Determination of kinematic indices corresponding to a solid particle on a flat oscillating surface

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Abstract. This article presents a mathematical analysis having as purpose the understanding of the behaviour of a solid particle on a flat oscillating surface. The starting point of the analysis is the initial identification of the actions direction of forces on a solid particle placed on a flat oscillating surface, in a 3D reference system. Following the distribution of forces, for different specific cases of the behaviour of the solid particle, the general equations of kinematic indices could be determined, kₛ and kₗ. Due to achieving the 3D distribution model of forces acting on a solid particle, a new kinematic index could be determined, index corresponding to the sideways moving of the solid particle kₗ. Moreover, a series of graphical representations have been carried out, having as purpose the emphasis of the variation mode of the newly determined kinematic indices, as following: friction coefficient μ = 0.4; the angle of the inertial force to the flat oscillating surface, Φ = 0 – 180°; the angle between the projection of the inertial force on XOY plane and OX axis, α₂ = 0 – 80°. After analyzing the graphical representations for the new calculation forms of the kinematic indices, kₗ variation has the same rate and trend as kₛ. If angle α₂ = 0°, the variation curve of kₗ index coincides with the variation curve of kₛ, and as we increase the value of angle α₂, the variation curve of kₗ index moves away from the kₛ curve.

1. Introduction

One of the most commonly used methods of mechanical separation of a heterogeneous solid-solid mixture, is the separation according to width and thickness of particles, and the on-site separation.

The separation process of heterogeneous mixtures on site is a very commonly used method, used in different industries such as food industry or chemical industry, and generally where solid aggregates are processed. This separation method is applied by those industrial processes in which the dimension of solid particles entering and resulting from these processes is very important [1].

Within this separation process, a very important role is played by the type of movement of the solid particle. In order to make the sieve separation process more efficient, the working surfaces undergo certain simple or complex movements with the purpose of bringing each particle of the heterogeneous mixture in contact with the sieve [2, 3, 4, 5].

In order to understand the behaviour of the solid particle, different mathematical models have been created on the surface of the sieve, taking into account the operating mode of the separation surface [6, 7, 8, 9, 10]. Different laboratory stands have been conceived in order to analyse the behaviour of the solid particle on the surface of the sieve, but also for the optimization of this process [11, 12, 13].
Also, in order to understand as profoundly as possible this process, a series of finite element analyses have been conceived [14, 15, 16, 17, 18].

The most commonly used method to separate a solid particles mixture is the separation on flat oscillating surfaces [19, 20].

Regardless of the type of the analysis carried out, the working process is characterized by the kinematic index.

This is why this article presents the calculation method of the kinematic index corresponding to a solid particle on a flat oscillating surface. Within this mathematical model, the 3D projection of the forces acting on the solid particles has been considered.

2. Theoretical background

According to professional literature, a solid particle, due to the motion way of the flat oscillating surface, can move down and up the oscillating surface [21, 22, 23].

This is why we analysed further this behaviour, corresponding to the motion of a single solid particle.

2.1. Analysis of downward motion of a solid particle on a flat oscillating surface

In this case, the partial distribution of the forces acting on the solid particle on the flat oscillating surface is represented in figure 1.

![Figure 1. Forces acting on the particle when this moves down the flat oscillating surface](image)

In this case, the inertial force is given by the relation:

\[ F = (F_x, F_y, F_z) \]  \hspace{1cm} (1)

or:

\[ m \cdot a_x = \sum F_x \]

\[ m \cdot a_y = \sum F_y \]

\[ m \cdot a_z = \sum F_z \]  \hspace{1cm} (2)

where m represents the weight of the particle, ax, ay, az are the projections of the acceleration on the three axes; \( \sum F_x, \sum F_y, \sum F_z \) represent the sum of the projection of forces acting on the solid particle.

After a thorough analysis of these forces, we have:

- Oz axis:
\[ m \cdot a_z = F_z - G \]  \hspace{1cm} (3)

- Ox axis:
\[ m \cdot a_x = F_x + G_x - F_f \]  \hspace{1cm} (4)

\[ F \cdot \cos \Phi + G \cdot \sin \alpha - \mu (G \cdot \cos \alpha - F \cdot \sin \Phi) = m \cdot a_x \]  \hspace{1cm} (5)

\[ F (\cos \Phi + \mu \cdot \sin \Phi) + G (\sin \alpha - \mu \cdot \cos \alpha) = m \cdot a_x \]  \hspace{1cm} (6)

- Oy axis:
\[ F_y - F_{fy} = m \cdot a_y \]  \hspace{1cm} (7)

where \(G\) represents the gravitational force; \(\Phi\) is the angle between the inertial force and XOY plane; \(\alpha\) is the angle between the gravitational force and XOY plane; \(\mu\) is the friction coefficient; \(F_{fy}\) represents the projection on OY axis of the friction force.

The friction force is given by the relation:
\[ F_f = \mu \cdot N = \mu (G_z - F_z) = \mu (G \cdot \cos \alpha - F \cdot \sin \Phi) \]  \hspace{1cm} (8)

where:
\[ \Phi = \alpha + \varepsilon \]  \hspace{1cm} (9)

in which \(\varepsilon\) represents the angle of the oscillation direction of the flat oscillating surface.

However, the projections of forces acting on the solid particle can be determined by using the following relations:
\[ F_z = F \cdot \sin \Phi \]
\[ F_{xy} = F \cdot \cos \Phi \]
\[ F_x = F_{xy} \cdot \cos \alpha_2 \]
\[ F_y = F_{xy} \cdot \sin \alpha_2 \]  \hspace{1cm} (10)

or
\[ F_x = F \cdot \cos \Phi \cdot \cos \alpha_2 \]  \hspace{1cm} (12)
\[ F_y = F \cdot \cos \Phi \cdot \sin \alpha_2 \]  \hspace{1cm} (13)

\[ m \cdot a_z = F \cdot \sin \Phi - G \]  \hspace{1cm} (14)

where \(\alpha_2\) is the angle between the projection of the inertial force on XOY plane and OX axis.
It is considered that:

\[ F_x = F_x \]  
\[ F \cdot \cos \Phi \cdot \cos \alpha_z + G \cdot \sin \alpha - \mu \left( G \cdot \cos \alpha - F \cdot \sin \Phi \right) = m \cdot a_x \]  
\[ F \left( \cos \Phi \cdot \cos \alpha_z + \mu \cdot \sin \Phi \right) + G \left( \sin \alpha - \mu \cdot \cos \alpha \right) = m \cdot a_x \]  
\[ F \cdot \cos \Phi \cdot \sin \alpha_z - \mu \left( G \cos \alpha - F \sin \Phi \right) = m \cdot a_y \]  
\[ F \left( \cos \Phi \cdot \sin \alpha_z + \mu \cdot \sin \Phi \right) - \mu \cdot G \cdot \cos \alpha = m \cdot a_y \]

The equations of the trajectories on the three axes are given by the relations:

\[ x = -r \cdot \cos \omega t \cdot \left( \cos \Phi \cdot \cos \alpha_z + \mu \cdot \sin \Phi \right) + g \left( \sin \alpha - \mu \cdot \cos \alpha \right) \frac{t^2}{2} + c_1 \cdot t + c_2 \]  
\[ y = -r \cdot \cos \omega t \cdot \left( \cos \Phi \cdot \sin \alpha_z + \mu \cdot \sin \Phi \right) - \mu \cdot g \cdot \cos \alpha \frac{t^2}{2} + c_1 \cdot t + c_2 \]  
\[ z = -r \cdot \cos \omega t \cdot \sin \Phi - g \cdot \cos \alpha \frac{t^2}{2} + c_1 \cdot t + c_2 \]

where \( \omega \) represents the angular velocity ; \( t \) is the time; \( C1 \) and \( C2 \) are integrating constants.

In order to be able to determine the kinematic index corresponding to the downward motion of the solid particle on the flat oscillating plan, the sum of the forces acting on the solid particle must comply with the downward moving condition:

\[ F \cdot \cos \Phi \cdot \cos \alpha_z + G \cdot \sin \alpha - \mu \left( G \cdot \cos \alpha - F \cdot \sin \Phi \right) \geq 0 \]  

Relation (23) is divided to \( m \cdot g \) and we obtain:

\[ \frac{\omega^2 \cdot r \cdot \cos \omega t \cdot \cos \alpha_z}{g} \left( \cos \Phi + \mu \cdot \sin \Phi \right) - \mu \cdot \cos \alpha \cdot \cos \alpha_z - \sin \alpha \geq 0 \]  

Within relation (24) the following substitution can be made:

\[ k = \frac{\omega^2 \cdot r}{g} \]  

in which \( k \) represents the actual index of the kinematic mode of the sieve

Relation (24) is written as following:
2.2. The analysis of the upwards motion of a solid particle on a flat oscillating surface

In this case, the forces acting on a solid particle moving up a flat oscillating surface are presented in figure 2.

In this case also the inertial force is given by the relation:

\[ F = \left( F_x, F_y, F_z \right) \]  \hspace{1cm} (29)

or:

\[
\begin{align*}
    m \cdot a_x &= \sum F_x \\
    m \cdot a_y &= \sum F_y \\
    m \cdot a_z &= \sum F_z
\end{align*}
\]  \hspace{1cm} (30)

However, in the case of a vectorial analysis of the distribution of forces, we have:

- On Oz axis:

\[ m \cdot a_z = F_z + G \]  \hspace{1cm} (31)

- On Ox axis:
\[ m \cdot a_x = F_x - G_x - F_f \]  
\[ \text{- On Oy axis:} \]
\[ m \cdot a_y = F_y - F_f \]  
The projections of the forces can be determined by the following formulas:
\[
\begin{cases}
  F_x = F \cdot \sin \Phi \\
  F_{xy} = F \cdot \cos \Phi \\
  F_z = F_y \cdot \cos \alpha_2 \\
  F_y = F_y \cdot \sin \alpha_2 
\end{cases}
\]  
Taking into consideration the aforementioned calculation methodology, we can determine the equations of the solid particle’s trajectory, given by the relations:
\[
x = -r \cdot \cos \omega t \cdot \left( \cos \Phi \cdot \cos \alpha_2 - \mu \cdot \sin \Phi \right) - g \cdot \frac{\left( \sin \alpha + \mu \cdot \cos \alpha \right)}{2} \cdot t^2 + c_1 \cdot t + c_2 \quad (35)
\]
\[
y = -r \cdot \cos \omega t \cdot \left( \cos \Phi \cdot \sin \alpha_2 - \mu \cdot \sin \Phi \right) - \mu \cdot g \cdot \cos \alpha \cdot \frac{t^2}{2} + c_1 \cdot t + c_2 \quad (36)
\]
\[
z = -r \cdot \cos \omega t \cdot \sin \Phi + g \cdot \cos \alpha \cdot \frac{t^2}{2} + c_1 \cdot t + c_2 \quad (37)
\]
Just like in the previous case, when the particle goes down the flat oscillating surface, the kinematic index must be determined. For this situation, we start from the equation of motion of the solid particle on Ox axis:
\[
\ddot{x} = \frac{F}{m} \left( \cos \Phi \cdot \cos \alpha_2 - \mu \cdot \sin \Phi \right) - g \left( \sin \alpha + \mu \cdot \cos \alpha \right) \geq 0 \quad (38)
\]
relation that can be also written:
\[
\frac{F}{m} \left( \cos \Phi \cdot \cos \alpha_2 - \mu \cdot \sin \Phi \right) - \mu \cdot g \cdot \cos \alpha \geq 0 \quad (39)
\]
Taking into account that:
\[
F = m \cdot \omega^2 \cdot r \cdot \cos \omega t \quad (40)
\]
and by dividing the equation (42) to \(g\), we obtain:
\[
\frac{\omega^2 \cdot r}{g} \cdot \cos \omega t \cdot \left( \cos \Phi \cdot \cos \alpha_2 - \mu \cdot \sin \Phi \right) - \sin \alpha - \mu \cdot \cos \alpha \geq 0 \quad (41)
\]
In order to determine the kinematic index for the situation when the particle moves up the sieve surface, the following formula is used:

\[ F \cdot \cos \Phi \cdot \cos \alpha_2 - \mu \cdot F \cdot \sin \Phi \cdot \cos \alpha_2 - G \cdot \sin \alpha - \mu \cdot G \cdot \cos \alpha \cdot \cos \alpha_2 \geq 0 \]  \hspace{1cm} (42)

By using the same calculation stages as in the previous case, we determine the value of the index:

\[ k_y \geq \frac{\mu \cos(\alpha - \alpha_2) - \sin \alpha}{\cos \omega \cdot \cos \alpha_2 \cdot (\cos \Phi - \mu \cdot \sin \Phi)} \]  \hspace{1cm} (43)

This kinematic index becomes the standard one for \( \omega = 0 \) and \( \alpha_2 = 0 \) meaning:

\[ k_y = -\frac{\sin \alpha - \mu \cos \alpha}{\cos \Phi - \mu \sin \Phi} \]  \hspace{1cm} (44)

### 2.3. The analysis of the sideways motion of a solid particle on a flat oscillating surface

Regardless of the motion type of a solid particle on a flat oscillating surface, if it moves up or down this surface, within this process it proves that it has not a straight line motion, meaning that a sideways motion occurs [24]. This motion is due to a series of factors, such as:

- The shape of the solid particle, meaning the contact surface between the solid particle and the flat oscillating surface;
- The quantity of material on the oscillating surface, due to impacts occurring between the solid particles;
- The way the flat oscillating surface is installed, i.e. the sieve on which the separation process takes place is not appropriately outstretched and wrinkles may occur;
- The flat oscillating surface has not been installed in the balance, and there is an inclination towards one of the ends.

Starting from the distribution of forces, for the two situations, the equation of equilibrium is determined:

\[ F_y - F_{fy} \geq 0 \]  \hspace{1cm} (45)

in which:

- \( F_y \) - projection of the inertial force on OY axis;
- \( F_{fy} \) - projection of the friction force on OY axis.

By replacing the equation elements in relation (45) we have:

\[ F \cdot \cos \Phi \cdot \sin \alpha_2 - \mu \cdot \left( G \cdot \sin \alpha - F \cdot \sin \Phi \right) \cdot \sin \alpha_2 \geq 0 \]  \hspace{1cm} (46)

or:

\[ \omega^2 \cdot m \cdot r \cdot \cos \omega t \cdot \cos \Phi \cdot \sin \alpha_2 - \mu \cdot g \cdot m \cdot \cos \alpha \cdot \sin \alpha_2 + \mu \cdot \omega^2 \cdot m \cdot r \cdot \cos \omega t \cdot \sin \Phi \cdot \sin \alpha_2 \geq 0 \]  \hspace{1cm} (47)

By dividing to \( (m \cdot g) \) and by using the substitution in relation (25) we obtain the calculation formula for the kinematic index corresponding to the sideways motion of the solid particle on the flat oscillating surface:
3. The numerical model of the dynamic process

In order to understand the importance of determining these kinematic indices, the parameters in relations (28), (43) and (48) shall be replaced, respectively:

- The angle of inclination of the flat oscillating surface, $\alpha$, is initially 0°;
- A value of the friction coefficient is chosen, $\mu = 0.4$;
- In order to simplify the calculation, we assume that the value of $\cos \omega t$ is 1;
- The angle made by the inertial force with the flat oscillating surface, $\Phi$, is 0 – 180°, and the angle between the projection of the inertial force on XOY plane and OX axis, $\alpha_2$, is 0°.

These replacements are made in order to see if the calculation formulas obtained for the 3D distribution model of the forces on a solid particle on a flat oscillating surface confirms the professional literature.

Starting from these values, figure 3 shows a diagram of the variation of indices presented above.

![Figure 3. Variation of kinematic indices according to angle $\Phi$.](image)

In figure 3 certain areas are located, the destination of which can be found in the professional literature:

- area I – corresponding to the relative motion system of the solid particle, downwards only, without being detached from the oscillating surface;
- area II – corresponding to the motion of the particle rather down than up on the flat oscillating surface;
- area III – in this area the systems are characterized by the detachment of the solid particle from the working surface and its motion downwards;
- area IV – characterized by the detachment of the solid particle from the working surface and its motion upwards;
- area V – includes all systems within which the motion of the solid particle on the flat oscillating surface is made with its displacement downwards only, but with the detachment of the solid particle from the working surface;
- area VI – this area contains the systems in which the solid particle has an upwards motion only on the oscillating surface, with its detachment from the working surface;
- area VII – area in which there is no motion of the solid particle on the flat oscillating surface.

If the angle of inclination of the screening block varies between 0-38°, the variation diagram of kinematic indices has the shape presented in figure 4.

When analysing the variation of kinematic indices analysed in figure 4, corresponding to the 0 – 3, the following conclusions can be drawn:

- with regard to the actual kinematic index, $k$, it shows that it has the maximum value for the value of $\alpha$ of 0° only for the value of $\Phi$ of 18° and 161°, for $\alpha = 38^\circ$ for the angle $\Phi$ is 15° and 165°. The minimum value of the index $k$ is obtained for the maximum angle $\alpha$, which is 0.78. Regardless of the value of the angle $\alpha$ the shape of the graphical representation is that of a reversed saddle;

- the kinematic index corresponding to the motion down the flat oscillating surface increases with the value of the angle of inclination of the working surface. The variation curve of the index $k_j$ is parabolic with a minimum value 0.371 for the angle $\alpha = 0^\circ$ and $\Phi = 20^\circ$ and 0.864 for the angle $\alpha = 38^\circ$ and $\Phi = 21^\circ$. For the maximum value of this index the angle $\Phi$ must be 104° (for $\alpha = 0^\circ$) and 95° (for $\alpha = 38^\circ$);

- With regard to the variation mode of the kinematic index corresponding the motion of the solid particle up the flat oscillating surface, it shows that this is divided in two. To the value of the angle $\alpha$ of 20° and for an angle $\Phi \in (0^\circ, 66^\circ)$, the index $k_s$ has an ascending trend line and for a value of the angle $\Phi > 66^\circ$ and the angle $\alpha > 20^\circ$ the index $k_s$ has a descending trend line;

For the above analysed situations we studied, theoretically, the variation mode of the kinematic index corresponding to the sideways motion of the solid particle (figure 5) on a flat oscillating surface, for a value of the angle $\alpha_2 = 0^\circ$ and $\alpha_2 = 90^\circ$.
Figure 5. Variation of kinematic indices corresponding to the motion of a solid particle on a flat oscillating surface according to the angle \( \Phi \) and to the angle of inclination of the flat oscillating surface \( \alpha \), for different values of the angle \( \alpha_2 \): a) 0°; b) 15°; c) 45°; d) 60°; e) 80°.

When analyzing the variation of the kinematic index \( k_i \) presented in figure 5, the following conclusions can be drawn:
- regardless of the value of the angle \( \alpha_2 \) it shows that this index has the same rate and trend line as \( k_j \) index;
- in the case of the angle \( \alpha_2 = 0° \) it shows that the trend line of \( k_i \) coincides with trend line of \( k_j \).

From the same analysis it shows that:
for the angle $\alpha_2 = 80^o$ when the value of the angle $\Phi$ is increased, it shows that the trend line of $k_i$ moves away from the trend line of $k_j$;

- in angle $\alpha_2 = 0^o$ we obtain values for $k_i$ and $k_j$ maximal for different values of the angle $\Phi$.

When we increase the value of the angle $\alpha_2$ it shows that we obtain $k_i=3$ for a larger scale of values of the angle $\Phi$, interval which includes also the values of the angle $\Phi$ corresponding to $k_i=3$;

- for a value of the angle $\Phi = 0^o$, $\alpha = 0^o - 38^o$ and for $\alpha_2 = 0^o$ we have $k_i \in (0.4; 0.93)$. When we increase the value of the angle $\alpha_2$ it shows an increment of the value of $k_j$, and thus for $\alpha_2 = 80^o$ we have $k_i \in (0.4; 3.8)$;

- also, when the angle $\Phi = 180^o$, $\alpha = 0^o - 38^o$ we have a value of $k_i \in (0; 0.29)$, corresponding to the value of $\alpha_2 = 0^o$, and for $\alpha_2 = 80^o$ we have $k_i \in (0; 1.76)$.

3. Conclusions

The most commonly used method of mechanical separation of a heterogeneous mixture of solid particles is the separation by size or separation on site. The separation process is characterized by the side kinematic index, parameter that describes the movement of the swing plane on the surface of the solid particle. Because in the literature is presented only flat distribution of forces acting on the solid particle on a flat oscillating surface, in this article was aimed how the same forces, but acts within the spatial movement of a solid particle. The equations of motion have been generated for two movement directions of particles or kinematic indexes of the particle movement on the sieve ($k_j$ and $k_s$), taking into account the three forces projection on planes XOY, XOZ and YOZ. For each plane, for both directions of motion, we determined the calculation formulas corresponding to the acceleration of the particle, to the speed of the particle and to the distance covered by the particle. Moreover, following the new motion equations se determined the general formulas for the kinematic indexes of the motion of the particle on the sieve ($k_j$ i $k_s$). For this specific case, the calculation formulas for the two indices $k_j$ and $k_s$ coincide with those presented in the professional literature. Following the same equations of motion we could determine the kinematic index of the sideways motion of the solid particle on the flat oscillating surface $k_l$, index that can help us for the optimization of the mechanical separation process. It proves that, regardless of the way of movement of the solid particle on the flat oscillating surface, u or dawn the surface, the calculation formula of the index $k_l$ is the same. This index $k_l$ helps us better understand the separation process of a mixture of solid particles according to their widths and thickness. Charts of the variation of the kinematic indices have been drawn, and following the analysis of these charts a series of conclusion have been reached.

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