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Sloshing cargo in silo vehicles †

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Abstract

The driving stability of silo vehicles is significantly affected by the type of cargo that is transported and the design of the tank. Cargo motion can have both beneficial and negative aspects in terms of driving stability and braking performance. Neglecting the influence of the dynamically moving cargo in driving simulations of silo vehicles leads to significant errors in the simulation results. We propose a new method for the dynamic simulation of silo vehicles carrying granulates. The method couples Lagrangian particle methods, such as the discrete element method, and multibody systems methods using co-simulations. We demonstrate the capability of the new approach by providing simulation results of two benchmark maneuvers.

Keywords: Sloshing; Co-simulation; Discrete element method; Multibody system dynamics

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1. Introduction

The motion of granular materials in silo vehicles may have a significant influence on the driving dynamics. Tank geometries and vehicle suspension systems have to be designed carefully to provide stability during braking and lane change maneuvers as well as to improve driving comfort. Dynamic simulations are an attractive tool to predict the influence of different design parameters during the design process. The size of separate tank compartments is only one example for an important design parameter which affects the wavelength of the sloshing motion and thus the eigenfrequencies of the system.

Approaches for the simulation of tank vehicles have been proposed in the past, mostly based on the coupling of multibody systems (MBS) and pendulum models or Eulerian fluid simulation methods such as the finite volume method [1]. However, such approaches have several drawbacks. First, sloshing liquids involve free surface flows which are difficult to handle by Eulerian approaches. Second, dry granular materials do not behave like fluids in terms of their dynamic behaviour. Piling, avalanches and pressure dependent shear stiffness are only some of the numerous phenomena and characteristics of granular materials which require a different simulation approach.

To allow for the simulation of both, sloshing fluids with free surfaces and granular materials in tank trucks, we implemented and tested a new co-simulation approach that couples PASIMODO [2], a Lagrangian simulation framework for the 3D simulation of granular materials and fluid models, with SIMPACK, a commercial Multibody System simulation software [3]. Our approach is flexible and robust and theoretically enables coupled simulations between PASIMODO and any other multibody system simulation software that provides a TCP/IP-co-simulation interface. We tested the coupled simulation approach on the basis of different driving maneuvers of silo vehicles and studied the influence of

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some characteristic design parameters on the stability of driving dynamics.

2. Dynamic model

The program system PASIMODO, used for our Lagrangian particle simulations, follows the most popular approach for the simulation of granular systems, the discrete element method (DEM) [4]. This method models granules as independent particles whose motion is only affected by applied forces and torques as, e.g., exerted by contact penalty spring-dashpot systems, and thus avoids constraint equations. By this means the DEM does not have to solve systems of differential algebraic equations and allows for the simulation of a very large number of particles.

2.1 Discrete element method

The discrete element method models granulates by a huge number of rigid bodies with a very simple geometry, e.g., spheres whose interactions are modeled via a penalty contact approach. Although fairly simple on the microscopic level, on a macroscopic level with millions of contacts, such granular systems can exhibit a very complex behavior featuring phenomena such as jamming, avalanches and piling.

As there are typically from several thousands up to millions of particles involved in a particle simulation, efficient contact detection is a key feature to identify adjacent particle pairs whose contact forces have to be calculated. There are a variety of different time integration methods [5], that may be used to integrate the dynamics of particle systems.

In PASIMODO, complicated freeform surface boundaries are defined as triangular surface meshes. The contacts between particles and the mesh geometry, which is defined relative to a moving coordinate system, are handled by the same penalty approach as the inter-particle contacts. Thus, to represent the moving geometry of an MBS body, it is sufficient to compute the motion of the body's associated coordinate system. Contacts between particles and the MBS geometry are detected automatically. The resulting contact forces and torques are accumulated with respect to the center of gravity of the MBS bodies.

2.2 Particle-MBS-co-simulation

For the simulation of the silo vehicle we chose the classical multibody system approach; see [6] and [7].

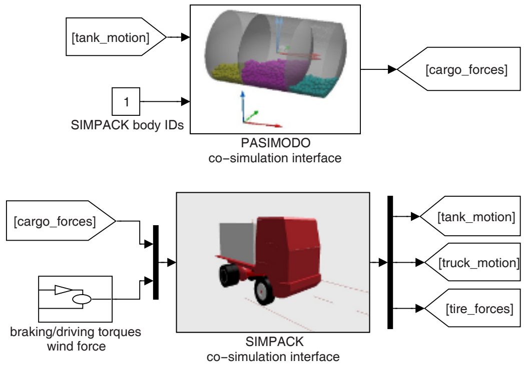

Fig. 1. Simulink model of a PASIMODO-SIMPACK co-simulation.

We used SIMPACK to create a 17 DOF model of the truck. SIMPACK provides a co-simulation interface that allows for data interchange with MATLAB/Simulink. Any kind of state or force/torque data can thus be exchanged.

To couple PASIMODO via MATLAB/Simulink with SIMPACK, we took advantage of PASIMODO's plugin interface. This interface enables users to program custom subroutines in C++ that can, e.g., be used to dynamically modify particle coordinate system states. In our case the plugin interface was used to transfer the state variables of the MBS tank from Simulink to PASIMODO to position the tank's surface geometry. In the same way the resulting contact forces and torques with respect to the tank's center of gravity are transferred back to Simulink. The data exchange is carried out via a TCP/IP interface both between Simulink and PASIMODO and Simulink and SIMPACK. The Simulink model for the silo vehicle co-simulation is depicted in Fig. 1.

3. Silo vehicle model

Different aspects of the silo vehicle are of interest in the multibody model and the particle model. In the MBS the particle forces acting on the tank are considered as applied forces. As the particle forces are calculated by the particle simulator, no geometrical representation of the tank is required in the MBS. The particle simulator, on the other hand, only considers the constrained motion of the tank whose state variables are integrated as part of the MBS. Thus, in PASIMODO no representation of the remaining MBS except of the tank is required.

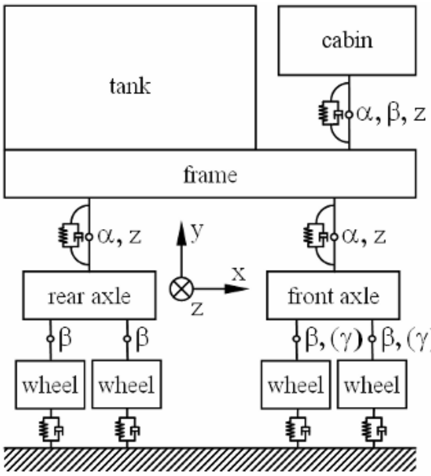

Fig. 2. Schematic representation of the MBS truck model.

The silo vehicle is modeled as an MBS with 17 degrees of freedom (Fig. 2). The tire forces are computed by means of the tire similarity model [8]. To account for a driver we added two additional degrees of freedom which are influenced by a feedback controlled driver model. All relative rotations are defined as Cardan angles. The rotations of the front wheel around the vertical axis are supplied by a driver model [9].

To observe the influence of a subdivision of the tank into compartments, we performed simulations with different tank geometries. The first configuration is a cubical tank with only one compartment, the second configuration is a cubical tank with two compartments of equal volume and the third configuration is a cylindrical tank with three compartments (Fig. 3).

For the simulations we used an artificial granulate material. The material consists of spherical particles that interact via visco-elastic penalty forces. The friction between the particles is modeled by a Coulomb model.

4. Driving maneuvers

For the simulation of driving maneuvers the cargo particles in the tank are considered to be initially at rest.

To investigate the influence of different tank designs on the driving behavior and to show the influence of the particle cargo model on the driving stability, especially compared to a model that regards the cargo as rigid, we performed two classical benchmark driving maneuvers.

Table 1. Load cases for the full braking maneuver.

load case	braking torques	
	front wheels	rear wheels
1	10000Nm	5000Nm
2	13000Nm	6500Nm
3	16000Nm	8000Nm

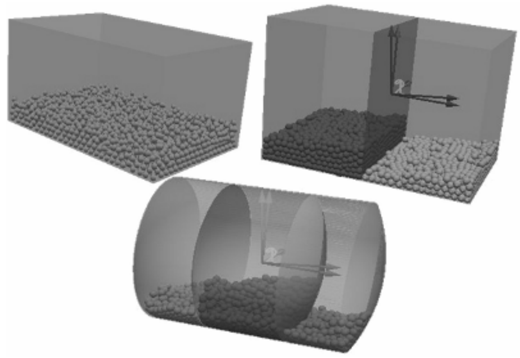

Fig. 3. Different tank geometries. Particles are depicted in equilibrium positions.

4.1 Full braking

As the first maneuver, a full braking is performed to observe how a dynamically changing load distribution can lead to tire locking (Fig. 4). During the braking process, the center of gravity of the cargo moves to the front of the tank.

This results in a discharge on the back wheels leading to a severe reduction of normal contact force and thus tire friction. The resulting loss of braking torque induces brake locking. A subdivision of the tank into compartments reduces the relative longitudinal particle motion and thus reduces the unloading of the rear wheels. To determine the limit of braking stability in terms of brake locking, we performed a series of simulations with different brake torques. The brake torque configurations are listed in Table 1 and the simulation parameters are shown in Table 2.

The results of the full braking maneuvers with a single compartment silo vehicle are depicted in Fig. 4, for three different braking torque load cases as defined in Table 1. Load cases 1 and 2 show a stable braking motion with constant deceleration. For load case 3 the load shift from the rear to the front wheels leads to a significant reduction of friction force at the rear wheels and thus to a locking of the rear tires. The sloshing motion of the particle cargo is depicted in Figs. 5 and 6. We investigated whether a baffle that

Table 2. Important simulation parameters.

cargo mass	4700 kg
cargo density	2500 kg/m^3
number of particles	~5000
contact stiffness (linear)	$1.12 \cdot 10^5$ N/m
contact damping parameter (linear)	0.7 Ns/m
friction coefficient	0.5
particle simulation time step size	10^{-4} s
initial velocity for braking maneuvers	20 m/s
truck dead weight	10310 kg
wheelbase	3.1 m
track	1.66 m
cubical tank dimensions(length/width/height)	(3m/2m/1.5m)

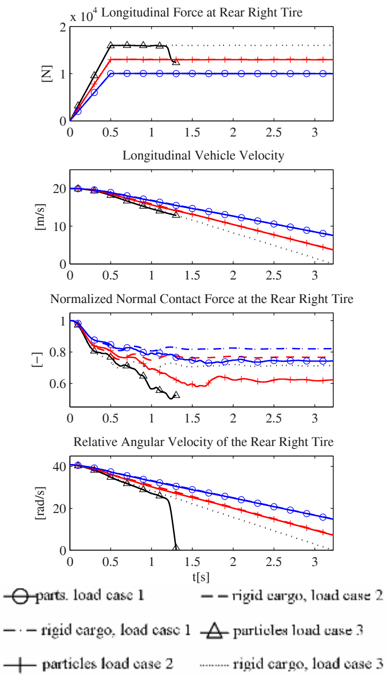

Fig. 4. Full braking maneuver with different braking torque load cases with a single compartment cubical tank.

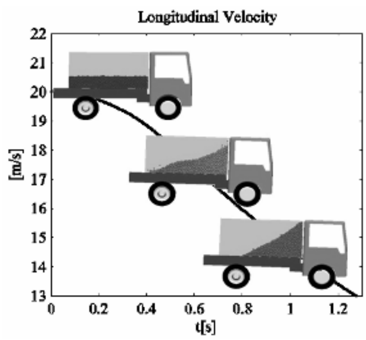

Fig. 5. Sloshing motion during the full braking maneuver with load case 3 and a single compartment tank.

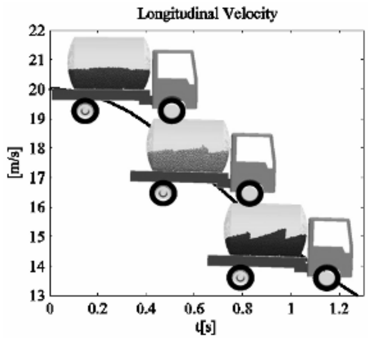

Fig. 6. Sloshing motion during the full braking maneuver with load case 3 and a tank with three compartments.

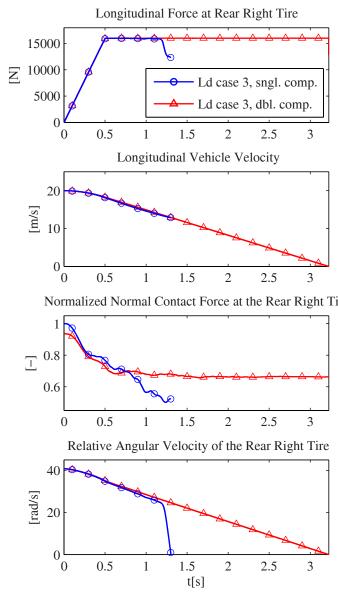

Fig. 7. Influence of a subdivision of the tank into compartments with respect to full braking.

divides the tank into two compartments can remedy the tire locking. Fig. 7 shows simulation results of a comparison for a full braking with load case 3. As expected, the baffle allows for a higher deceleration without brake locking.

4.2 Double lane change

The second maneuver is a double lane change. The sloshing motion of the cargo has a significant impact on the driving stability, as the whole particle system behaves as a huge nonlinear spring-dashpot system that severely influences the lateral motion. We compared the particle cargo with a rigid cargo of equal weight. Its position relative to the tank and its inertia

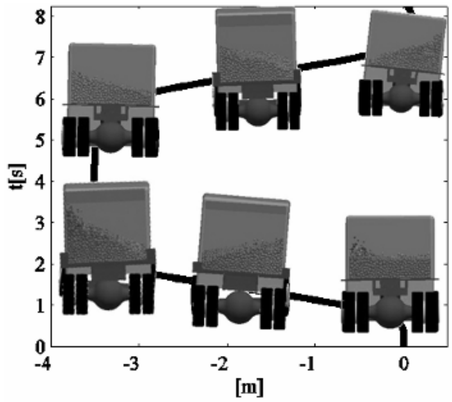

Fig. 8. Double lane change maneuver with v=20m/s.

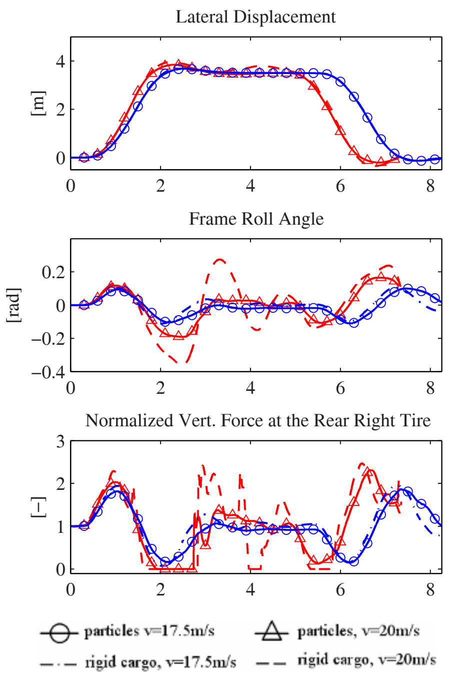

Fig. 9. Double lane change maneuver with two different initial velocities.

properties were chosen in such a way that they reflect the properties of the particle system at rest. The lateral sloshing of the particle cargo is depicted in Fig. 8.

The influence of the lateral motion of the particle cargo on the driving stability turned out to be positive in comparison to the rigid cargo (Fig. 9). The rolling motion of the frame-tank system is significantly reduced. The dynamic reduction of the normal contact force that is crucial for tire friction is generally larger for the simulations with a rigid cargo.

5. Conclusions

We have demonstrated how a co-simulation approach that couples Lagrangian particle methods and classical multibody dynamics can be used to predict the stability of driving maneuvers of silo vehicles. This method can be used to investigate the impact of different tank designs on the stability of the silo vehicle system. Comparisons between two different tank designs showed the positive effect of a subdivision of the tank into compartments in terms of braking stability. Moreover, our simulations show that the lateral motion of a sloshing cargo can be beneficial in terms of rolling stability in lane change maneuvers.

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