Static and dynamic friction coefficients of grain crops and mineral materials

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Abstract. There are many devices for determining the coefficients of external friction, but there are almost no devices for determining the coefficients of internal friction of bulk products. The paper considers the question of physical and mechanical characteristics of bulk materials - the coefficients of external and internal friction. The purpose of this study was to create a device for determining the friction characteristics of bulk materials and its approbation by determining the coefficients of static and dynamic friction of grain materials. The basic parameters of the installation to determine the friction characteristics of bulk materials were defined - static and dynamic, internal and external friction coefficients. The developed installation allows measurements of shear forces inside the bulk material. The relationship between the coefficient of static and dynamic friction in organic and inorganic bulk materials is revealed. Grain crops have a higher value of the dynamic coefficient of friction at a speed up to 0.215 m/s. The difference between the values of static and dynamic friction coefficients was not revealed in the specified speed range of legumes. Dynamics of change in the coefficient of friction for grain crops depending on speed is studied using the example of wheat, and for mineral materials - using the example of table salt. For a speed range of 0-0.215 m/s, the relative change in the coefficient of friction for grain crops has a polynomial regression model, for mineral materials it has a logarithmic.

1. Introduction
When designing and operating agricultural machines, it is necessary to take into account the physical and mechanical properties of grain crops, with which the working bodies of the machines directly interact. The coefficient of friction is an important physical and mechanical property of grain crops, as its value affects the process of unloading grain materials from bins [1-4]. Friction is one of the most common physical phenomena in agriculture. Studies have shown that there are many devices for determining the external friction coefficients, but there are practically no devices for determining the internal friction coefficients of bulk products [5-7].

In this regard, the determination of friction characteristics of bulk materials is an urgent task. There is a wide variety of facilities for determining the frictional characteristics of bulk materials, which are based on three main methods for measuring the static coefficient of friction (inclined plane method, the method of “embankment” and the method of “Torsion”).

Based on the analysis, it can be concluded that each installation or device [8-10] determines only one type of friction coefficient, either static or dynamic.

The purpose of this study was to create a device for determining the friction characteristics of bulk
materials and its approbation by determining the coefficients of static and dynamic friction of grain materials.

2. Materials and methods

To achieve our goal, a simple device for determining the friction characteristics of bulk materials was designed and manufactured [11]. This device is guaranteed to shift and measure the shear force in the gap between the rotating cup and the holder. This is due to the exclusion of uncontrolled shift relative to the holder.

Figure 1 shows the general view of the device to determine the effect of the layer displacement rate on the dynamic friction coefficient of bulk products.

The main task that provides the device - providing of accuracy of the results of the research of the friction characteristics of bulk materials: the coefficient of internal static friction and the coefficient of internal friction of the movement of one bulk material, the coefficient of mutual friction of static and friction of motion of different bulk materials, as well as coefficient of static friction and coefficient of friction of different granular materials by different hard materials, as well as simplifying the design of the device due to the mutual centering of the holder and the cup.

The scheme of the device for determining the dynamic and static friction coefficients of bulk products is shown in figure 2. The device includes a gear motor with adjustable frequency, which rotates the cup. The cylindrical holder with the formation of the contact plane freely moves in the cup.
To form a contact surface, the cup has an inner ring stage, on which the holder rests. The bulk material is poured into the cup and then into the holder, thus forming a contact surface between the samples. The fixed holder is connected with the dynamometer, which has a digital panel to display the values of forces of interaction between the layers, and the data is exported to the program Forcegaugesoftwarev6.0 to render the indications of the dynamometer in the online mode (picture3).

![Diagram of the device](image)

**Figure 2.** Scheme of the device for determining the dynamic and static friction coefficients of bulk products: 1 – housing; 2 – output shaft-reducer; 3 – cup; 4 – cylindrical holder; 5 – contact plane; 6 – dynamometer; 7– fixed partitions 8 – sample material; 9 – sample material.

At the first stage, we receive the value of the interaction force of the cup and the holder without the filled bulk material $F_{X.X}$ (idling), then fill the bulk material and receive the total force (measured in newton) of the interaction $F_{SUM}$. The difference between these values will show us the force of interaction between the layers of bulk material on the contact plane of the $F_{LOOSE}$.

$$F_{LOOSE} = F_{SUM} - F_{X.X}. \quad (1)$$

If the body slides on any surface, its movement is prevented by the sliding friction force.
\[ F_{TP} = \mu \cdot N \]  

(2)

where \( N \) - the reaction force of the support (the weight of the bulk material and the holder), \( N \); \( \mu \) - dimensionless coefficient of sliding friction [12-13]. The sliding friction force is always directed opposite to the movement of the body. When the direction of the velocity changes, the direction of the friction force also changes.

\[ \mu = \frac{F_{TP}}{N} \]  

(3)

where \( F_{TP} \) – the force measured on the dynamometer, Н.

The linear velocity of the relative displacement of the layers is determined by the angular velocity [2]:

\[ \vartheta = \frac{2\pi R}{T} = 2\pi R \nu \]  

(4)

where \( \nu \) – cup rotary speed, rpm; \( T \) - the period of rotation of the cup, 1/sec; \( R \) - the inner radius of the cup, m.

Since the bulk material in the contact surface is located at a distance from the axis of rotation from 0 to \( R \), the linear velocity is determined by the position of the center of gravity of the elementary sector within a radius. Then the dependence (4) takes the form:

\[ \vartheta = \frac{4\pi R}{3T} = \frac{4\pi R \nu}{3} \]  

(5)

where \( \frac{2}{3} \) – position of the centre of gravity of the elementary sector on the radius.

The following bulk materials were selected for conducting search experiments to determine the coefficients of static and dynamic friction:
- vegetable origin – grain of wheat, barley, soy millet and peas. (condition of humidity, nature - typical)
- mineral origin – table salt.

3. Results

During the experiments, shear forces on the contact surface were measured. The static coefficient of friction was determined at the beginning of the displacement of the cup relative to the holder. The dynamic coefficient of friction was determined by the rotation of the cup relative to the holder in steady state at the following rotational speeds providing a linear velocity of 0.043; 0.086; 0.152; 0.215 m/s.

The results of measuring the friction coefficients of wheat and table salt are listed in table 1.

| Conditions for determining the coefficient of friction | Coefficient of friction for the material |
|------------------------------------------------------|----------------------------------------|
|                                                      | Wheat | Table salt |
| Static coefficient of friction \((\nu=0)\)          | 0.31  | 0.57       |
| Dynamic coefficient of friction \((\nu=0.043 \text{ m/s})\) | 0.38  | 0.61       |
| Dynamic coefficient of friction \((\nu=0.086 \text{ m/s})\) | 0.44  | 0.71       |
| Dynamic coefficient of friction \((\nu=0.152 \text{ m/s})\) | 0.47  | 0.85       |
| Dynamic coefficient of friction \((\nu=0.215 \text{ m/s})\) | 0.49  | 1.07       |

The results of the experiment show that the coefficient of friction increases with an increase in the
relative velocity of the bulk material and this dependence is nonlinear.

The relative change of the coefficient of friction \( y \) of the linear velocity of the bulk material \( x \), determined by the formula:

\[
y' = \frac{t}{f},
\]

(6)

where \( t \) - is the dynamic dimensionless coefficient of friction, \( f \) - is the static dimensionless coefficient of friction.

Based on this, we summarize the data in Table 2.

**Table 2. The dependence of the relative change in the coefficient of friction.**

| Linear velocity (x), m/s | Wheat | Table salt |
|--------------------------|-------|------------|
| 0                        | 1     | 1          |
| 0.043                    | 1.22  | 1.07       |
| 0.086                    | 1.42  | 1.25       |
| 0.152                    | 1.53  | 1.49       |
| 0.215                    | 1.58  | 1.88       |

As a result of modeling, the following dependence of the dynamic friction coefficient on the relative velocity of the movement of layers of wheat and salt is obtained (figure 4).

**Figure 4.** The dependence of the dynamic coefficient of friction on the relative velocity of the movement of layers of wheat and salt.

Nonlinear models have a high coefficient of determination \( R^2 \), which at the same time exceeds this indicator of linear models. Consequently, the change in the dynamic coefficient of friction is really nonlinear (for wheat logarithmic, and for salt polynomial dependence).

In order to determine the dependence of the friction coefficient on the type of material, experiments were carried out using the following crops: wheat, barley, millet, soybeans and peas. The dynamic coefficient for these crops was determined at a linear velocity of 0.215 m/s (table 3).
Table 3. Static and dynamic friction coefficients for cereals and legumes.

| Crop    | Coefficient of friction for the material |       |       |
|---------|-----------------------------------------|-------|-------|
|         | Static                                 | Dynamic |       |
| Wheat   | 0.587                                  | 0.685  |       |
| Barley  | 0.838                                  | 0.754  |       |
| Millet  | 0.489                                  | 0.601  |       |
| Soybeans| 0.742                                  | 0.742  |       |
| Peas    | 0.625                                  | 0.625  |       |

4. Discussion of the results

The dynamic and static friction coefficients for most materials are different in the course of research. At the same time, the dynamic coefficient of friction in cereals (wheat, barley, millet) is higher than the static one (table 4).

Table 4. The absolute difference between the coefficients of friction.

| Crop    | Coefficient of friction for the material | Absolute difference of coefficients $\Delta = t \cdot f$ |
|---------|-----------------------------------------|-----------------------------------------------|
|         | Static                                 | Dynamic |       |
| Wheat   | 0.587                                  | 0.685  | 0.098 |
| Barley  | 0.754                                  | 0.838  | 0.084 |
| Millet  | 0.489                                  | 0.601  | 0.112 |
| Soybeans| 0.742                                  | 0.742  | 0     |
| Peas    | 0.625                                  | 0.625  | 0     |

The table shows that for legumes (soybeans, peas) in the speed range 0-0.215 m/s, coefficients do not differ.

The change of the coefficient of friction with increasing shear rate is nonlinear, as can be seen from the results of the experiment with wheat and table salt. At the same time, polynomial dependence of the second order is revealed for wheat, and for table salt – logarithmic.

5. Conclusions

The developed installation allows measurements of shear forces inside the bulk material. On the basis of the obtained data, taking into account the mass of portions of the shifted bulk product, the static and dynamic friction coefficients for cereals and legumes, as well as for the mineral material – table salt are calculated. There is higher value of the dynamic coefficient of friction at a speed of up to 0.215 m/s in grain crops. The difference between the values of static and dynamic coefficients of friction in the specified range of speeds in legumes was not revealed. Dynamics of change of coefficient of friction for grain crops depending on speed is investigated using the example of wheat. For a speed range of 0-0.215 m/s, the relative change in the coefficient of friction has a polynomial regression model of the form $y = 0.0505 \cdot \varphi^2 - 0.0857 \cdot \varphi + 1.0376$. The influence of the layer shear rate on the dynamic coefficient of friction for mineral materials is studied using the example of table salt. For a speed range of 0-0.215 m/s, the relative change in the coefficient of friction has a logarithmic regression model of the form $y = 0.375 \ln(\varphi) + 0.991$.

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