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FLEXIBLE BODIES FOR INVESTIGATION OF CHIP JAMMING AND DRILL BREAKAGE IN DEEP-HOLE DRILLING

Andreas Baumann, Peter Eberhard

Institute of Engineering and Computational Mechanics, University of Stuttgart
Pfaffenwaldring 9, 70569 Stuttgart, Germany
[andreas.baumann,peter.eberhard]@itm.uni-stuttgart.de, www.itm.uni-stuttgart.de

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Abstract. In this contribution several approaches for modeling flexible bodies for investigations in deep hole drilling are presented. Based on a preliminary investigation of the chip jamming the basic behavior is investigated and key aspects for more detailed future research are shown. Therefore, a virtual barrier is placed within the chip flute, which blocks the chips but is permeable for the cutting fluid. Then, based on a simple model of a water tank with a deformable gate the modeling of the flexible gate with SPH solid particles is compared to rigid multibody systems. Based on these results the next step of using the floating frame of reference approach is sketched.

1 INTRODUCTION

Deep hole drilling is a challenging machining process due to its high length-to-diameter ratio, especially single lip drilling (SLD). Besides non-vanishing resulting forces because of its asymmetrical single-lip design the evacuation of produced chips is a major concern. While a twist drill acts as an Archimedean screw, which supports besides the transport of the cutting fluid also the transport of the chips, the single-lip drill has only a single straight flute for the chip evacuation [3]. Therefore, the cutting-fluid flow and the chip shape have a major influence on the process reliability. Especially, long-shaped chips can cause chip jamming and thereby breakage of the drill.

In our work we want to better understand the process of deep hole drilling and, thereby, reduce the risk of drill breakage. For earlier investigations of the fluid flow and the chip evacuation we assumed the chips to be rigid. As this investigation shows, this assumption is appropriate if the motion of the chips is mainly caused be the fluid flow. However, when we block the chips manually from their evacuation it becomes clear that in reality the chips are deforming under the pressure of the blocked flow. Therefore, the chips need to be modeled as flexible bodies for future investigations. The aim of this contribution is to present several approaches to include deformable bodies in SPH simulations and compare them for the use of modeling flexible chips in deep hole drilling simulations.

2 THEORY

Smoothed Particle Hydrodynamics (SPH) is a method for the description of fluids by moving interpolation points, so-called particles. Therefore, the Navier-Stokes equations describing the fluid movement are represented by weighted sums over a set of neighbor particles [14]. The Discrete Element Method (DEM) allows the description of granular media or multiple uncoupled bodies which are interacting with each other by the Newton-Euler equations and a contact law [8].

Its Lagrangian and meshfree nature allows SPH to describe arbitrary and moving surfaces and interfaces. Furthermore, the similarities between SPH and DEM allow the integration of both within the same simulation framework. In this investigation, the simulation framework Pasimodo [6] is used which is developed at the ITM and allows the integration of co-simulations and extension by plugins.

For the interaction of SPH particles with rigid walls multiple approaches are possible like fictitious boundary particles with dummy or mirror particles or repulsive functions [14]. Due to the arbitrary geometries of the drill, the borehole and the chips, we prefer a simple modified Lennard-Jones force as given in [9], which is calculated by

$$F(d) = \begin{cases} k\frac{(R-d)^4-(R-r_0)^2(R-d)^2}{R^2 r_0(2R-r_0)} & \text{if } d \leq R, \\ 0 & \text{otherwise,} \end{cases} \tag{1}$$

where R is the maximum interaction range and k defines the stiffness of the interaction. It is designed to be zero for $d = r_0$ at the preferred distance of fluid particles from the wall.

The equations of motion for a multibody system can be derived by applying D'Alembert's principle resulting in the Newton-Euler equations

$$\boldsymbol{M}\boldsymbol{J}\ddot{\boldsymbol{y}} + \boldsymbol{q}_c = \boldsymbol{q}_e + \boldsymbol{Q}\boldsymbol{g} \tag{2}$$

with the mass matrix $\boldsymbol{M}$ and the Jacobian $\boldsymbol{J}$ of the system, the vector of generalized coordinates $\boldsymbol{y}$, the vector of Coriolis and centrifugal forces $\boldsymbol{q}_c$, the internal forces $\boldsymbol{q}_e$ and the distribution matrix $\boldsymbol{Q}$ of the generalized constraint forces $\boldsymbol{g}$ resulting in

$$\boldsymbol{M}\ddot{\boldsymbol{y}} + \boldsymbol{k} = \boldsymbol{q} \tag{3}$$

where $\boldsymbol{k}$ is the vector of the generalized gyroscopic forces and $\boldsymbol{q}$ the vector of generalized internal forces [10].

For flexible multibody systems, this is expanded by the concept of floating frames of reference. Therefore, the total motion of the system is separated into the rigid body motions, which are represented by motion of the floating frames of reference of each body, and the superimposed elastic deformations [2].

3 APPLICATION

For a first investigation of the chip jamming a virtual barrier is added in the chip flute, which is permeable for the fluid but blocks the chips from their further evacuation. The first results are shown in Figure 1 with the fluid in blue and the chips colored in red for increased contrast. The first row shows the collision of the first chip with the barrier and the second row the blockage of the second chip by the first one. It can be seen that the first chip also partially blocks the cooling fluid from its further movement as the chip flute below is filled after the first chip hits the barrier. Furthermore, the pressure of the trailing fluid causes a rotation of the first chip until it comes in contact with the wall at its other end. If the drill keeps rotating while the chip is pressed against the wall of the borehole by the fluid flow, unwanted damage of the borehole is caused. Furthermore, the additional torque required to rotate the drill causing friction of the chip against the borehole further increases the torque and this could lead to a breakage of the drill. Thereby, the borehole would be jammed and the workpiece becomes garbage.

However, the assumption of rigid chips may be sufficient for the investigation of the evacuation of the chips and the general fluid flow [11, 12] but is not suitable for chip jamming because of the low stiffness due to the small thickness of the chips, resulting in their deformation by the forces of the trailing fluid. Therefore, several methods to model flexible chips are investigated and compared.

3.1 Water tank with an elastic plate

The type and shape of the produced chips during drilling depend on many parameters like the machined material, the feed rate, the rotational speed, and many more [3]. As pointed out before, chips are flexible and need to be treated that way for further investigations. Therefore, different approaches are analyzed based on a simple model of a water tank with a deformable plate. The model is described in [1] and it consist of a plexiglas channel with a deformable gate in one of its walls. The gate itself is made of rubber and is clamped at one end and free at the other one. At the beginning of the simulations the water is at rest. Afterwards the water pressure caused by the height of the water column is acting on the walls and the gate. Thereby the gate is deformed until the water flows underneath it out of the tank. Figure 2 shows the dimensions of the water tank and the deformable plate. According to [1] the experiments show that the model can be studied as a two-dimensional phenomenon, which is also applied in our investigation.

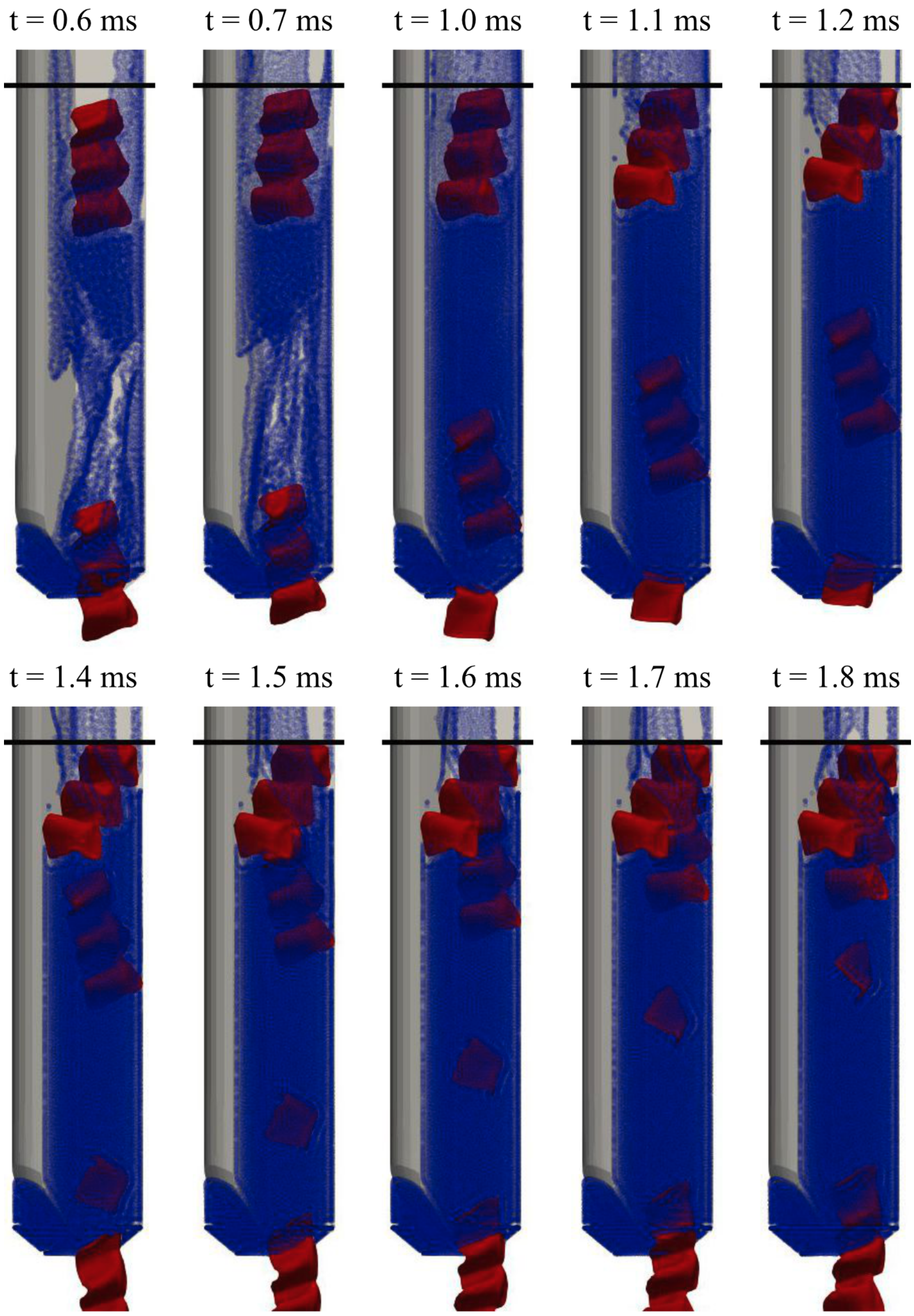

Figure 1: Simulation of the evacuation of rigid chips blocked by a fluid-permeable barrier. The chips are colored red for contrast to the blue colored fluid. The view is perpendicular on the evacuation flute.

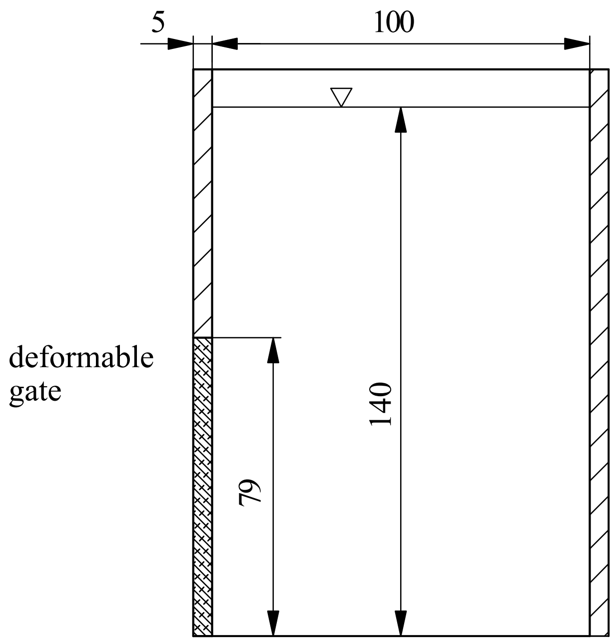

Figure 2: Scheme of the tank and its deformable gate [1].

3.2 SPH Solid Particles

A straight forward approach is to use SPH solid particles for the modeling of the flexible gate. These were implemented into Pasimodo as described in [13]. The gate is modeled by six layers of solid particles with the same initial distance as the fluid. The clamping of the upper end of the plate is realized by eight-by-four solid particles which are fixed. The material properties of the rubber gate particles and simulation parameters are given in Table 1. Figure 3 shows the simulation for the deformable gate modeled with SPH solid particles. It can be seen, that the gate deforms under the pressure of the water column and the fluid flows out of the tank. The deformation of the gate is limited by the increasing stress caused by the deformation when the inner forces equal the water pressure. The height of the water decreases by the outflowing water and thereby, the water pressure is reduced which results in a closing of the gate. This leads to a steady state where the water pressure deforms the gate but the deformation is not enough to let any more fluid flow out of the tank.

Figure 4 shows the X and Y displacements of the free end of the plate for the different investigated models in comparison with the experimental results from [1]. It can be seen that the initial opening of the gate matches well with the experimental results but the

Table 1: Material properties of rubber and simulation setup.

property	value	unit
density	1100	kg/m^3
Young modulus	$1.2 \cdot 10^7$	N/m^2
Poisson coefficient	0.4	
bulk modulus	$2 \cdot 10^7$	N/m^2
shear modulus	$4.27 \cdot 10^6$	N/m^2
initial particle distance	$1 \cdot 10^{-3}$	m
artificial stress factor	0.2	

gate made of SPH solid particles closes earlier than in the experiment. In general, the approach of using SPH solid particles seems to be well able to model the deformable rubber gate. However, the required number of particles to model more complex geometries like the desired chips would result in a major increase of the computational effort due to the much increased number of particles. Furthermore, the representation of arbitrary shapes imposes further problems for SPH boundary treatment by particles for thin structures in addition to the incomplete kernel support in the multi-phase interface.

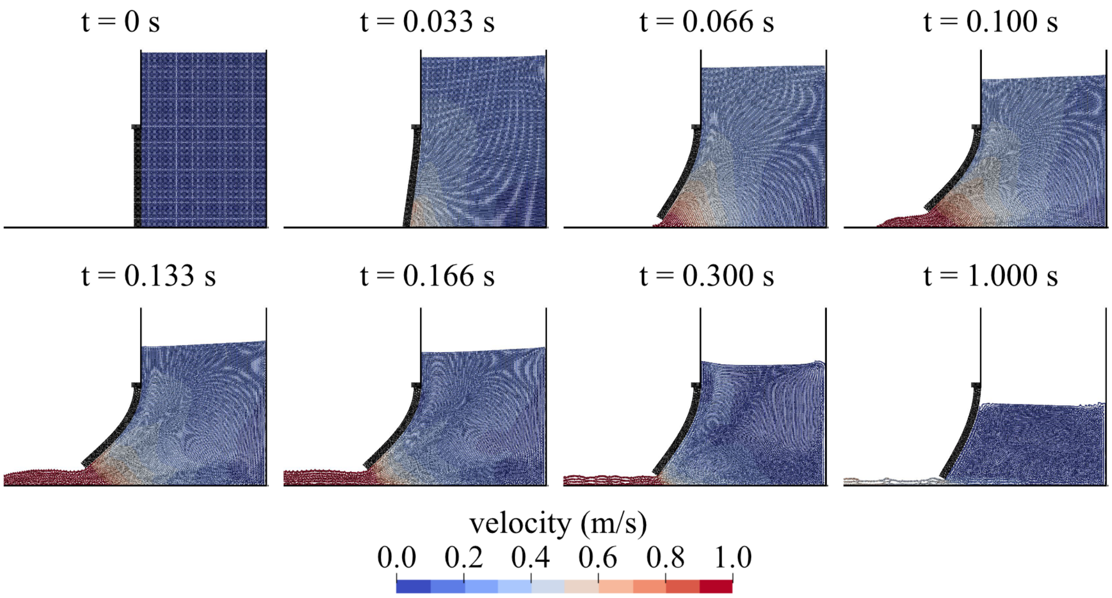

Figure 3: Simulation results for a flexible gate modeled with SPH solid particles.

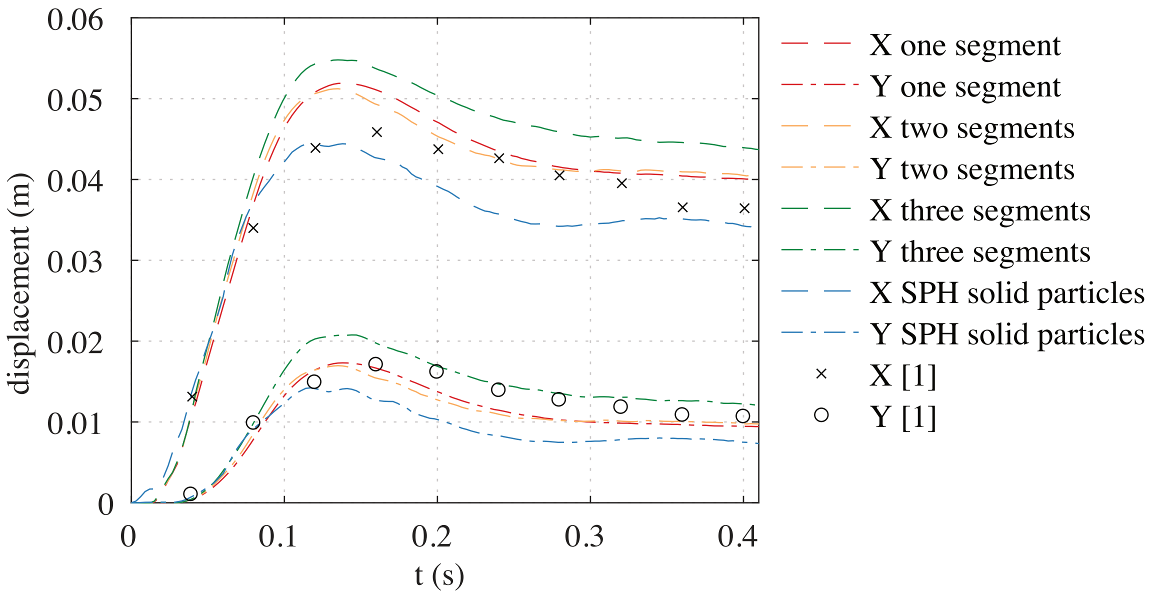

Figure 4: Displacements of the free end of the plate for the different investigated models and the experimental results of [1].

3.3 Rigid Multibody System

In comparison to the modeling of the gate by SPH solid particles, the modeling as rigid multibody system allows the reduction of the degrees of freedom and thereby resulting in a lower computational effort. A simple approach is the modeling of the flexible body by coupling multiple rigid bodies with springs and/or dampers. The simulation is carried out with a co-simulation of Pasimodo with Neweul-M^2 [7]. Neweul-M^2 is a software package for the dynamic analysis of multibody systems which is also developed at the ITM. Neweul-M^2 itself is running in MATLAB but allows the export of c-libraries containing the equations of motion for the multibody system which can be dynamically linked with Pasimodo to perform a co-simulation of the multibody system with the SPH simulation.

For this investigation, the flexible gate is discretized with up to three segments linked with joints with torsion springs between them. The model parameters are estimated with the simulation software ANSYS using a finite element model of the gate which is deflected by a force at its lower end. The segments are modeled of equal length and the torsion spring rates are estimated by overlaying the rigid multibody system and taking the relative deflection of each segment relative to its length assuming to be caused by the nominal force. The resulting model parameters are listed in Table 2. The initial particle distance is set to $2 \cdot 10^{-3}$ m and all other parameters are the same as in the previous simulation.

The comparison of the simulation results for the rigid multibody system based on the displacement of the free end of the gate is shown in Figure 4 and achieves reasonable results in modeling the deformable gate. The initial openings of the gates are similar to the experimental results. Also the closing later on with a small overshot at their largest

Table 2: Model parameters for the rigid multibody system.

segment lengths	torsion spring rate
$L_1 = 79$ mm	$c_1 = 3.95$ Nm
$L_2 = 39.5$ mm	$c_2 = 3.95$ Nm
$L_3 = 26.33$ mm	$c_3 = 2.633$ Nm

opening position makes sense. The model made of three segments shows a larger displacement compared to the other models which is most likely caused by the weaker torsion spring rate. However, while the initial model definition results from physical qualities, the definition of the model parameters for the rigid multibody system, such as the torsion spring rate, is partially not directly linked to physical parameters. This requires a parameter identification as it is done in this example by an FEM simulation with ANSYS. This is feasible for simple models like a plate which is represented as couple of beams but reaches its limits for more complex models like the investigated chips. Furthermore, for every change in the dimensions of the system a new parameter identification has to be carried out.

4 CONCLUSIONS

Deep hole drilling is a challenging process. Especially, long chips can cause chip jamming and thereby, increase the torque load on the drill until its breakage. In previous investigations for the chip evacuation and the fluid flow of the cooling liquid the chips and drill were assumed to rigid. In this contribution it has been shown that this assumption is not sufficient for the investigation of the chip jamming and the drill breakage. Based on a water tank with a deformable gate two approaches were investigated. On the one hand the modeling of the gate with SPH solid particles describing elastic solid properties is shown and on the other hand a rigid multibody system approach.

Both approaches are well able to model the flexible deformation of the gate under the water pressure of the tank as the comparison to experimental results from literature showed. However, the increased computational effort by adding additional SPH solid particles and the limited approximation of the rather complex chips geometries are disadvantages. Additional, the rigid multibody system approach is limited by the geometries of the rigid segments as well as by the determination of the model properties for the spring and dampers coupling the segments.

Consequently, as both approaches do not satisfy the requirements of modeling the flexible chip geometries sufficiently additional investigations are necessary. As next step we will model the chips by the floating frame of reference approach using a fully elastic approach as sketched in the short outlook.

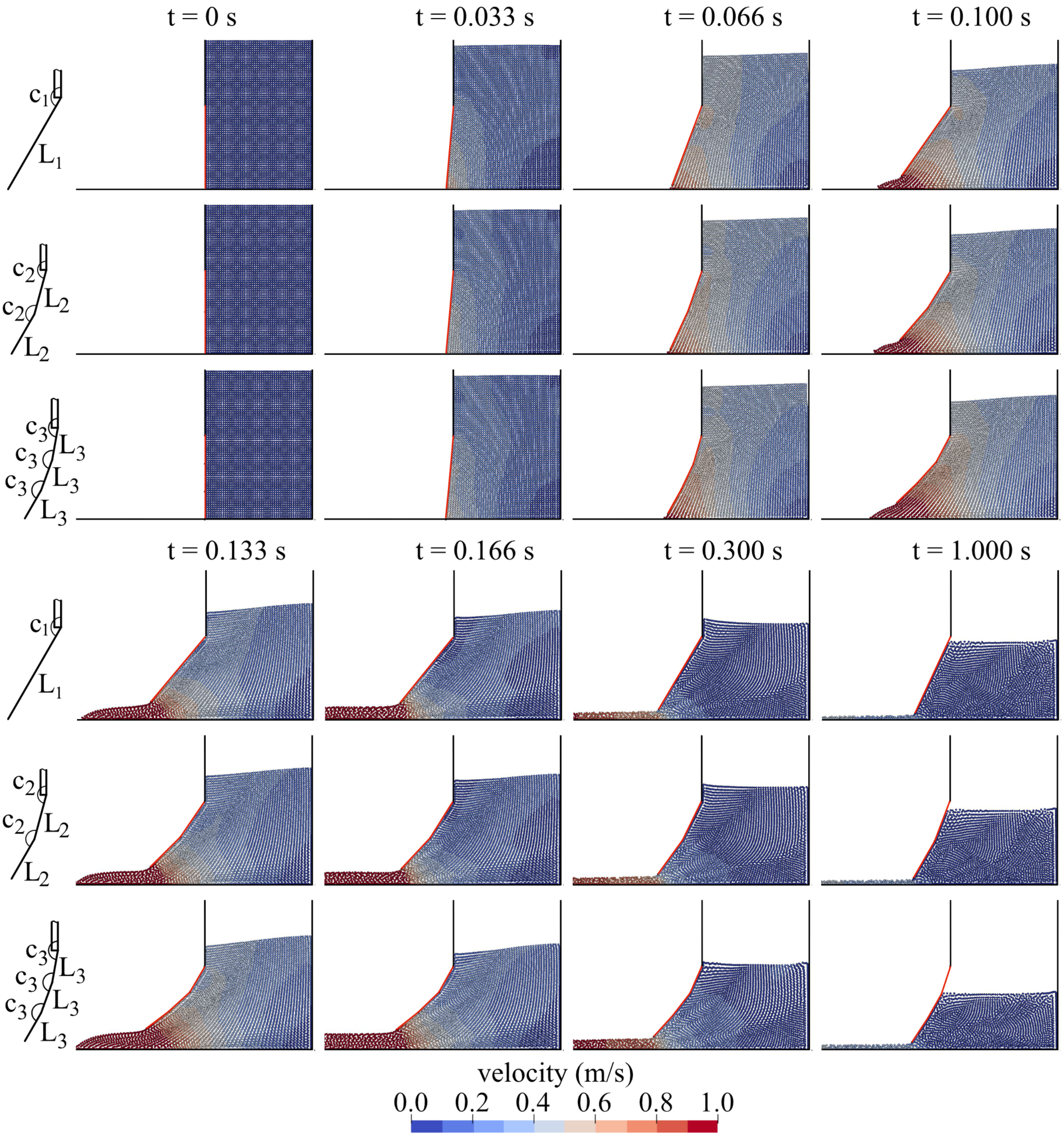

Figure 5: Simulation results for a flexible gate modeled as rigid multibody system with 1 to 3 links.

5 OUTLOOK

The software package Neweul-M^2 allows besides the formulation of rigid multibody systems also the direct consideration of deformable bodies based on the floating frame of reference method. Thereby the elastic deformation of a body is described in a coordinate system attached to each body superimposing the elastic deformations on the rigid body movement of the floating frame. For the calculation of the elastic deformations of the body its mass and stiffness matrices are imported from an FEM software. The import is done with the software package MatMorembs [5] into Neweul-M^2. In comparison with rigid multibody systems, this approach does not require the identification of nonphysical model parameters as the calculation of the mass and stiffness matrices are done by FEM taking the meshing and material properties of the body into account. Furthermore, the meshing of the body allows arbitrary geometries in contrast to the rigid multibody system which is limited by the representation of the segments.

The existing coupling of Pasimodo and Neweul-M^2 is extended to be capable of handling the flexible properties of this approach. Therefore, the Neweul-M^2 exported model will be wrapped into a co-simulation container defined by the Functional Mock-up Interface standard [4] and a new plugin for Pasimodo is written. This allows for the automatic import of the model into Pasimodo as the old coupling required manual definitions which becomes tedious for larger models. Furthermore, options to reduce the complexity and the required computational effort by applying model order reduction techniques for flexible multibody systems [5] on the modeled chip geometries will be analyzed.

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