Application of Discrete Element Method in the Analysis of Loader Shovel Loading Process

Abstract: Distinct element method is a numerical method which is applicable to the analysis of granular material system, and its theoretical model is more suitable for the discontinuous, large displacement material particles. In this paper, the application of the EDEM software based on the Discrete Element Method in the analysis of the loader bucket loading process is introduced. From the force curve of the simulation, it shows that the bucket resistance can be increased first, and then gradually decreased to a stable value. Through the analysis, the simulation results are in accordance with the engineering application, which has certain reference value.

Keywords: Distinct element method; EDEM simulation; Loader shoveling

1 Introduction

Wheel loader (Figure 1) is a type of widely used transport equipment, mainly used in mining, construction, railways, roads, ports construction. Its main working process can be divided to shovel - Transport - unloading, is one of the main engineering machineries. The loader bucket in service, must meet the high loading efficiency, small operation resistance, low shovel wear etc. As the direct function parts with material, the size of the bucket working resistance directly affects the integral design of the loader. Therefore, in the design of bucket, it is very significant to study the interaction between the bucket and material.

However, the bucket is a continuum while the material is discontinuous, and material system of shoveling and unloading process is complex and changeable, moreover, the interaction force is dynamic, thus the traditional finite element analysis for the continuum can not satisfy the needs of bucket design analysis [1]. Therefore, it is necessary to explore the new technology which can be used in bucket force analysis.

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Discrete element method is a numerical method mainly used for study of granular materials. It is proposed by Cundall and Strack after their study of the rock mass, using rigid element to simplify discontinuous system, and then Newton's second law motion equation and time-step iterative method to obtain the overall state of motion of discontinuous system. The calculation process can be summarized as follows: Firstly, contact force and the relative displacement are determined according to the interparticle contact model; secondly, unbalanced forces between particles were calculated on the basis of Newton's second law; finally, use the time-step iteration law and repeat the two process above until the final claiming iterations or system tends to force balance.

The choice of the particle contact model is the core part of the discrete element method. Cundall initially proposed a two-dimensional disk contact model shown in Figure 2, two spheres’ contact was simplified as springs, dampers, Kn meant normal stiffness, dn as the normal damping, Kt as the tangential stiffness, dt as the tangential damping. Normal force and tangential force were respectively determined according to the Hertz theory [2] and Mindlin-Dereciewicz theory [3]. To achieve a more accurate model of the discrete material system, scholars improved contact model of discrete element method constantly. In literature [4-8], when the adhesion effect between unit was considered, Thornton formed the Thornton theory, in which tangential force was calculated based on Savkoor and Briggs theory [9], normal force combined with the adhesion force JKR (Johnson - Kendall - Rorberts) theory [10] on the basis of the original Hertz theory. In document [11], Rothenburg used a two-dimensional elliptic disk model for numerical simulation. In document [12], the effect of particle shape on the strength and deformation mechanism of the particle system was analyzed by Ting. In Document [13], Lin used the three-dimensional ellipsoid contact model, while in the literature [14], Oda took into account the rotation of the element, and improved the Cundall discrete element model on the basis of the Cundall model.

In short, the model DEM has been developed from simple 2D model to complex 3D model for the following 40 years since 1971, whose calculation results are getting closer to the actual situation. Gradually, it shows the advantage in certain areas.
2 Domestic engineering applications of Discrete Element Method

With the development of the discrete element method, the related simulation software has emerged. EDEM is a Discrete Element Method analysis CAE software, mainly used in the simulation of industrial particles and manufacturing equipment. EDEM, having been launched by the Solutions DEM Company since 2002, is recognized by more and more users. EDEM simulation is mainly applied in agricultural engineering and mining engineering in China. In document [15], by simplifying soybean grain as tetrahedral configuration, the process of seed filling, retaining, cleaning, seeding and other movement in a mechanical soybean high speed precision metering device was simulated. In [16], researchers used EDEM to analyze movement law of rapeseed in a centrifugal metering device, as well as the related factors influencing the metering performance. Finally, the simulation results compared with the experimental results, proved the EDEM reliable. In the literature [17] and [18], authors used EDEM to simulate the movement of particles in the large capacity silo, and discussed the factors which influenced the material flow blockage in the process of using, which provided theoretical basis for optimizing the structure of the silo. In [19], the particle motion characteristics in the dense medium cyclone were obtained based on the coupling of EDEM and other CFD software.

3 The advantages of using discrete element method to analyze the bucket force

The materials that loaders load mainly include iron ore, sand, coal. These materials have rough surfaces, angular edges, a variety of shapes, and large size distribution
range. Besides, they are interconnected with each other, being very loose, belonging to the granular materials.

Granular materials are a complex systems consisting of a large number of discrete solid particles in which particle size $d$ is greater than $1 \mu m$, interstitial fluid viscosity is low and saturation is less than 1, the contact force between the particles is leading role, while the thermal motion of the particles and fluid action weak [20]. Bulk materials systems can be divided into micro-scale, meso-scale and macro-scale, their relationships [21] are shown in Figure 3. The micro-scale mainly refers to the contact force and adhesion between particles. Meso level mainly refers to the force chain formed by the inner contact force. Force chain is relatively stable, net distributed structure formed by granular material that contact with each other, which supports the gravity and external load of the whole system, but only afford small shear. Its main properties related to not only the granular material elastic modulus, surface friction coefficient, Poisson's ratio, but also to the particle system external conditions, such as boundary conditions, initial state, external load, bulk particles dispersion. Macro scale is the mechanical behavior of the whole particle system to the external environment.

![Figure 3. Multi-scale mechanics research framework of particle system](image)

Theoretical model of the discrete element method fully takes account of the system discontinuity and large displacement. Therefore, the application in granular material system can perform its accuracy. Loading material is mainly ore, sand, coal. These materials are discrete, theoretically, it is feasible to adopt discrete element method for bucket force analysis. Discrete element method has been applied to the design of the loader bucket abroad, while China started relatively late in this field. Traditional method of mechanical structure analysis is using the patch to measure stress, and the bucket directly contacts with material when working, it is difficult to direct patch measurement. Only by indirect measurement method, can the force be measured. This is not only cumbersome operation, and experimental design of a great impact on the measurement accuracy. Through setting reasonable parameters, EDEM simulation can get the interaction force between the material and the bucket, providing qualitative reference for bucket design, which is conducive to shorten the design cycle and response to market demand rapidly.
4 The edem simulation of bucket shovelling process

EDEM mainly contains three modules: Creator, Simulator, analyst. EDEM has a powerful geometric modeling capability, allowing users to directly import mechanical structure CAD and particle CAD model, which can reduce the difficulty of its modeling, and also makes the particles model more accurately reflect the actual particle, improving simulation accuracy. What is more, EDEM software can also set the physical characteristics of the particle in the custom database, and thus reduce repeating operation.

EDEM software simulation module supports multiple operating system platforms, users can directly be offered by software contact model, and program custom contact model via the software interface; EDEM can be coupled with the CFD software simulation, to achieve a solid - liquid / gas two-phase analysis, in addition, EDEM can also be coupled with the FEA tool to complete the analysis of the structure of the manufacturing equipment. EDEM and other mainstream CAE tools coupled, which greatly expanded the discrete element method applications.

EDEM post processing module can achieve visualization and graphics operations, users can observe the physical quantity of the measurement that is not easy to measure, and can obtain 3D animation, to facilitate the dynamic display of simulation results. After calculated by EDEM, the users can get the speed and position of each particle, the interaction force chain between particles and the force between the particle and the manufacturing equipment. At last, users can get the information about the granular system behavior.

The realization of EDEM simulation in the manufacturing industry, we must determine the material properties of the granular system parameters, the relevant experiment can refer to the literature [22-24]. In theory, simulation parameters of EDEM are Poisson's ratio, shear modulus, coefficient of restitution, static friction coefficient and rolling friction coefficient. The following part describes EDEM simulation of loader shovel in loading process.

4.1 Setting global model parameters

Global model parameters need to be set are: global unit, contact model, gravity acceleration, material characteristics, material contact characteristics, and parameters were selected in Table 1, Table 2, Table 3.

Table 1. Main parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Length</th>
<th>Angle</th>
<th>Quality</th>
<th>Acceleration of gravity</th>
<th>Contact Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mm</td>
<td>°</td>
<td>kg</td>
<td>-9.81 m/s²</td>
<td>Hertz-Mindlin(no slip)</td>
</tr>
</tbody>
</table>
Table 2. Material characteristics

<table>
<thead>
<tr>
<th>Material</th>
<th>Poisson ratio</th>
<th>Shear Modulus / GPa</th>
<th>Density / kg · m⁻³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stone</td>
<td>0.29</td>
<td>11.1</td>
<td>2090</td>
</tr>
<tr>
<td>Steel</td>
<td>0.3</td>
<td>79</td>
<td>7850</td>
</tr>
</tbody>
</table>

Table 3. Material contact properties

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Coefficient of restitution</th>
<th>Coefficient of static friction</th>
<th>Coefficient of rolling friction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stone-Stone</td>
<td>0.5</td>
<td>0.84</td>
<td>0.002</td>
</tr>
<tr>
<td>Stone-Steel</td>
<td>0.45</td>
<td>0.47</td>
<td>0.002</td>
</tr>
</tbody>
</table>

4.2 Defining the basic particles and geometry

Material particles shown in Figure 4 was defined as “stone”, size was 14*13*10m³. The bucket model shown in Figure 5 was created by the UG, and then imported into the EDEM, material selected for the “steel”, the movement of the bucket was set as following: 0s-2s, shoveled into material with uniform velocity of 0.12 m/s to the X-axis direction; 2s-3s for rotating bucket stage, the angular velocity was 25°/s; 3s-3.27s as backing stage with speed of 0.5m/s to negative X-axis direction; 3.27s-4s as lifting phase with velocity of 0.1 m/s to the Z-axis direction.

Figure 4. Particle model
4.3 Defining the particle factory

Factory type was set to generate statically, and the total number of simulation particles was 1000, generated at a rate of 1000 per second. The distribution of particles was normal distribution, the particle generation location was random, with the velocity of 0.1m/s to negative Z-axis. After generated, the particle factory was shown in Figure 6.

4.4 Simulation parameter setting

The simulation step size was set to 20%, and the total simulation time was 4s, outputting interval was 0.01s.
4.5 Analysis of simulation results

Simulation process was shown in Figure 7. After the simulation, by using EDEM post-processing tools, loading weight was measured to be 1.39 kg, shown in Figure 8. Eventually, changes of resistance force by bucket were presented in Figure 9.

Figure 7. Simulation process

Figure 8. Loading quality
Conclusion

The simulation results showed that the bucket’s resistance increased rapidly and reached the maximum value, and then decreased gradually to a stable value. Through the analysis, the simulation results were in accordance with the engineering application. Because the materials system was in a static state at the beginning, a stable force chain was formed inside. When the bucket was horizontally inserted into the bottom of the material system, the materials contacted with the bucket not only formed a force chain with the materials above but also with the rear materials. In this case, material system could withstand greater external force, so the resistance suffered by the bucket gradually increased. As the bucket rotated, the materials contacted with the bucket just formed a force chain with the materials above it. Thus, the bucket could shovel into the materials with less force, so the resistance force was reduced gradually. When the bucket was lifted at a uniform speed, the bucket would only be subjected to the gravity of the materials loaded, and its size would be fixed.

Bulk materials are abundant in agricultural and mining production. Loaders bucket traditional design method is the empirical formula calculation and experimental comparison. The interaction force between material elements and bucket is difficult
to be accurately measured, and test cycle is long and costly. Discrete element method is a numerical method to solve the problem of granular system. Compared with the finite element method, the discrete element method is still applicable to large displacement and discontinuous systems, which gives the discrete element method a unique advantage in specific fields. EDEM software based on discrete element method can facilitate the simulation of particle production process, reduce the prototype test and shorten the design cycle, which provides an effective tool for the design of bucket.

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References


