A DEM-FEM coupling approach to model wheel loader bucket loading

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***Abstract*— A coupling of the Discrete Element Method and the Finite Element Method is presented to demonstrate its value in wheel loader simulations, particularly focusing on the simulation of a wheel loader bucket loading granular material. This approach enables the evaluation of stresses on the bucket during loading, expanding the possibilities for assessing bucket designs. Different bucket filling strategies are compared based on key metrics, including the loaded material mass, the work done by the bucket, and the resultant stress responses within the bucket.**

Keywords: DEM; FEM; wheel loader; bucket; coupling;

1. Introduction

In the past decade, simulations coupling Multi-Body Dynamics (MBD) with the Discrete Element Method (DEM) have been applied in the heavy machinery industry. With the DEM-MBD simulations, the interaction between machinery and soil or granular material can be analysed, such as in modelling wheel loader operations [1-3]. The coupled simulations accurately depict how machinery interacts with granular materials, thereby effectively capturing the impact on machine movement during operation. This enables trade-off analyses and optimisations for the wheel loader operations, as done by [2,3].

With the capability to model both machine-granular material interactions and the detailed behaviour of granular materials themselves, the next logical progression involves considering stresses and strains within machine components during operation. This can be accomplished, for example, through the application of the Finite Element Method (FEM). While a combined MBD-DEM-FEM approach for simulations poses computational challenges, we introduce a DEM-FEM coupling for heavy machinery, marking an initial step toward comprehensive MBD-DEM-FEM modelling.

2. Method

2.1. Numerical approach

The DEM-FEM surface coupling is based on the GPU-based state-of-art explicit solver Demify® for DEM and an in-house solver for FEM simulations. Both solvers have a C++ backend and provide a Python interface, which is accessed within the DEM-FEM coupling algorithm.

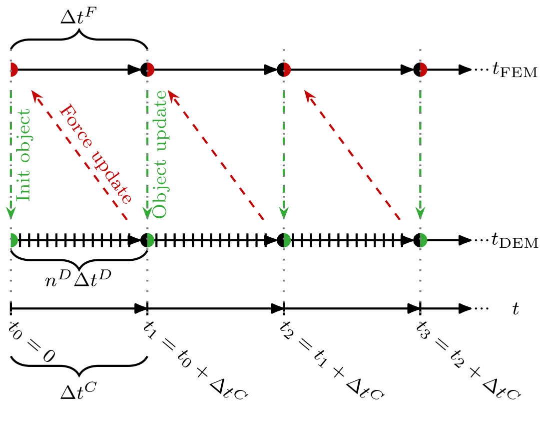

Figure 1. Schematic of the DEM-FEM coupling algorithm, modified from [4]. *(figure caption)*

A schematic for the coupling algorithm is depicted in Figure 1. At the beginning of the coupled simulation, the FEM object is initialised in the DEM domain for co-simulation to resolve the interaction with the particles. After some timesteps in the DEM simulation, the forces arising from the interaction between the bucket and the granular material are gathered from DEM and given as point load boundary conditions on the bucket in FEM. Then, after one timestep in FEM, the positions, velocities and accelerations of the FEM object nodes are applied as motion to the co-simulated bucket object in DEM.

For brevity, details of the implementations are omitted, and the interested reader is referred to [5] for DEM and [6] for FEM.

2.2. Simulation of wheel loader bucket loading

The bucket is modelled as a tetrahedral volume mesh in FEM, based on the design of a Volvo L180 bucket, with material properties corresponding to quenched and tempered steel. Boundary conditions for the bucket's motion are applied to a set of nodes at the typical positions of the attachment brackets.

In this study, five different load cases are considered and compared. The trajectories for these load cases, shown in Figure 2, follow the same rotational motion but vary in their starting positions. All motions simulate the action of loading rocks from a pile of granular material.

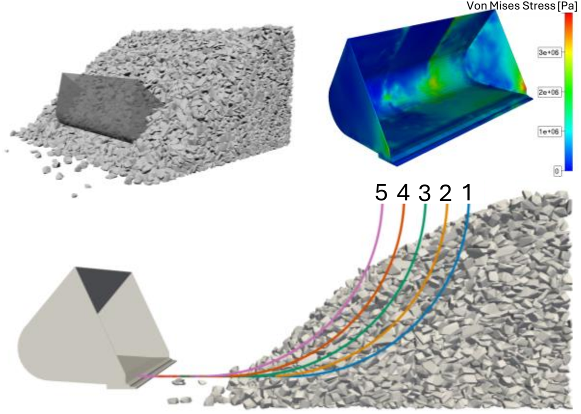

Figure 2. Illustration of the simulated particle pile (top left), the stresses on the bucket during a load operation (top right) and the bucket trajectories corresponding to the five load cases considered in this study (bottom). *(figure caption)*

The rocks are simulated as convex dilated polyhedral particles based on six scans from real rocks. The Hertz-Mindlin-Deresiewicz interaction model is used to resolve interactions both between the particles and between the particles and the bucket. The particle sizes are uniformly distributed between 90 and 150 mm, and the material properties of the rock particles correspond to those of granite.

3. Results

The five load cases are evaluated based on the loaded mass of rocks at the end of the motion, the total work done by the bucket, and the maximal von Mises stress on the bucket tip measured during the load operation. The work done by the bucket is calculated at each timestep as the product of the interaction forces and the distance travelled by the bucket. This work is accumulated over all timesteps to determine the total work done.

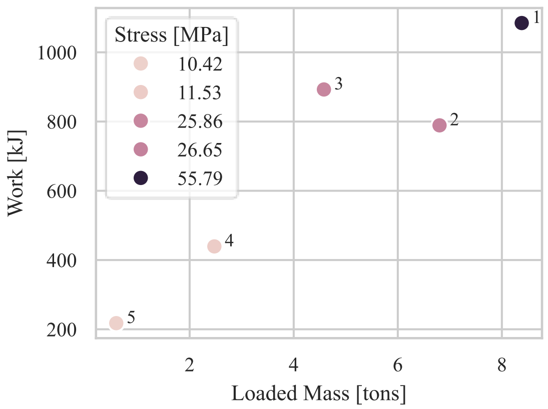

Figure 3. Evaluation of the 5 load cases (load case number indicated by label for each data point) with the total loaded mass on the x-axis, the total work done on the y-axis and the colour indicates the maximal measured von Mises stress on the bucket tip during the load scenario. *(figure caption)*

Figure 3 presents the results of these three metrics for each load case, with the loaded mass on the x-axis, the total work done on the y-axis, and the maximal von Mises stress on the bucket tip indicated by colour. The labels on the data points denote the load case number, according to Figure 2. The total mass ranges from 0.5 tons for load case 5 to 8.3 tons for load case 1, showing a linear increase correlated with the starting position of the motion. Similarly, the von Mises stress on the bucket tip increases correlated to the starting position. Further, the total work done increases as well from 200 kJ for load case 5 to 1080 kJ for load case 1. However, load case 3 is an outlier, as it shows a total work done of 900 kJ, which is higher than the 800 kJ for load case 2, despite load case 3 having a lower loaded mass than load case 2.

In Figure 4, the maximal von Mises stress from the bucket nodes on the tip over time is presented for the five load cases. The von Mises stress increases for all cases as soon as the bucket reaches the pile of granular material. Load case 1, being closest to the pile, shows the earliest increase and the highest stress response, followed by load cases 2, 3, 4, and 5, respectively. Load case 5 shows the latest and smallest stress response increase. Specifically, load case 1 peaks at 55 MPa, load case 2 at 26 MPa, load case 3 at 25 MPa, load case 4 at 11 MPa and load case 5 at 10 MPa. The maximal von Mises stress response tends to decrease as the starting position is farther from the pile. Interestingly, there is only a slight difference in the maximal stress response at the bucket tip between load cases 2 and 3, as well as between load cases 4 and 5. Additionally, load case 3 shows the highest stress response after 2.5 seconds, maintaining a stress level around 20 MPa until 5 seconds.

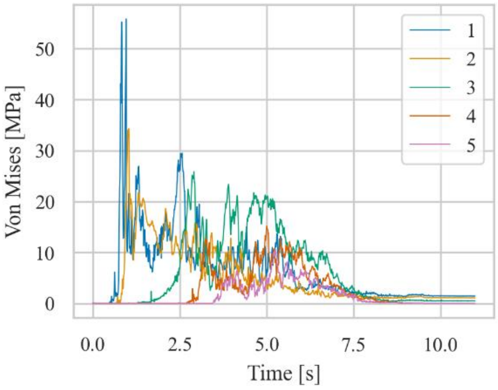

Figure 4. Maximal von Mises stress on the bucket tip over time for the 5 load cases from Figure 2. *(figure caption)*

4. Discussion

The observed increase in total mass loaded for starting positions closer to the pile aligns with expectations. This outcome is intuitive, as a shorter distance to the pile allows for more material collection, resulting in higher loaded.

An interesting result is the total work done by load case 3, which surpasses that of load case 2. This could partly be attributed to the simulation setup and the lack of statistical variance, as only a single specific pile and one simulation run were considered within the scope of this study. However, it might also be due to timing factors, where the bucket in load case 3 simultaneously starts a rotational motion as it begins to dig into the gravel pile. These two stress sources can contribute to the observed stress peak.

It is challenging to draw definitive conclusions from these specific results, since the DEM-FEM coupling, although generally verified and validated, still requires calibration and validation for the specific modelling of a wheel loader bucket. Therefore, the presented results should be viewed as a demonstration of the evaluation capabilities of DEM-FEM simulations for bucket operations rather than precise predictions.

The stress results from these simulations can be further utilised for fatigue analysis, which is an important aspect for optimising load operations and bucket design. Incorporating FEM in the analysis allows for a detailed examination of specific geometrical aspects of the bucket, particularly the stress on critical points such as welding joints. This enables more informed decisions in optimizing and conducting trade-off analyses between material loading capacity and bucket durability for different bucket designs and operational strategies.

5. Conclusion

This study demonstrates that the DEM-FEM coupling algorithm is effectively applicable for simulating the operations of a wheel loader bucket. By coupling DEM and FEM, this approach allows for a comprehensive analysis of the stress experienced by the bucket. The simulations account for various factors, including the bucket's geometries, material properties, and loading motions. This capability facilitates detailed evaluations that can inform the optimisation and design of wheel loader buckets, enhancing their performance and durability in practical applications.

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