Method for determining dynamic coefficient of friction of bodies

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Abstract. To study the effect of the material and the roughness of the impact surface, the velocity of impact interaction and the properties of bodies on the value of the dynamic coefficient of friction, a shock testing machine is proposed that provides an impact contact effect on the bodies in a plane located at an angle adjustable from 0 to 45 ° relative to the normal line drawn to the point of impact, in the range of speeds from 12 to 72 m/sec. It is found that at an impact velocity of 25 m/sec with an increase in the angle of inclination of the impact steel plane, the angle of friction and the corresponding dynamic coefficient of friction increase in a linear relationship. The maximum values of angles $\varphi$ and dynamic coefficients of friction $f$ make: - for steel balls $\varphi = 8.3^\circ$, $f = 0.146$; - for lead balls $\varphi = 11.4^\circ$, $f = 0.167$; - for grains of the wheat $\varphi = 6.8^\circ$, $f = 0.12$. The results obtained indicate that the elastoplastic properties and shape of the bodies do not have any significant effect on the angles of reflection of bodies from the impact plane.

1. Statement of Problem

Every year, dozens of machines and mechanisms are designed in the country, with their working bodies having an impact effect on the processed material. These are agricultural, grain processing machines and many others. The calculation and optimization of their working bodies are carried out on the basis of a theoretical analysis of the dynamic contact interaction of surfaces with bodies of various configurations. The majority of researchers and designers accept the theory of contact deformations by H. Hertz as the basic theory, which is designed to calculate the parameters of the impact process of elastic, homogeneous, anisotropic bodies with a certain geometry in the contact zone.

The study of the process of dynamic contact interaction of grains with the working bodies of machines is carried out by the method of imitation modeling on a complex of laboratory instruments with subsequent recalculation of static parameters into dynamic ones using special computer programs. This approach arises from the fact that the existing measurement technique does not allow to determine the dependence of the impact force on the deformation of grains in the contact zone at a high rate of impact interaction.

Until now, the contact interaction of working bodies made of polymeric materials with grain of agricultural crops has practically not been studied. The use of existing working bodies in the construction of harvesting machines leads to a high degree of grain damage.

It was found that the growth of micro-damage to grain by 10-13% reduces wheat yield by 1-2 dt/ha [1].

One of the ways to reduce crushing and micro-damage of grain is to replace the steel working bodies of the combine with polymer ones.
With the advent of polymers of high strength and wear resistance, it becomes possible to manufacture polymer replaceable rasps of the threshing and separating device (TSD), which is undoubtedly advisable for harvesting seed plots in farms and seed-growing companies.

The aim of the study is to develop theoretical foundations for calculating the parameters of contact interaction of elastoplastic bodies with the impact surface, to create a method for calculating these parameters as applied to grain of agricultural crops.

Many authors [2] paid much attention to the study of the coefficient of friction of various materials in sliding friction with a rough surface. It is known from a number of sources that when the impact surface is affected, the body is reflected at an angle to the normal line drawn at the point of impact, the value of which is equal to the dynamic angle of friction.

Many scientists studied the problem of contact force interaction of grains of agricultural crops with the surface of working bodies [3, 4, 5, 6]. The process of destruction of seeds of legumes (peas, soybeans, beans), with an emphasis on the dependence of the compression load on deformation, was considered by M.V. Kalashnikova [4]. A theoretical analysis of the force interaction of wheat grains with the surface of working bodies of a combine threshing device is presented in the works of V.P. Glotov, J. Fu et al., E.C.O. Osueke, L. Špokas et al. [3, 5, 7, 8].

A.N. Shpolyanskaya [9] showed that the work on the destruction of one grain of wheat under shock compression was several times greater than the work spent on the destruction of grains under static compression, which indicated a significant increase in the resistance of the grains under dynamic loads.

The authors [10, 11] established dependences on the type and state of the grain; upon impact, the velocity recovery coefficient varies within 0.34 ÷ 0.77.

In the process of strength dynamic tests of single grains of barley by their impact along the longitudinal axis of the grain against an obstacle (piezoelectric sensor), S.V. Melnikov [12] came to the conclusion about the wave nature of grain destruction.

In the work of G.N. Plokhov [13], it was found that the wave theory of impact could be extended in the cases of any impact of a wheat grain against an obstacle in various positions of its axis. In this case, the impact time is reduced by 1.2 ÷ 1.4 times compared to the time of impact of the grain in the direction of the longitudinal axis. Accordingly, the impact force increases. At an impact velocity V <8 m/sec, no permanent deformations occur in the grain.

A number of works were devoted to the question of determining the elastic modulus of grain [3; 13; 14; 15; 16]. In some works [3; 9; 10], the numerical determination of the elastic modulus was based on the application of some results of solving problems of the theory of elasticity with a number of assumptions. I.A. Naumov [15] determined the modulus of elasticity by an exemplary method, which consisted in compressing a grain, taking into account general elastic deformations. According to the author, the grain of wheat has residual deformations after unloading, however, if they are small, then the grain can be considered practically elastic.

Compression diagrams given in the works of A.N. Shpolyanskaya, I.A. Naumov, V.P. Glotov, A.S. Matuev and other authors confirm that the grain has elastoplastic properties [3; 9; 15; 17]. In studies [4; 18; 19], the calculation methods based on the analogy of static and dynamic compression are considered, and the theory of elastoplastic deformations is disclosed in the work of A.A. Ilyushin [20].

2. Conditions for Solving
To study the effect of the roughness of the impact surface, its material, the impact interaction velocity, as well as the properties of bodies on the value of the friction coefficient, a special device has been developed – a shock testing machine equipped with two steel planes diametrically located on a rotating disk (Figure 1). Disk 2 with impact planes 1 is driven by a DC electric motor 3 with speed control in the range from 500 to 3,000 rpm, which provides a speed of impact from 12 to 72 m/sec.
Figure 1. Shock Testing Machine Construction.

The tests were carried out by putting fifty studied bodies through a hollow pipe 4 (height – 200 mm, terminal falling velocity of bodies – \( V_p = 2 \) m/sec) into the impact zone of two planes fixed on a rotating disc.

During the free falling in the impact zone (25 mm), most bodies were subjected to impact with the impact velocity \( V_0 = 25 \) m/sec. Bodies that were not hit were excluded from the experiment.

To study the influence of the physical and mechanical properties of bodies and the angle of inclination of the impact plane on the value of the dynamic coefficient of friction, experiments were carried out to determine the angles of reflection from the steel impact plane (surface roughness Ra25) bodies of different shapes, sizes, and material properties, namely:

- steel balls with the diameter of 1.3 ÷ 2.1 mm, average weight of 0.11 g (shot-blasting machine balls);
- lead balls with the diameter of 3.2 ÷ 3.6 mm, average weight of 0.23 g (buckshot);
- wheat grains with a moisture content of 12% (length of 6 ÷ 6.3 mm, average width of 3.5 mm, average height of 3.3 mm, average weight of 0.04 g).

The bodies reflected from the impact plane were fixed on a cylindrical screen covered with a layer of viscous material (plasticine) with the axis coinciding with the axis of the hollow tube to put the bodies into (Figure 2, a).

In the experiments, the coordinates \( X_i, Z_i \) of the imprints of the reflected bodies were fixed with the subsequent determination of their arithmetic mean value \( X_\bar{\varepsilon}, Z_\bar{\varepsilon} \) (Figure 2, b).

The bodies reflection parameters were calculated using the following formulas:

- angle of reflection \( \chi \):
  \[
  \tan \chi = \frac{Z_\bar{\varepsilon}}{R} \Rightarrow \chi = \arctg \frac{Z_\bar{\varepsilon}}{151.5} \, ;
  \]

- dynamic friction angle \( \varphi \) (see Figure 2, a):
  \[
  \varphi = \beta - \chi \, ;
  \]

- friction dynamic coefficient:
  \[
  f = \tan \varphi \, .
  \]

The maximum possible accuracy of setting the values of the angles \( \beta \) was achieved due to:

- the design of the testing machine, which ensured the parallelism of the plane of the disk carrying the impact planes to the plane of the instrument table with an accuracy of \( \pm 0.05 \) mm, with a maximum runout within approximately the same limits;
- the fact of setting the values of the angles \( \beta \) with an accuracy of \( \pm 0.5^\circ \) by means of a technical protractor, which was fixed on a height-gauge based on the instrument table.

Taking into account that the radius of the cylindrical screen was 151.5 mm, inaccuracy in setting the angle of 1° led to a displacement of the normal line by 2.5 mm.
Figure 2. Scheme for recording the angles of reflection of bodies from the impact plane from their imprints on the screen: a – angle of friction depending on the angle of inclination of the plane, $\alpha$ and $\beta$; b – coordinates of body prints on the screen.

Table 1 shows the results obtained when impacting bodies with a plane at an angle $\beta$ adjustable in the range from 0 to 30° by rotating it around the radial (relative to the rotating disk) axis X (see Figures 1 and 2a). At large angles, the design of the screen did not provide fixation of the reflected bodies.
Table 1. Friction Dynamic Coefficient depending on Angle of Inclination of Impact Plane.

| Angle β, grade | \( Z_2 \), mm | Angle \( \chi \), grade | Friction angle \( \phi \), grade | Friction dynamic coefficient, \( f \) |
|----------------|-----------------|-----------------|-----------------|-----------------|
| Steel balls    |                 |                 |                 |                 |
| 10             | 15.3            | 5.8             | 4.2             | 0.073           |
| 20             | 31.6            | 11.8            | 8.2             | 0.144           |
| 30             | 60.5            | 21.7            | 8.3             | 0.146           |
| Lead balls     |                 |                 |                 |                 |
| 10             | 10.5            | 4.0             | 6.0             | 0.105           |
| 20             | 22.9            | 8.6             | 11.4            | 0.201           |
| 30             | 56.8            | 20.5            | 9.5             | 0.167           |
| Wheat grains   |                 |                 |                 |                 |
| 10             | 21.0            | 7.9             | 2.1             | 0.037           |
| 20             | 45.6            | 16.7            | 3.3             | 0.058           |
| 30             | 65.0            | 23.2            | 6.8             | 0.120           |

3. Analysis of Results

The results obtained confirm the conclusion that the trajectory of motion of the reflected bodies deviates in the direction opposite to the possible sliding of the body under the action of an impulse of friction forces.

The angle formed by the trajectory of the reflected body with the normal line to the plane drawn at the point of impact is practically independent of the elastoplastic properties of the bodies and their shape.

For all the objects studied, the angle \( \phi \) increases with an increase in the angle of inclination of the contact plane in a linear relationship.

The maximum values of the angles and dynamic coefficients of friction are as follows:
- for steel balls \( \phi = 8.3^\circ; \ f = 0.146 \);
- for lead balls \( \phi = 11.4^\circ; \ f = 0.201 \);
- for wheat grains \( \phi = 6.8^\circ; \ f = 0.12 \).

The data obtained require clarification by conducting experiments at different impact speeds for impact surfaces made of various materials with different roughness parameters.

Figure 3 shows body imprints captured on the screen for lead, steel balls and wheat grains at various angles \( \beta \).

A scale with divisions equal to one degree makes it possible to estimate the dispersion of bodies according to the value \( X_2 \). The position of the point of intersection of the normal line with the screen plane is marked with an inscription indicating the value of the angle \( \beta \), for example, ‘normal line 10’.

It follows from the tables and figures that wheat grains with an ellipsoidal shape are reflected similarly to spherical bodies (lead and steel balls).

When steel balls of high hardness (shot-blasting machine balls) strike, a hole is formed at the contact point, which prevents the balls from sliding relative to the plane. However, steel balls are reflected with a deviation from the normal in the same way as lead (deforming at the moment of impact) balls. This series of experiments should be repeated with the impact plane of higher hardness (with better heat treatment).
\[ \beta = 10^\circ \text{ (the left are the lead balls; the middle are the steel balls and the right fragment is the wheat)} \]

\[ \beta = 20^\circ \text{ (the left are the lead balls; the middle are the steel balls and the right fragment is the wheat)} \]

\[ \beta = 30^\circ \text{ (the left are the lead balls; the middle are the steel balls and the right fragment is the wheat)} \]

Figure 3. Body Imprints Captured on Screen for Lead Balls, Steel Balls and Wheat Grains.

4. Conclusion
The developed method for the experimental determination of the dynamic coefficient of friction of bodies made of homogeneous materials and grains of agricultural crops makes it possible to establish the regularity of the change in the dynamic coefficient of friction depending on the angle of inclination of the impact plane.
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