Applications of Discrete Element Method (DEM) in modeling the impact of dynamic and technological parameters on the material movement on the vibrating screen surface

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Abstract. A vibrating screen is a device for sorting materials, which is widely used in screening plants [1-3]. The availability of a vibrating screen relies on various parameters, such as dynamic parameters, technological parameters, and so forth [4-8]. When using the traditional method to calculate the design and determine the reasonable parameters for the machine to work efficiently, it would be rather challenging, and the accuracy is high. Also, this process would likely take a lot of time, as well as an increasing cost. This study aims to apply the Discrete Element Method (DEM) to simulate the influence of dynamic parameters and technological parameters on the operating capability of the machine. The results of the paper are graphs showing the importance of the oscillation frequency, the amplitude, the incline angle of the screening surface, the angle of oscillation on material velocity, and material elevation on the sieve. These are essential parameters that significantly affect the performance and productivity of the screen. The findings of the study may be useful for scientists to design parameters for vibrating screen reliability.

1. Introduction
A vibrating screen is a sorting machine, used to split bulk materials with various kinds into different size particles thanks to rails. The vibrating screen working principle is given in Figure 1. When the vibrator assembly (exciter) (1) works, the two the eccentric shafts which have counterweights will rotate simultaneously in opposite directions, creating centrifugal forces. The force components acting along x-x axis will be opposite and cancel out, while the force components acting along y-y axis will combine to produce oscillating forces. This force is transferred to the sieve boat (3), associated with springs (2) generating vibrations and carrying out the sieving process to classify materials [9].

When the vibrating screen operates, it depends on the dynamics and technology of the sieve, such as the vibration frequency \( f \), the vibration amplitude \( A \), the angle of vibration direction of screen \( \delta \), and the inclined angle of screen \( \alpha_o \). Hence, the material on the vibrating screen may have four relative motions to the screening surface, namely slide-forward motion, slide-back motion, stop (lie on the screening surface) and jump movement. Unless the third scenario in which the vibrating screen does not perform the sieving process, the others operate the screening process [10]. However, since the material travels and jumps up, the screen will be the most effective when working. Therefore, as designing a screen, designers tend to choose this working state.
Nevertheless, it is challenging to employ traditional methods to design parameters for a well-screened sieve. In this study, the author is going to utilize the discrete element method (DEM) to simulate and solve the mentioned problem.

**Figure 1:** The working principle of a vibrating screen: 1- Unbalance exciter; 2- Springs; 3- Screen body; 4- Screen mesh;

- $m$ = mass of each eccentric plate (kg);
- $m_o$ = total unbalanced mass (kg);
- $t$ = time (s);
- $r$ = eccentric radius (mm);
- $\omega$ = angular speed (rad/s);
- $\delta$ = angle of oscillation (°);
- $F_o$ = exciter amplitude of fluctuations caused by unbalanced mass (N);
- $F_y$ = excitation force in the y-direction at time $t$ (N).

$$F_y = \sum m_o r \omega^2 \sin \omega t = m r \omega^2 \sin \omega t = F_o \sin \omega t$$ (1)

2. **Movement principle of material on the screening surface**

**Figure 2:** Principle of material movement on the screening surface

The principle of material movement on the screening surface is shown in Figure 2. When the screen is working, the movement position of the screen is determined as follows [11,12]:

$$S = A \sin \omega t$$ (2)

Assume that the material falls downwards at the beginning is due to its weight, followed by a collision with the screening surface and bounces.

Consider the collision time between the screening surface and the material at the $i$ th time is $t_i$. Ignore changes of the speed of the screening surface before and after the collision, as well as the duration of the collision process. By applying the law of momentum conservation, the velocity of the material after the collision in the y-direction is defined as:
\[ v_{ti+} = \left| v_{ti-} - \dot{S}_{ti} \sin \delta \right| e \]  

Where,
\[ v_{ti} \] = the velocity of the material before the \( i \)th collision in the y-direction (m/s),
\[ \dot{S}_{ti} \] = the instantaneous velocity of the sieve at the \( i \)th collision (m/s),
\[ e \] = the elastic coefficient of the material.

Applying the law of conservation of energy, we yield the jump height of the particles compared to the screening surface after the collision as follows:
\[ h_i = \frac{v_{ti+}^2}{2g \cos \alpha_o} \]  

Where,
\[ g \] = the gravitational acceleration (m/s²),
\[ \alpha_o \] = the inclined angle of screen (°).

Then the average jump height according to the theory of particles is:
\[ \bar{h} = \frac{\sum_{i=1}^{n} h_i}{n} \]  

Where \( n \) = number of bounces of material particles.

Because the material hasn’t acted along the x-direction of the screening surface, the material’s average velocity, then, will be theoretically calculated using the following equation [16].
\[ v_d = \omega A \cos \delta \frac{\pi i_{K_v}}{K_v} \left( 1 + \tan \alpha_o \tan \delta \right) \]  

Where,
\[ i_{K_v} \] = the jump factor (which is the ratio between a jump time and an oscillation period);
\[ K_v \] = the jumping index, is given as:
\[ K_v = \frac{(2\pi f)^2 A \sin \delta}{g \cos \alpha_o} \]  

### 3. Applications of Discrete Element Method (DEM) in modeling the impact of dynamic and technological parameters on the material movement of the vibrating screen surface

The discrete element method (DEM) is a type of numerical method developed in the 1970s and used in a variety of fields (geological engineering, mining techniques, mineral sorting, etc.). The application of DEM can assist us in solving the problem of discrete materials, such as the position of space, the velocity, the force and energy change of particles, and so forth [13-15].

**Figure 3:** A simulation model of material on the screening surface (a) and the motion of materials in space (b)
In this article, the author uses DEM to build up a simulation model of the material on the sieve (Figure 3a) with the following basic parameters, including the size of the screen 60x30 cm, the screen mesh a = 2 cm, the diameter of material d = 4 cm, the elastic coefficient of material e = 0.5. After the simulation, achieving the result of the motion of materials in space (Figure 3b) and some results, as shown in Figures 4 to 7.

- **Effect of the vibration frequency f:**
If the vibration amplitude, the inclined angle of the screen and the angle of vibration direction of the screen are constant (i.e., A = 5.5 mm, α₀ = 6°, δ = 50°), and only adjust the vibration frequency of the screen. The trajectory of material is drawn in Figure 4.

![Figure 4: Effect of the vibration frequency on material movement](image)

Figure 4 illustrates that when the vibration frequency of the screen increases, the average speed of the material increases initially and then decreases. The reason is that when the vibration frequency increases, the number of material collisions with the surface of the screen increases and occurs other random collisions, even happen phenomenon of "jumps later", thereby increasing the number of jumps of material on the sieve and extending the sieving time. When f = 13 Hz, the number of jumps on the surface of the screen equals 6, the time to complete the sieving process is 1.15 s, the average speed of the material yields the maximum value. By contrast, when f = 15 Hz, the number of material jumps on the screening surface is 16, the completion time of the sieving process is 2.267s, and the average speed, as well as the average jump height of the material, hit the minimum values.

From the simulation results (Figure 4), we find out the average velocity and the average jump height of the material (v, h). Also, as compared with the theoretically calculated value (v₀, h₀), we have the data, as shown in table 1.

| Table 1. The value of average velocity and average jump height when adjusting the vibration frequency |
|-----------------|--------|--------|--------|--------|
| f (Hz)          | 12     | 13     | 14     | 15     |
| v (m/s)         | 0.2978 | 0.4458 | 0.2140 | 0.2056 |
| v₀ (m/s)        | 0.2849 | 0.3087 | 0.3324 | 0.3562 |
| h (cm)          | 26.4468| 25.1961| 26.4119| 22.6399|
| h₀ (cm)         | 23.4401| 18.6786| 21.9001| 17.5194|

Table 1 reveals that when the vibration frequency changes, the average velocity and average jump height of the material change slightly, which means that the frequency of vibration only has a small effect on the average velocity and the average jump height of the material. On the other hand, when f
= 13 Hz, the average velocity and the average jump height of the material are both relatively large values.

- **Effect of the vibration amplitude A:**

  If the frequency of vibration, the inclined angle of the screen and the angle of vibration direction of the screen are unchanged (i.e., \( f = 14 \) Hz, \( \alpha_0 = 6^0 \), \( \delta = 50^0 \)), only vary the vibration amplitude, the trajectory of material is shown in Figure 5.

  ![Figure 5: Effect of the vibration amplitude on material movement](image)

  From Figure 5, it is evident that as the vibration amplitude of the screen increases, the relative collision velocity between the material and the screening surface increases, the average speed and the average jump height of the material increase, the number of jumps of material decreases (similar to the theory). When \( A = 3.5 \) mm, the number of jumps of material on the screening surface is 20 times, the completion time of the screening process is 2,417s, the average speed and the average jump height reach the minimum value.

  When increasing the value of \( A \), the required time for accomplishing the sieving process decreases (approximately 1,567 s), and if \( A = 6.5 \) mm, the average velocity and the average jump height of the material hit the maximum value.

  From the simulation results (Figure 5), the average velocity and the average jump height of material (\( v, h \)) are computed, and as compared with the theoretically calculated value (\( v_d, \bar{h} \)), we yield the data, as shown in table 2.

| A (mm) | 3.5   | 4.5   | 5.5   | 6.5   |
|--------|-------|-------|-------|-------|
| \( v \) (m/s) | 0.2078 | 0.2088 | 0.2140 | 0.2977 |
| \( v_d \) (m/s) | 0.2116 | 0.2417 | 0.3324 | 0.3929 |
| h (cm)  | 19.4694 | 21.5484 | 26.4119 | 40.9729 |
| \( \bar{h} \) (cm) | 19.7285 | 19.8357 | 21.9001 | 24.2023 |

  From Table 2, one thing that can be described is the vibration amplitude of the screen shifts; the average velocity of the material also changes relatively. But the average jump height of the material varies greatly, which means the amplitude of the sieve relatively fluctuates to the average velocity of the material. Besides, this has a considerable influence on the average jump height of the material.

  Thus, paying attention is required during screen design processes. The selection of reasonable parameters means that the vibration amplitude only affects relative to the average velocity of the material, but has a significant influence on the average jump height of the material. As a result, when designing sieves, we need to choose proper parameters (In terms of materials which are difficult to...
screen, we should opt-out such a large amplitude when the screening machine is likely to achieve high velocity, high jump, and high efficiency).

- **Effect of the inclined angle of screening surface $\alpha_0$**

If the vibration frequency, the vibration amplitude and the angle of vibration direction of screen are constant (i.e., $f = 14$ Hz, $A = 5.5$ mm, $\delta = 50^\circ$), the inclined angle of screening surface is altered, the trajectory of material is mapped in Figure 6.

![Figure 6. Effect of the inclined angle of the screen on material movement](image)

The implication of Figure 6 is that when the inclined angle of the screening surface increases, the number of jumps of the material will decrease, the average velocity will increase, and the average jump height will decrease. When $\alpha_0 = 0^\circ$, then the number of jumps of the material is 20 times, the time to complete the sieving process is maximum 3.3 s, the smallest average velocity. When $\alpha_0 = 6^\circ$, the average jump height of the material reaches the maximum value. When $\alpha_0 = 9^\circ$, the initial distance between the surface screen and the material is small, the relative speed between screen and material reaches the minimum value, resulting in low jump height.

From the simulation results (Figure 6), we find the average velocity and the average jump height of material ($v$, $h$) and as compared with the theoretically calculated value ($v_d$, $h_\bar{\cdot}$), we yield the numbers, as shown in Table 3.

| $\alpha_0$ (°) | 0    | 3    | 6    | 9    |
|---------------|------|------|------|------|
| $v$ (m/s)     | 0.2477 | 0.2917 | 0.2509 | 0.3169 |
| $v_d$ (m/s)   | 0.2954 | 0.3139 | 0.3324 | 0.3512 |
| $h$ (cm)      | 21.5082 | 22.6978 | 26.4119 | 15.1523 |
| $h_\bar{\cdot}$ (cm) | 18.4471 | 16.7279 | 21.9001 | 15.3953 |

Results are given in Table 3 shows that when the inclined angle of the screen changes, the average velocity and average jump height of the material change slightly. To put it simply, the angle of the screening surface has little effect on the average velocity and the average jump height of the material. When the value of the inclined angle of the screening surface lies within the range of $3^\circ$ - $6^\circ$, the average velocity and average jump height will reach the maximum value.
Effect of the angle of vibration direction of screen $\delta$

If the vibration frequency, the vibration amplitude and the inclined angle of screening surface are constant (i.e., $f = 14$ Hz, $A = 5.5$ mm, $\alpha_0 = 60^\circ$), only changes the angle of vibration direction of the screen; the trajectory of material is represented in Figure 7.

![Figure 7. Effect of the angle of vibration direction of the screen on material movement](image)

As demonstrated in Figure 7, when the angle of the vibration direction of the screen increases, the average jump height increases, but the average velocity decreases. When $\delta = 40^\circ$, the number of jumps of the material equals 6, the average speed reaches the maximum value, the shortest time to complete the screen is 1,067s. When $\delta = 60^\circ$, the number of jumps of the material is 11, the average velocity reaches the smallest value, the time to complete the most prolonged sieving process (2.15s), and the average jump height hits the maximum value.

From the simulation results (Figure 7), it is definite that the average velocity and the average jump height of material ($v$, $h$), and as compared with the theoretically calculated value ($v_d$, $h_\bar{}$), computed numbers are listed in table 4.

| $\delta$ ($^\circ$) | 30  | 40  | 50  | 60  |
|---------------------|-----|-----|-----|-----|
| $v$ (m/s)           | 0.3672 | 0.5293 | 0.2509 | 0.1903 |
| $v_d$ (m/s)         | 0.4222 | 0.3831 | 0.3324 | 0.2716 |
| $h$ (cm)            | 19.8286 | 22.5425 | 26.4119 | 48.2712 |
| $h_\bar{}$ (cm)     | 15.9063 | 18.4471 | 21.9001 | 25.9641 |

The above table indicates that when the angle of vibration direction of screen changes, the average velocity and the average jump height of the material change substantially. In other words, the angle of the vibration direction of the screen will dramatically affect the average velocity and the average jump height of the material. Thus, in order to gain great average speed and a high jump at the same time, it is highly recommended to choose the angle of oscillation within the range of about 40$^\circ$.

4. Conclusions

By dint of using the discrete element method, the paper has simulated and analyzed in detail the effects of technological parameters, dynamics parameters on the velocity, and jump height of materials on the screening surface when the machine is working. The research results indicate that the vibration amplitude and angle of the vibration direction of the screen have a great influence on the velocity and
jump height of the materials. On the contrary, the vibration frequency and the inclined angle of the screening surface are insignificant.

For the machine working correctly with materials that are tough to screen, the authors suggest opting for the vibration frequency $f = 13$ Hz, the vibration amplitude $A = 6.5$ mm, the inclined angle of screening surface $\alpha = 6^\circ$, the angle of vibration direction of screen $\delta = 40^\circ$. The results of this study may be favorable for scientists in their field of vibrating screen design and calculations.

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