An Efficient 3D FEM - DEM Coupling for Granular Matter Applications

Mark Michael*, Bernhard Peters* and Frank Vogel†

* Faculty of Science, Technology and Communication (FSTC)
University of Luxembourg
6, rue Coudenhove-Kalergi, L-1359 Luxembourg, Luxembourg
e-mail: mark.michael@uni.lu, web page: http://www.xdem.de

† inuTech GmbH
Fürther Strasse 212, 90429 Nürnberg, Germany
email: frank.vogel@inutech.de - Web page: http://www.inutech.de

ABSTRACT

The presented approach is relevant to almost all engineering applications that deal with granular matter such as off-road tire performance, transport on conveyor belts or displacement of granular material as in mixers or excavation of soil. For all these applications an engineering device is in contact with granular matter which causes responses due to the interaction forces. The proposed Extended Discrete Element Method (XDEM) as a combination of the Discrete Element Method (DEM) and the Finite Element Method (FEM) allows to sufficiently resolve the different domains involved in these engineering applications. Herein the motion of each grain is accounted for individually. Simultaneously, the finite element method accurately predicts the deformations experienced by the engineering device. Thus, the simulation domain occupied by the device is efficiently described as a continuous entity. The coupling of both methods is based on the interface shared by the two spatially separated domains. The interface coupling enables to apply a contact model suited to the particular contact behaviour between the grains and the surface material if the engineering device. In contact, forces develop at the interface and generate an responce in each domain. The coupling method enables to capture both responses simultaneously. Each grain in contact with the device surface generates a contact force to which it reacts repulsively. The contact forces sum up over the surface and cause deformations of device body. It further employs a fast contact detection algorithm to save valuable computation time. This concept is supported by the software tools of the Discrete Particle Method (DPM) and Diffpack. To exemplify the presented method, the tractive performance of different tire treads has been studied on a soil layer of the stony terrian. The simulation results are used to analyse the gross tractive effort, running resistance and drawbar pull of the different tread patterns.

Keywords: Finite Element Methode (FEM), Discrete Element Methode (DEM), DEM – FEM Coupling Simulations

1 INTRODUCTION

A broad range of engineering applications are facing multi-scale problems. A large number of these problems involve heterogeneous materials such as granular media. Application in fracture mechanics, soil-structure interaction, fluidized particle beds and tire-terrain interaction are major fields to name when it comes to dealing with different length scales. The ever increasing computation power allows to account for these problems by different numerical simulation techniques.

The combination of discrete and continuum approaches (CCDM - Combined Continuum and Discrete Model) is a powerful tool to account for different scales within problems. Traditional numerical methods, such as the Finite Element Method (FEM), describe materials as continuous entities. This assumption allows an increasing number of engineering problems to be solved conveniently at the macroscopic scale by means of numerical simulations. But this approach inherits one fundamental drawback the averaging of all individual characteristics of the grain scale. However, high performance computer technique now enables the employment of methods, such as the Discrete Element Method (DEM), able to account for the individual behaviour of each grain within a granular assembly. This allows to derive the macroscopic characteristics from the behaviour observed at each single grain. But since the discrete approach requires for contact detection, calculation of all contact reactions and a high resolution of the time scale, the method inherits large computation time as a significant disadvantage. Hence, the idea seem quite natural to utilize the advantages of both the continuum and the discrete approach and thereby compensating the shortages of each method. Thus, numerical methods of coupling continuum and discrete approaches are under constant development with the purpose to resolve different scales within engineering applications.

2 EXTENDED DISCRETE ELEMENT METHOD (XDEM)

Phenomena including a particulate phase may basically be modelled by two approaches: An ensemble of particles is treated as a continuum on a macroscopic level or is resolved on a particle-individual level. The former is well suited to process modelling due to its computational convenience and efficiency. However, detailed information on particle size, shape or material is lost due to the averaging concept. As a consequence, this loss of information on a particle scale has to be compensated for by additional constitutive or closure relations.

In this study the newly Extended Discrete Element Method (XDEM) is used to describe the motion of particulated matter by the integration of Newton's second law over time. Contrary to the continuum mechanics approach, XDEM considers the solid phase consisting of a finite number of individual particles similar to the Discrete Element Method. Its prediction of the dynamics of a particulate system is extended by the thermodynamics state of each particle, and therefore, is referred to as the Extended Discrete Element Method. Thus, the shortcomings of the Discrete Element Method that does not provide results on the thermodynamic state of particles are alleviated. The thermodynamic state of a particle may simply include an internal temperature distribution, but may also contain transport of species due to diffusion or convection in a porous matrix in conjunction with thermo-/chemical conversion due to reaction mechanisms. Hence, the Extended Discrete Element Method opens a broad domain for application in process engineering, food industry and solid reactor engineering as addressed in the current contribution. Differential conservation equations for energy, mass, species and momentum within a particle describe the thermodynamic state, and thus, applying it to each particle furnishes particle resolved results of a packed bed. Due to a discrete description of the solid phase, constitutive relations are omitted, and therefore, lead to a better understanding of the fundamentals. It offers a significantly deeper insight into the underlying physics as compared to the continuum mechanics concepts for a packed bed, and thus, advances extensively knowledge for analysis and design. In order to keep CPU time requirements within acceptable margins, fast and efficient algorithms have to be developed , which are preferably combined with High Performance Computing (HPC).

3 FINITE ELEMENT METHOD (FEM) FOR ELASTIC BODY DEFORMATION

The Finite Element method is a highly practical and common tool in engineering and research faculties. The amount of problems attacked with the help of this method became as numerous as articles and books in this field. This study applies a fully time dependent model to describe the elastic body deformations. The mathematical model of elastic deformation of solid bodies is also based on Newton’s second law, which has already serves in here as the foundation of the discrete element method. Additionally, for the description of deformation a constitutive relation between stress and strain has to incorporated. Thereafter, the finite element formulation is introduced as a general numerical approach to discretize the derived mathematical models and to solve the established PDEs. The continuum description of elastic deformation by means of finite element method played a key role and was a the biggest success while establishing mathematical modelling and scientific computing into the engineering world.

4 EFFICIENT DEM - FEM COUPLING METHOD

In the following the coupling procedure is described within the time loop. The first key part is the efficient algorithm for a fast prediction of potential contact pairs between particle and surface element. After the prediction of potential contact pair, the actual intersection of particle and surface element of the FE mesh must be predicted. Finally, as the major key of the coupling the interpolation of the contact force onto the element nodes is computed.

Within the context of explicit time integration the procedure of the DEM – FEM coupling algorithm is relatively straight forward. Before the procedure enters the time loop to predict the motion of particles and the deformation of the solid body an initiation phase is required to establish the foundation for later information exchange. The efficient contact detection is base on the intersection between spheres and triangles as particles and surface elements respectively. The initiation starts with solving the stationary problem with in the FEM domian. This step provides two informations to the procedure. First, it established the matrices and initial displacement values of the FEM domain. On the other hand it serves with the first deformed structure for the DEM domain. The second step of the initiation phase mirrors the deformed surface elements of the FEM mesh into DEM domain. Hence, at all time the surface geometry of the deformed body exists in the similar way inside the DEM domain. On this basis the coupling algorithm is linking the particular surface element with the according boundary shape between FEM and DEM domain respectively.

The loop over time is separated into four major parts. Thereby, the order of the computations follows the physical events logically. First, the motion of the granular assembly is integrated. Following this step, the impacts between particles and the elastic body are predicted. Thereafter, the deformation of elastic body due to the impacting forces can be solved by the FEM scheme. The last part of the procedure updates position of the boundary shapes before the particle motion is repredicted within the new time step.

5 APPLICATIONS

The interface coupling between the Discrete Element Method (DEM) and the Finite Element Method (FEM) is applicable to almost all engineering applications that deal with granular matter.
Figure 1 shows the DEM - FEM simulation of a belt conveyer. Applications of a conveyer belts are widespread through all engineering companies concerned with the transport of industrial and agricultural materials, typical bulk ma terial transported are grain, coal and ores. Under loading with a particle assembly, the belt experiences deformation, presented by colors in Figure 1.
The interaction between terrain and tire tread is investigated within the second application, depict in Figure 2. The purpose of those computation is to study the traction mechanisms between the tire and the granular ground. The traction force not only the integral force from the friction of each individual grain in contact with the tire surface. The traction is also influenced by interlocking mechanisms between tread parts and granular in contact. To resolve this scale and the deformation of the tire a DEM - FEM coupling simulation suits very well.

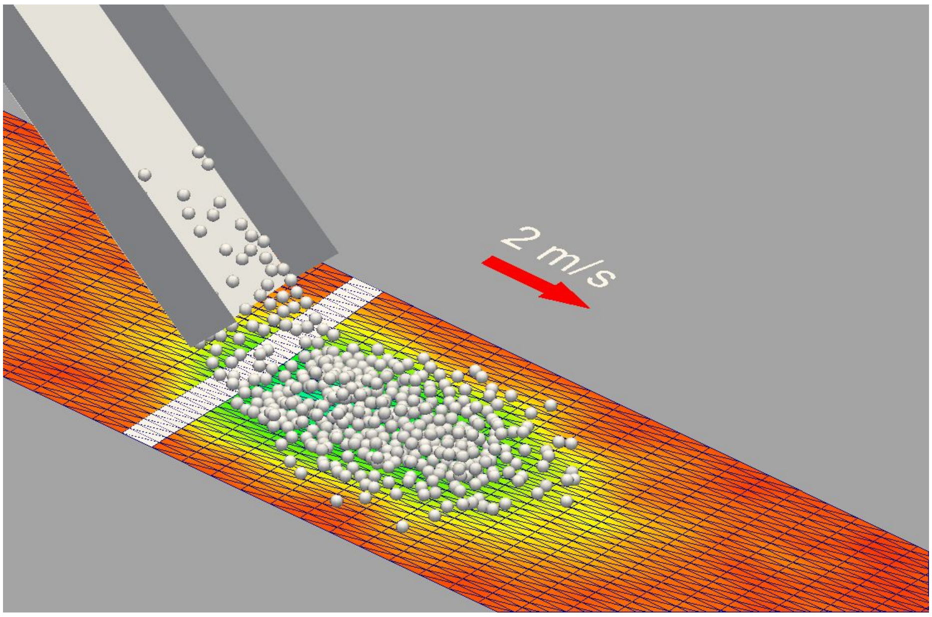

Fig. 1 DEM-FEM Coupling Simulation of Conveyer Belt Loading

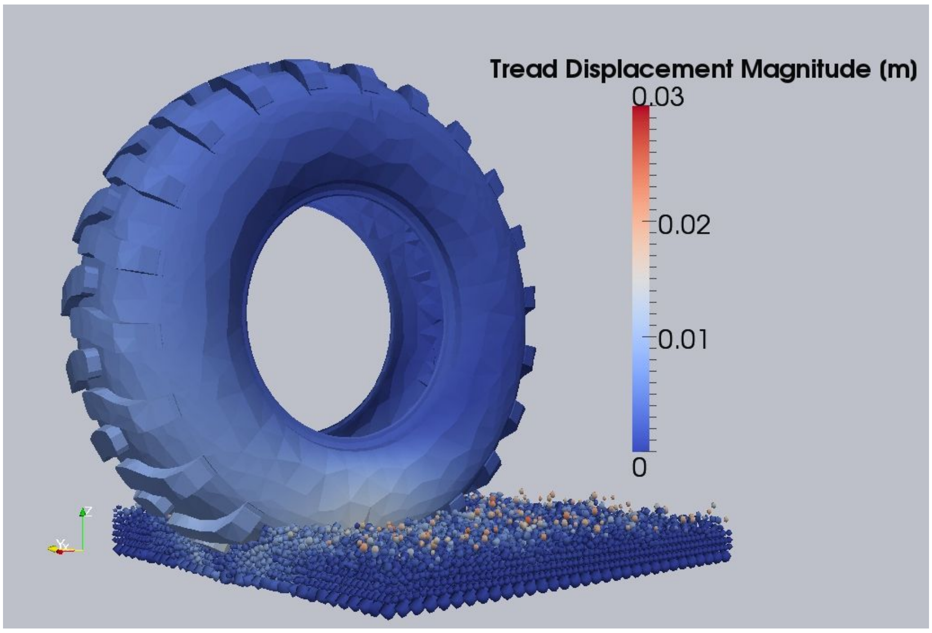

Fig. 2 Tire–Terrian Interation by Means of DEM-FEM Coupling Simulation