi_b \).

Substituting inequalities (6) and (7) into the left side of formula (9), which ensures the frontal position of the active part of spindle surface, the equation is solved for the drum lead coefficient in the form

\[ r_n^2 \left( k^2 - 2k \cos \alpha_b + 1 \right) \leq k^2 r^2 \sin^2 \beta \] (10)

Inequality (10) can be transformed concerning “k” to the form
The solution to this quadratic equation is known from mathematics

\[ k_{1,2} = \frac{\cos \alpha_b + \sqrt{\cos^2 \alpha_b - \frac{1}{C^2}}}{C} \]

Where: \( C = 1 - \frac{r^2}{r_k^2} \sin^2 \beta \)

The resulting equation (12) includes the geometrical and kinematic parameters of the vertical-spindle harvesting unit, namely: \( R \) is the radius of the spindle drum at the spindle centers, \( \alpha_b = 90^\circ - \varphi_b \) is the angle of drum rotation, \( r \) is the radius of the spindle, and \( r_k \) is the rolling radius of the spindle roller, defined as \( r_k = R_i/\omega_{sh} \) or \( r_k = R/(i + 1) \), \( i \) is the gear ratio between the spindle and drum rotational frequencies, the \( \beta \) – the angle that characterizes the position of the active part of the spindle surface in the zone of interaction with the cotton bolls. This allows predicting the changes in the lead in each active and frontal position of the spindle in the working area of the harvester.

As already mentioned above, in [13, 14, 16, 19, 20], for the accepted conditions, the recommendations were given to choose “\( k \)” for specific types of cotton-picking machines. From the experience of those studies, we are interested in the question: how high should be the lead at the steady-state rotation of the spindle under condition \( \cos \alpha_b = k - 1 \). Substituting this condition into (12) we obtain

\[ k_{1,2} = \pm \sqrt{\frac{1}{1 - \frac{r^2}{r_k^2} \sin^2 \beta}} \]

In formula (13) we are interested only in the “+” sign because by physical nature, the passage of the cotton plant in the apparatus in its natural state is ensured within certain limits only when the spindle drums are leading. Also, for the harvester to function following agro-technical and technical and economic requirements, the denominator in formula (13) must be greater than zero. This is ensured by a rational choice of spindle parameters \( R, r, r_k, \beta, \omega, \omega_{sh} \). The expressions to determine the drum lead coefficient in general (12) and in particular (13) forms allow reasonable selection of geometrical and kinematic parameters at the design stage of cotton pickers following the established requirements; evaluation of existing machines operation and prediction of the performance of promising machines with spindle harvesting units.

As an example, we have analyzed the parameters of existing vertical-spindle machines of the MX-1.8 and MX-2.4 types, manufactured by the Tashkent Agricultural Engineering Plant.

According to the technical specifications for the MX-1.8 machine: the first working speed is 4.13 km/h, the drum rotation frequency is 118 min\(^{-1}\) or \( \omega = 12.35 \text{s}^{-1} \), the radius of the spindle drum is \( R = 0.146 \text{ m} \), and the radius of the spindle is 14 mm, gear ratio with hypo cyclic spindle drive in the working area is \( i = 11.6 \), spindle tooth sharpening angle is 50°, cotton friction angle with spindle material is 20°.

For these initial data, in accordance with formula (1), the drum lead coefficient is \( k = 0.146 \cdot 12.35/1.147 = 1.57 \), and at this, the value of “\( k \)”, the spindle angle of entry into the working area of the machine, is equal to \( \alpha_c = \arccos \frac{1}{k} = 50^\circ 27' \) or \( \varphi_b = 90^\circ - 50^\circ 27' = 39^\circ 33' \). The width of the input part of the working chamber of the harvesting apparatus at a working gap of 30 mm is equal to \( B = 2R \cos \alpha_c + 2r + b_{sh} = 2 \cdot 146.06369 + 2 \cdot 14 + 30 = 244 \text{ mm} \) and without a working gap to 214 mm. In this case, the value of the linear velocity of the point on the spindle surface is \( \omega_{sh} = \omega_i = 143.26 \text{ s}^{-1} \), \( g \cdot \omega = 14 \cdot 143.26 = 2.00 \text{ m/s} \).
Now we will perform the same calculations taking into account the well-known research results submitted by the research and design organizations of the republic.

The maximum speed of slice winding on the spindle of the harvesting unit, according to M.I.Landsman [10], is equal to 1.5 m/s, and according to D.M.Shpolyansky [17] 1.7 ... 1.9 m/s or an average of 1.85 m/s. Then the maximum spindle rotating frequency should be equal at \( r = 14 \, \text{mm} \) to \( \omega_{\max} = 1850/14 = 132 \, \text{s}^{-1} \), and the rational one to \( \omega_{sh} = 1675/14 = 120 \, \text{s}^{-1} \).

In recent years, the republic’s area of cotton sowing by varieties "Sultan", "S-6524", "Namangan-77" is growing. Therefore, if we take the arithmetic mean value of the spindle speed \( \omega_{sh}=126 \, \text{s}^{-1} \) accounting the specifics of these cotton varieties, then in the subsequent calculations we have \( \omega_6=\omega_{sh}/\approx11 \, \text{s}^{-1} \), then the rolling radius of the spindle roller is equal to \( rk=146/(11.6-1)=13.8 \, \text{mm} \). With this in mind and taking into account condition (6) based on the formula (13) for the input part of the apparatus, the lead coefficient should be greater than \( k\leq2.9 \), which differs significantly from the known recommendations [17]. By condition (7), the lead coefficient should be less than \( k\leq1.41 \), and the speed of the cotton picker at that is \( V_m=U/k=1.14 \, \text{m/s} \) or 4.1 km/h.

4. Conclusions
From above it follows that to ensure more efficient operation of the harvesting units of the MX-1.8 and MX-2.4 machines at motion speeds of 4.1 km/h (or 1.14 m/s), the drums should rotate at a speed of \( n_b = 105 \, \text{min}^{-1} \), and the angular velocity of spindles rotation in the working area should be \( n_{sh}=1200 \, \text{min}^{-1} \). With such machines speed \( V_m \) their productivity increases.

The calculated value of the lead coefficient, equal to 1.41, practically corresponds to the recommendations given by D.M.Shpolyansky [17], \((k = 1.3 \ldots 1.5)\) based on many years of experience.

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