Reliability Modelling while Designing and Improving Working Members of Agricultural Implements

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Abstract. The author suggests the method of reliability prediction in making new constructions of working members of agricultural implements by using the solid diagrams of their real load.

The efficiency of using agricultural implements is evaluated as a rule by their maintenance reliability. Forced stoppage of agricultural units and failures of particular assemblies trouble agrotechnical operation rhythm and reduce final productivity. The most frequent cause of agricultural implements failure is the necessity of replacement of rapidly wearing parts of working members. Wear mechanism is due to the presence of abrasive particles in the natural soil consistency the cultivation of which results in galling (fretting) from the soil-cutting parts surface.

The friction force between the soil and the parts of working members in the Amontons – Coulomb relation

\[ F = N \cdot \mu \]

determines the magnitude and the rate of wear, where \( N \) means normal pressure and \( \mu \) means friction ratio. Normal pressure magnitudes on distinct segments of soil-cutting parts differ which determines various wear rate.

In general the initial problem of modelling reliability of a soil-cutting part comes to the determination of estimated nature of their loading in the conditions of real maintenance. It is important to know the normal pressure magnitudes on distinct segments of a soil-cutting part. The efforts to find hydromechanical analogy for the determination of cutting resistance are familiar but they cannot be a reliable determination basis [1]. At the same time the dynamical soil deformation taking place in the practice of agrotechnical operations performance that can be predicted in calculating the mode of deformation rates also depends on initial physical properties of a plot [2]. Thus, bottom pressure testing on different segments of a soil-cutting part by an experimental approach is a rather complex engineering problem.

The objective of this research is to investigate the display technique of the load diagram of the surface of a soil-cutting part according to a priori determined general force load characteristics and in further reliability prediction.

It is not difficult to determine the total external load by an experimental approach with the help of familiar devices for application of solid dynamometry of tillage implements (certificate of authorship 1744527, patent 2498245).

As a result of solid dynamometry, as a rule, essential spatial load bearing characteristics acting from the soil on a given part or a working member are defined. Load bearing characteristics in most cases represent the projections of the resultant vector and principal moment on proper coordinate axes [3].
Figure 1 shows the outlines of the soil-cutting part $ABCD$ with the coordinate positions of the points $A(x_1, y_1, z_1)$; $B(x_2, y_2, z_2)$; $C(x_3, y_3, z_3)$; $D(x_4, y_4, z_4)$; where $\vec{F}$ means the resultant vector and $\vec{M}$ means the principal moment.

The resultant vector and principal moment magnitudes are defined by the following formula (Eq.1):

$$F = \sqrt{F_x^2 + F_y^2 + F_z^2}; \quad M = \sqrt{M_x^2 + M_y^2 + M_z^2},$$  \hspace{1cm} (1)

where $F_x, F_y, F_z, M_x, M_y, M_z$ mean the projections of the resultant vector and principal moment on the coordinate axis.

The resultant vector of external resistance forces is an invariant quantity and doesn’t depend on reduction centre, and the angle between the resultant vector and principal moment can change subject to the chosen reduction centre. In the event that the direction of the resultant vector and principal moment coincide “the wrench” takes place, in other words, there is a force and a couple of forces acting in the plane perpendicular to the force.

The wrench axis is a line in the space that is defined by the formula (Eq.2):

$$\frac{M_y - (y \cdot F_z - z \cdot F_y)}{F \cdot x} = \frac{M_x - (z \cdot F_x - x \cdot F_z)}{F \cdot y} = \frac{M_z - (x \cdot F_y - y \cdot F_z)}{F \cdot z},$$  \hspace{1cm} (2)

where $x, y, z$ are current coordinates.

Since the vectors $\overline{AB} = (x_2 - x_1, y_2 - y_1, z_2 - z_1)$; $\overline{AD} = (x_4 - x_1, y_4 - y_1, z_4 - z_1)$; $\overline{AM} = (x - x_1, y - y_1, z - z_1)$ are complanar, we can work out the equation of plane (Eq.3):

$$\begin{vmatrix}
x - x_1 & y - y_1 & z - z_1 \\
x_2 - x_1 & y_2 - y_1 & z_2 - z_1 \\
x_4 - x_1 & y_4 - y_1 & z_4 - z_1 \\
\end{vmatrix} = 0. \hspace{1cm} (3)$$

The solution of the set of equations (2) and (3) allows to define the unknown $x, y', z$ (Eq.4)

$$\begin{cases}
\frac{M_x - (y \cdot F_z - z \cdot F_y)}{F \cdot x} = \frac{M_y - (z \cdot F_x - x \cdot F_z)}{F \cdot y} = \frac{M_z - (x \cdot F_y - y \cdot F_z)}{F \cdot z} \\
\begin{vmatrix}
x - x_1 & y - y_1 & z - z_1 \\
x_2 - x_1 & y_2 - y_1 & z_2 - z_1 \\
x_4 - x_1 & y_4 - y_1 & z_4 - z_1 \\
\end{vmatrix} = 0
\end{cases}$$  \hspace{1cm} (4)

Within the framework of the given model it is assumed that the current coordinates $x, y, z$ determine the position of the point of intersection of the wrench axis with the soil-cutting part surface. Received values of the current coordinates determine the position of the point
\( n \left( x_0, y_0, z_0 \right) \) (Fig. 1), which can be considered with the reasonable approximation as a certain
centre of pressure of the force whose modulus is equal to the resultant vector magnitude \( \mathbf{F} \), the value
of a quantity \( M \) can be neglected as a source of pressure for it can be considered as influencing
rather the path of motion of abrasive particles on the soil-cutting part surface.

In the figure 1 the position of the soil-cutting part is chosen so that the coordinate axis oz is parallel
to the resultant vector \( \mathbf{F} \) of the external resistance forces.

The key condition in modelling a solid or distributed load diagram acting from the soil on the soil-
cutting part is to be the following equality (Eq.5):

\[
\mathbf{F} = \sum_{i=1}^{m} p \cdot S_i \cdot h_i
\]  

where \( p, S_i, h_i \) are the unit values of the specific pressure, the pressure surface and of the
load diagram height in the place of the load action (Fig. 2). Let us imagine conditionally that the soil-
cutting part \( A, B, C, D \) being under the influence of the force equal to the resultant vector rests only
on three points \( A(x_1, y_1, z_1); D(x_4, y_4, z_4); E(x_5, y_5, z_5) \) located on the sides of the part.
Responses \( R_A, R_D \) and \( R_E \) are defined from the equilibrium condition (Eq.6):

\[
\begin{align*}
\sum_{npos} & = R_A + R_D + R_E - F = 0 \\
\sum_{momx} & = F \cdot y_0 - R_A \cdot y_1 - R_D \cdot y_4 - R_E \cdot y_5 = 0 \\
\sum_{momy} & = F \cdot x_0 - R_A \cdot x_1 - R_D \cdot x_4 - R_E \cdot x_5 = 0
\end{align*}
\]  

Solving the set of equations (6) we will have (Eq.7):

\[
\begin{align*}
R_A & = F \frac{(y_5 - y_0)(x_4 - x_0) - (x_4 - y_0)(x_5 - x_0)}{(y_5 - y_1)(x_4 - x_1) - (y_4 - y_1)(x_5 - x_1)}; \\
R_E & = F \frac{(y_0 - y_1)(x_4 - x_1) - (y_4 - y_1)(x_0 - x_1)}{(y_5 - y_1)(x_4 - x_1) - (y_4 - y_1)(x_5 - x_1)}; \\
R_D & = F \frac{(y_5 - y_1)(x_0 - x_1) - (y_2 - y_1)(x_5 - x_1)}{(y_5 - y_1)(x_4 - x_1) - (y_4 - y_1)(x_5 - x_1)};
\end{align*}
\]  

Let us change the point \( E \) by the points \( B \) and \( C \) and determine the responses in these points
on the basis of the equilibrium condition \( R_E, R_B \) and \( R_C \) (Eq.8):
\[
\begin{align*}
\sum_{ax} &= R_B + R_C + R_E = 0 \\
\sum_{mox} &= R_B y_2 + R_C y_3 + R_E y_5 = 0
\end{align*}
\] (8)

\[R_C = R_E \frac{y_2 - y_5}{y_3 - y_2}; \quad R_B = R_E \frac{y_5 - y_3}{y_3 - y_2}\]

In the model under study the vectors \(\vec{R}_A, \vec{R}_B, \vec{R}_C, \vec{R}_D\) are defined, therefore, the extreme points of these vectors are the points \(a\left(x_1', y_1', z_1'\right)\); \(b\left(x_2', y_2', z_2'\right)\); \(c\left(x_3', y_3', z_3'\right)\); \(d\left(x_4', y_4', z_4'\right)\). We write down the equation of the plane in which the vectors \(\overrightarrow{ab} = (x_2' - x_1', y_2' - y_1', z_2' - z_1')\) and \(\overrightarrow{ad} = (x_4' - x_1', y_4' - y_1', z_4' - z_1')\) are located (Eq.9).

\[
\begin{vmatrix}
    x - x_1' & y - y_1' & z - z_1' \\
    x_2' - x_1' & y_2' - y_1' & z_2' - z_1' \\
    x_4' - x_1' & y_4' - y_1' & z_4' - z_1'
\end{vmatrix} = 0
\]

(9)

Thus, the received outlines of the solid figure \(A, B, C, D, a, b, c, d\) represent the required volume of the diagram of external force load of the soil-cutting part. Comparing the vectors \(\vec{R}_A, \vec{R}_B, \vec{R}_C\) and \(\vec{R}_D\) according to the absolute values and defining minimal of them, for example \(|R_C| < |R_A|, \ |R_B|, \ |R_D|\) we draw the plane parallel to \(ABCD\) through the point \(C\) and obtain the points \(c, a', b', a\) corresponding to the limits of this plane. The total volume of the load diagram \(V\) includes the volume of the prism \(ABCDa'b'cd' - V_1\) and the volumes of two pyramids with vertices in the point \(c\) and with bases \(a'b'ab - V_2\) and \(a'ad'd - V_3\) (Fig.1).

Consequently (Eq.10):

\[V = V_1 + V_2 + V_3 \quad \text{or} \quad V = \sum_{i=1}^{n} S_i \cdot h_i\] (10)
While estimating the compliance of the derived diagram of the solid load with the real maintenance conditions we should mention that the given load diagram has some averaged values and doesn’t take into consideration the variability of operation by the value and the direction of the resultant vector and principal moment. To obtain more accurate calculations one can consider the variability of characteristics of the solid load diagram.

Multiplying the right and left sides of the equality (10) by the specific volume weight $\gamma$ we have (Eq.11):

$$V \cdot \gamma = \left( \sum_{i=1}^{n} S_i \cdot h_i \right) \cdot \gamma,$$

the value $V \cdot \gamma$ which is equal to the value of the force $F$, that is $V \cdot \gamma = F$, then the required quantity $\gamma$ is defined by the formula:

$$\gamma = \frac{F}{V}.$$

For the practical use of the derived load diagram let us consider a certain element of the section $e_k$ of the soil-cutting part separately (Fig.2). Consider the element of the section $e_k$ in the rectangular coordinate system (Fig.3). The figure 3 illustrates $R_i$ (load forces). The expected wear rate (fretting) $\Delta \tau$ from the surface of the part (Fig.3b) is known to be proportional to the normal pressure.
\[ \Delta \tau = f(k \cdot R_i \cdot \mu), \]  

where \( \Delta \tau \) means the wear rate,  
\( k \) means the factor allowing for departure \( R_i \) of from normal,  
\( \mu \) is the friction ratio.

Indeed, in the relationship (12) \( k \) and \( \mu \) are constants, therefore, the wear rate is proportional to the response of load forces. At the same time \( \Pi P \), the limiting state of the soil-cutting part followed by the failure of the agricultural machinery, is achieved after the instant of time \( t_1 \) (Fig.3c). In the event of availability of a split construction of the soil-cutting part in case of its replacement at the instant of time \( t_1 \) the regular limiting state takes place at the instant of time \( t_2 \).

While designing and improving the working members of agricultural implements the results of this research can be carried out in a different way. For that purpose the additional work hardenings of separate areas of the front face of the working member of an agricultural implement can be applied. It is reasonable to carry out the work hardenings by applying abrasion-resistant alloy. At present we know the empirical equations derived in vitro characterizing the wear rate of working members of ploughs [4]. Unfortunately, they are valid only for particular plots and therefore can not extend to other soil types. Welding alloys are good protection from abrasive wear and represent high-chrome cast iron alloy or alloys with different content of carbide phase [5]. It is reasonable to choose the thickness \( \Delta m \) of carbide phase application to the section of the soil-cutting part according to the load diagram or expected wear rate (12). Figure 3d shows change in thickness of carbide phase layer along
the length of the section of the soil-cutting part. Figure 4 illustrates the working member of an agricultural implement – the plough body and the outlines of additional work hardening segments.

**Conclusion**

Therefore, while designing and improving the working members of agricultural implements with specified reliability life time it is essential to have the real load diagram derived by using solid dynamometry. Then, focusing on material costs we should choose a constructive way of designing a split soil-cutting part with a changeable wearing segment or an integral part with application of hardening layer to wearing segments.

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