Simulation of Bottle Conveyors — Opportunities of the Discrete Element Method (DEM)

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ABSTRACT The Discrete Element Method (DEM) provides an approach to recognition of the problems within bottle conveyors at an early stage of the engineering process. Key points in bottle conveyor systems, such as buffers, ejectors, diverters and transfers can be numerically analyzed. It is possible to calculate forces on lateral guides and forces between bottles within accumulation situations. The DEM provides an alternative opportunity for the virtual process optimization and numeric case studies of conveying systems at beverage and food industries.

KEYWORDS discrete element method, conveyor system, bottles, food industry, simulation

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KURZFASSUNG *Simulation von Flaschenförderern — Möglichkeiten der Diskreten Elemente Methode (DEM):* Die diskrete Elementmethode (DEM) ermöglicht in einem frühen Stadium des Engineering-Prozesses die Erkennung von Problemen in Flaschenförderern. Wichtige Systemelemente wie Puffer, Ausschleuser, Weichen und Übergabestellen können numerisch analysiert werden. Es ist somit u. a. möglich, Kräfte auf Seitenführungen und Kräfte zwischen den Flaschen innerhalb von Stausituationen zu berechnen. Die DEM bietet eine alternative Möglichkeit für die virtuelle Prozessoptimierung und die Durchführung numerischer Fallstudien von Fördersystemen u. a. in der Getränke- und Lebensmittelindustrie.

SCHLAGWÖRTER Diskrete Elemente Methode, Fördersystem, Flaschen, Lebensmittelindustrie, Simulation

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1. Introduction

Engineering, development, and optimization of new continuous conveyor tracks, buffers, ejectors and diverters in the field of bottle conveying, necessitate the knowledge of different process parameters. These include the properties of each product and its motion paths within the conveying system as well as the goal criteria, throughput and conveying speed. Currently, the engineering of new bottle handling systems is based on experience and frequent experimental tests on prototypes or test rigs with industrial size. If the process parameters

could be estimated using numerical studies, the number of expensive prototype tests would be reduced. Continuous conveyor tracks, buffers, ejectors, and diverters could be optimized to specific target criteria if simulations are used in the development process. In many industrial fields, simulations are state-of-the-art, supporting the industrial design process and avoiding the high count of expensive prototypes and tests.

Simulations of the conveying processes in bottle conveyors, the representation of accumulation, the evaluation of forces on lateral guides and the tendency of bottle overturning require numerical models of these bottles. Especially the numerical examination of processes within buffers and diverters assumes a high number of virtual bottles in a simulation model. These requirements often lead to the unsuitability of certain simulation methods, e. g. multi-body simulations with an exponential link between body count and simulation time. Hence, the calculation with such methods become very slow. In contrast to this, the Discrete Element Method has a linear relationship between the number of particles included and the absolute simulation time. Hence, this paper should show, how DEM simulation can be used to model bottle conveyors.

2. Discrete Element Method

2.1. Introduction

The Discrete Element Method (DEM) is a numerical method for describing the motion and behavior of particulate systems as the sum of individual contact events within the system. It was developed by Cundall and Strack [1] in the 1970s. Over the last years, the DEM has become a valuable tool in the analysis of granular media. The method is widespread in the field of bulk solids simulation. This development is caused by the continuing growth of computing performance. Nevertheless, it is a computationally intensive approach. The correlation between the number of particles within a simulation system and the equations that must be solved limits the system dimensions.

The DEM describes each individual particle P by means of its mass m, its acceleration $\overrightarrow{\ddot{x}_p}$ and the sum of the forces F_n acting on it (1). The moment of inertia J_P and the angular acceleration $\overrightarrow{\ddot{\varphi}_P}$ are in an equilibrium state with the sum of the moments T_n acting on the particle. The resulting Lagrangian force equilibrium is integrated over all time steps.

$$\begin{aligned} m_P \cdot \overrightarrow{\ddot{x}_P} &= \sum F_n \\ J_P \cdot \overrightarrow{\ddot{\varphi}_P} &= \sum T_n \end{aligned} \tag{1}$$

The effective forces within the numerical system are represented by the so-called contact model. Different contact models are available. They represent the physical interaction of the simulation entities. The simplest contact model is a linear spring-dashpot model. Figure 1 shows a schematic diagram of this contact case for the particles $\{i, j\}$ with the particle mass m,

the friction coefficient μ, the tangential and normal components of the spring stiffness k and the damping γ.

In addition to the contact models, the particle models are liable for the geometric shape of the particles. They form the basis for the modeling of realistic particle simulations. The numerical representation of particle shape determines the quality of the representation of real particle geometries but also significantly influences the necessary computational effort. Due to the geometric complexity of the particle model, the numeric complexity of a simulation increases. Hence, a compromise between shape complexity and computational demands must be found. The most common particle models are circles in 2D-case and spheres in 3D-case. The spherical particles have advantages regarding the contact detection algorithms and the numerical contact calculation. Particles or bodies with more complex shape can be formed by spherical particles using the so-called multisphere or clump approach. In contrast, more complex particle shapes are polygons and superquadrics. The possibility of using superquadrics as a particle model was non-existent at the time of editing in the used DEM software LIGGGHTS® [2]. Podlozhnyuk introduces in [3] the planned implementation of this particle kind into this software.

A significant advantage of the DEM as a simulation method is the possibility to include an enormous number of particles within a simulation. With the current level of performance, particle systems with up to 1 million particles can be calculated on conventional desktop PCs within a few hours. This time expenditure also depends on the contact model and the complexity of the depicted situation.

The software used for the simulation examples and case studies within this work is called LIGGGHTS®-PUBLIC [2]. It is an open source DEM simulation code. The software is released under the GNU General Public License. It is highly capable using a great amount of CPU cores.

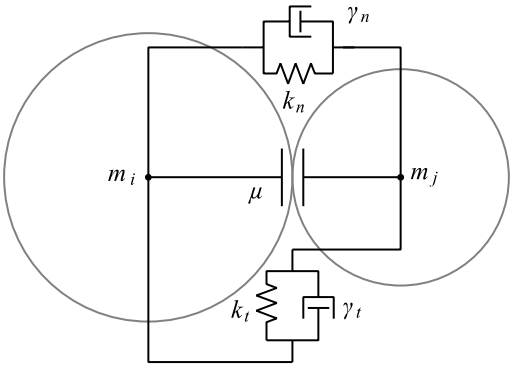

Figure 1: Spring-dashpot contact model (sphere-sphere contact)

2.2. Simulation Time Dependencies

The energy transmission within a granular particle system occurs through body and surface waves. It is assumed that most of the energy is transferred by so-called Rayleigh waves (surface waves). In this case, the transmission amounts of the transverse and longitudinal body waves are neglected. To take account of the phenomenon of wave propagation within the simulations

the selected iteration time steps must be correspondingly short. The critical iteration time step t_{crit} depends on the propagation time of a Rayleigh wave t_{Ray} in the particle. Equation (2) shows the approximation equation for the Rayleigh time t_{Ray} and a guideline for the critical iteration time step t_{crit} of a simulation.

$$t_{crit} = 0{,}1 \cdot t_{Ray}, \qquad t_{Ray} = \frac{\pi \cdot r_p \cdot \sqrt{\frac{\rho_p}{G_p}}}{0{,}1631\nu_p + 0{,}8766} \tag{2}$$

$$t_{C,t} = \frac{t_{R,t}}{t_{crit}} \cdot t_{C,I}$$

The equations (2) show how the total computation time $t_{C,t}$ required for the simulation is calculated, based on the real time to compute a single iteration step $t_{C,I}$, the total time which should be simulated $t_{R,t}$, and the critical time step t_{crit}. The quotient reflects the number of iteration steps of a simulation. The user often has to find a compromise between the critical time step size t_{crit} and the physical particle characteristics when calibrating the boundary values (contact model parameters) of the substitute material. In addition to their significance as physical system variables, the boundary conditions of the particle also influence the magnitude of the critical simulation time step. These quantities are the density ρ_p, the shear modulus G_p, the Poisson's ratio ν_p, and the particle radius r_p.

For DEM simulations it can be generally said, that the bottlenecks regarding the absolute simulation time are the contact detection and the neighbor sorting algorithms. In LIGGGHTS® there is also an overhead regarding the MPI (Message Passing Interface) managing system in case of multicore simulations.

3. Building up the Simulation

3.1. Geometries, Surfaces and Meshes

For the simulation of goods passing handling systems and production machines within the conveyor track, it is necessary to model the interfaces between the goods and the machine. The geometries in direct contact with the conveyed goods can be imported as STL meshes into the simulations. The STL format describes surfaces by means of triangles, using the corner points of the triangle and the surface normal to the triangle.

The imported geometries can be driven by predetermined movements. Possible motions include translation, rotation, translatory and rotatory vibrations, as well as the conversion of a surface speed without moving the mesh as such. This surface speed is used to accept a belt conveyor. All of the motion specifications mentioned above can be superimposed on each other per superposition principle. The common polygon effect can be applied to conveyor chains. Vibration excitations, starting and braking processes can also be integrated into the simulation.

The DEM software evaluates the frequency of the contacts and the contact forces between the particles and walls. This evaluation allows the contact forces to be viewed more precisely on the

particles, e. g. the bottles. The resulting forces on the geometries with particle contact can also be evaluated. These forces represent to be the lateral forces on the side guides or the forces on stopper plates due to jamming. If the geometries very finely meshed, the con-tact zones can be resolved accordingly. However, with an increasing number of triangular facets of a mesh, the required calculation time also increases for an iteration step. Thus, the meshes should not generally be meshed with high resolution.

Figure 2a shows a meshed stopper plate in front of the gray bottle models. The colors visualize the normal stress within the contact zone. The bottles are moving against the plate. The graph in Figure 2b represents the total force on this stopper plate over the simulation time. The shown force peaks result from the impacts between the bottles and the plate.

(a): normal stress distribution on a stopper plate at a bottle jam

(b) normal force on stopper plate over time

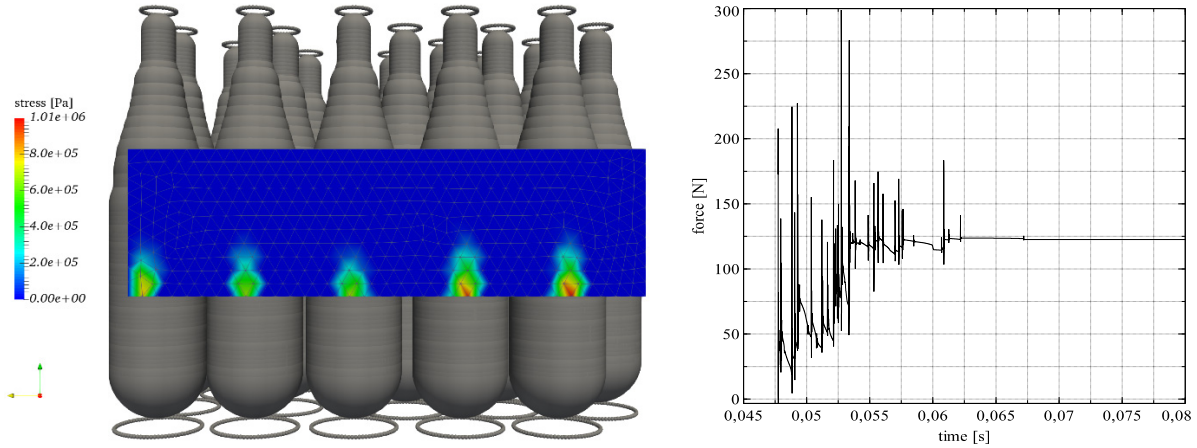

Figure 2: Examples of calculated forces on meshes of boundary equipment

(a) Milk bottle (b) NRW beer bottle (Mod. A) (c) NRW beer bottle (Mod. B)

Figure 3: Examples of different bottles modeled as clump

3.2. Particle modeling, development of the bottle

For the simulation of complex goods, individual spherical particles are linked together. These particle clusters are known as clumps or multi-sphere particles. During clump generation, the individual particles can overlap within the clumps. For further simulations, a rigid coupling between the clumped particles is considered.

The forces generated by these overlaps will be excluded from the calculations. To allow a realistic motion of the clumped structures, the center of gravity and the inertia with respect to the principal axes of the clumps are given as boundary values. There are different strategies for building the clumps. The strategy depends on the objectives of the simulation and the actual processes which should be modeled. The references [6-9] give an overview of the clump internal force calculation and validation methods for these particle classes.

Figure 3 outlines two different approaches for the modeling of a beverage bottle. The bottle model 3a stands for a diary product bottle. The bottle model in figure 3b shows a bottle consisting of 6172 individual particles. The particle diameters correspond approximately to the wall thickness of an NRW beer bottle cf. [4]. Thus, the models of figure 3a and figure 3b are hollow inside like a real bottle. Their glass coating is represented by a high number of small spheres along the circumference. However, this approach has a number of disadvantages.

Firstly, the high number of clump internal particles limits the number of computable bottles within the simulation. This fact is a consequence of the limited computational power. Secondly, small particle diameters cause short iteration time steps and an increase of the absolute simulation time. Section 2.2 describes the relation between the simulation time and particle properties in detail.

Another problem of clumping the small spheres along the circumference are the gaps be-tween the individual particles. Even if the particles are overlapping, still there are notches, because of their spherical shape. These notches lead to interlocking effects during the bottle to bottle contact case. Figure 4 shows these circumstances. During jamming, the bottles gar-land kinks against the lateral guides. However, only two bottles within the steady state of this jam are in contact with the lateral guides. This problem and the unsteady cylindrical bottle surface leads to a wrong force calculation between the lateral guide and the bottle.

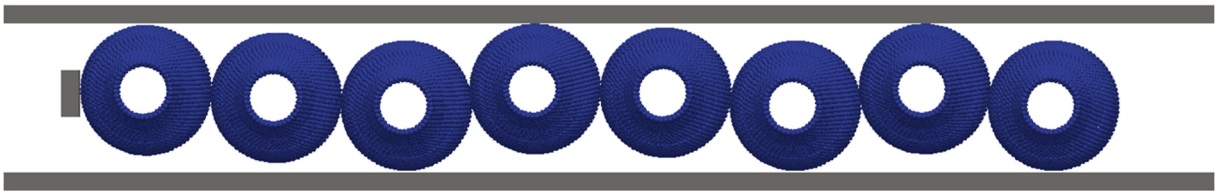

Figure 4: Interlock effect within the case of bottle jam

The modeled bottle shown in figure 3c consists of 182 clumped spheres. A transparent view of the detailed structure is shown in figure 5. The spheres diameter corresponds the bottle diameter except for the spheres building up the footprint and the head of the bottle. Hence, the bottle is not hollow inside. To ensure the stability, the footprint is modeled as a ring of spheres.

Even the bottle head is represented as a clumped ring of spheres. Both rings of particles still belong to the bottle clump although they are not physically connected. The linked particles within a single clump don't necessarily need to be in touch with each other. But areas without particle covering within the clump are not able to be in contact with other clumps or geometries. In the case of bottle overturning, the rings of the head and the foot could get caught in each other. Hence, this is a critical effect, which is currently worked on to avoid complications in bottle crash cases.

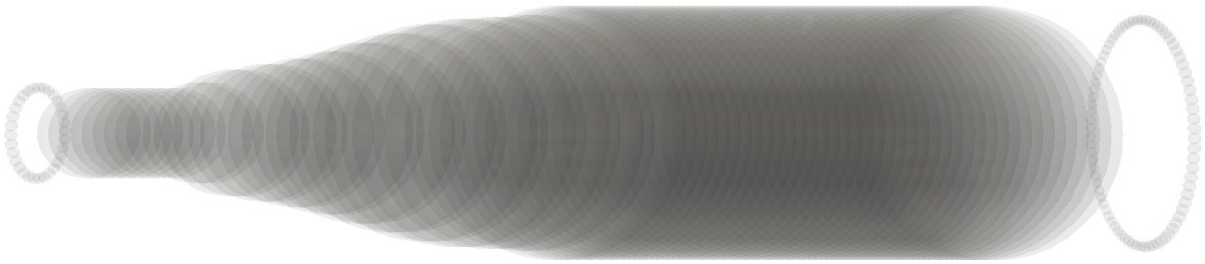

Figure 5: Transparent structure of clumped bottle model (Mod. B) in detail

Table 1 shows a comparison of the two different NRW beer bottle models, regarding the number of possible bottles in the simulation. As an example, the number of particles in the simulations is being held constant. Although the simulation times are related to each, they are not necessarily constant, even if the total number of particles is held fixed. The models were created with computer scripts, specially developed for bottle conveying application. These speed up and simplify the operation of preprocessing.

Table 1: Comparison of the two different NRW beer bottle models

Model	Particles per clump	Number of particles to simulate	Bottles in simulation
A	6172	50000	8
B	182	50000	274

3.3. Boundary conditions and material models

Besides the geometrical shape of a body, the material properties are also important. These material properties depend on the contact model which defines the simulation. The contact models of the DEM define the contact properties at the microscopic level. The macroscopic behavior of the simulated goods results from the multiplicity of the individual contact cases. These fundamental properties of the DEM lead to the experimental character of the simulations and allow macroscopic regularities to be deduced directly from the simulation results.

The carried-out simulations use a contact model specially adapted for granular media which is shown in figure 1. The elastic contact force in the normal direction is based on Hertz's contact of spherical bodies. The elastic tangential contact force is calculated by the integral of the relative tangential velocity over the duration of the contact.

The necessary boundary conditions include the modulus of elasticity, the coefficient of friction, the coefficient of restitution, the Poisson's ratio and the density. It is also possible to add force components representing the cohesion and the rolling friction of the particles, which requires further boundary conditions.

The specified material characteristics describe the microscopic level of the individual contact. There are usually no data sets available for these characteristic values. Especially it is difficult to generate these values in complex models based on clumps. The vague physical quantities such as the coefficient of restitution, which is dependent on the geometric shape of the con-tact and the material properties, do not represent the macroscopic system behavior, defined on the microscopic level.

In order to achieve results which are as realistic as possible, it is necessary to calibrate the simulations and the boundary parameters with the aid of additional calibration experiments. The calibration is based on different fundamental real-world experiments. Each of this experiments has a numerical counterpart. The real-world experimental results are compared with the corresponding results of the equivalent numerical DEM experiments. By means of parameter studies, certain material characteristics within the simulations are adapted until the numerical system correlates to the real experiment. The experiments depend on the material characteristic to be calibrated, and the simulation system applied. In many cases, they are developed specifically for a certain application. The references [9-12] outline the necessity of calibration tests and show examples in the field of bulk solid calibrations.

In the case of the DEM simulations for bottle conveyors, we are currently developing suitable methods for calibrating the friction values and investigating the influence of the coefficient of restitution on the contact characteristics of the bottle to bottle contact. The inclusion of electrostatic attraction forces within the DEM to simulate the properties of the individual plastic bottles, the lateral guides, and the conveyor chain are also a research area. It is possible to include the electrostatic attraction directly or through cohesion forces as a substitute. Calibration experiments, regarding the attraction forces, are under development.

4. Examples

Various simulations have been carried out so far to test the suitability of the DEM as a simulation method for bottle handling systems. For this purpose, selected sections of conveyor tracks were modeled, meshed and loaded with virtual bottles. The current models were only used for qualitative review. These reviews showed good correlation with the expected conveying characteristics. If the necessary calibration methods are developed, it can be expected that DEM simulation of bottle conveyors will also provide quantitative results.

Figure 6 shows a conveyor section with lateral guides and a bottle count of 145. These lateral guides taper the flow of the bottles. The implemented bottles comply with the bottle model B mentioned in table 1. The material parameters are based on the characteristics of glass.

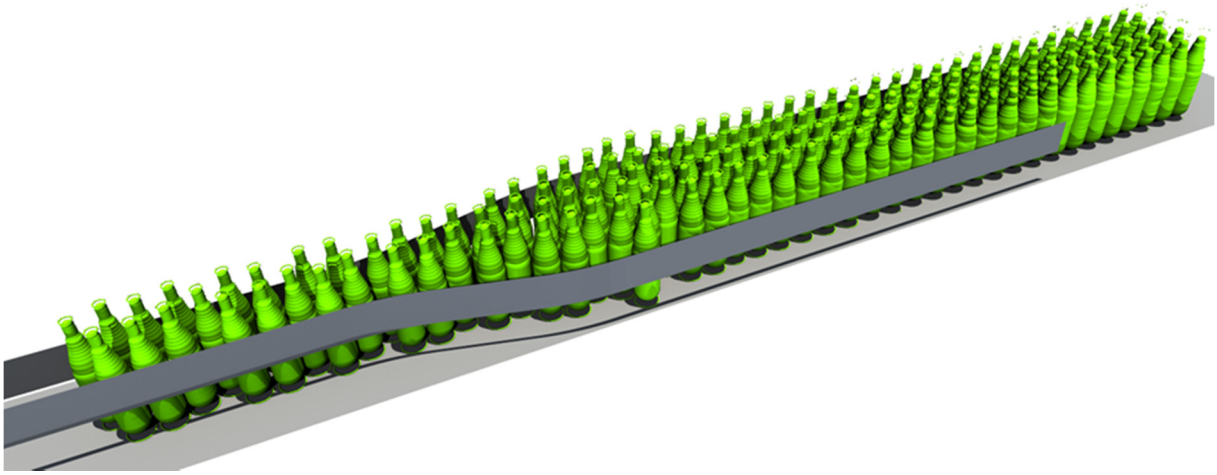

Figure 6: Example of a conveyor track loaded with 145 bottles

5. Conclusion

This paper has shown the possibilities for the accomplishment of numerical simulations of handling and conveying systems in general and for beverage bottles, in particular. The DEM represents an efficient calculation method for the implementation of simulation systems with a high number of considered bodies.

The bottles were constructed with rigidly connected single particles, so-called clumps. Different approaches to the construction of the clumps were described to show their pros and cons. It was also shown that a reasonable modeling of a body out of particles could save many particles per clump and speed up the simulation or even make it possible to calculate more bottles.

The use of the DEM as a direct replacement for prototype tests requires reliable quantitative results. To obtain these quantitative results, calibration procedures have to be developed which cover the real boundary conditions, deliver the parameters of the DEM contact model and hence result in a realistic simulation behavior.

The aims of planned numerical experiments are the determination and evaluation of the forces and contact frequencies on the supporting walls. There are also efforts to implement more complex conveying tracks and a higher number of clumps in the simulations. In this process, benchmarks regarding the simulation runtime and parametric studies in terms of geometric optimizations are also planned.

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