Prediction of Fuel Impact Effects on Tank Pitch Characteristics during Jettison

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ABSTRACT

Separation Clearances for tanks provide in general the most limiting conditions for the emergency jettison envelope on a fighter aircraft.

Tanks are almost wide but light weighted bodies with poor aerodynamic characteristics as far as stability is concerned. Especially when partially filled, the physical characteristics of the residual fuel become an additional driver for the separation characteristics. The dynamic fuel-tank interaction influences the tank trajectory mainly in two ways. First, during the trajectory itself the physical properties rapidly change in dependency of the tank motion. In addition to that, fuel impact on the tank walls is a delicate problem because it has a major influence on the pitch characteristics of the tank. The target of this paper is to highlight a scheme that allows the representation of fuel impact effects in such a fuel tank during separation.

The analysis is done within two steps, a parameter analysis using a particle cloud method and available experimental data, and a dynamic analysis using the state of art separation code at EADS Deutschland (SSP). With an external fuel tank usually consisting of three separated compartments, in this consideration the fuel impact on the forward tank compartment top is assumed to have the most important effect on the pitch characteristics. Immediately after jettison, the ejection release unit accelerates the tank quickly. Because of its inertia, the fuel inside the tank sloshes towards the tank top and impacts on the tank walls. The force on the tank due to this impact results in an additional vertical acceleration and a pitching moment that forces the tank to pitch up. It is of extreme importance whether the overall pitch characteristics after jettison is still dominated by the ejector forces (pitch down) or by the additional short-time impact pitching moment (nose up) when the tank is still close to the aircraft. A resulting tank pitch up bears the risk of aircraft damage due to an upcoming tank.

It will be shown that the force on the top resulting from fuel impact mainly depends on the tank acceleration (rotation and translation), fill level and the shape of the fuel free surface immediately before the tank is jettisoned. Experimental results obtained from partially filled and quickly accelerated cylinders have been taken as reference values for the numerical simulation. The computation of the fuel impact forces has been carried out using a 3D particle cloud method calibrated with the experimental results. Therefore, the tank is partially filled with fuel and a variety of parameters have been analyzed. The independent variables have been chosen to pitch rate, vertical acceleration and fill level. The influence of the free surface shape has been determined in a modal analysis for the first natural frequency of the fuel. Functional dependencies between flight mechanics pitch rate, acceleration) and fuel impact forces have been derived. Further, an estimation of the shock damping during the impact due to fuel sloshing is presented. From the impact pressure distribution

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on the tank top, the resulting force and point of attack are computed. Trajectories with fuel impact in an external tank are presented.

0.0 ABBREVIATIONS & SYMBOLS

a : acceleration [m / s^2]

b : channel width [m]

cg : centre of gravity

d : dissipation parameter [-]

E_{kin} : kinetic energy [kJ]

E_{pot} : potential energy [kJ]

ERU : **E**jection **R**elease **U**nit

f : specific mass force [N / kg]

F : force [N]

h : channel height [m]

i,j : loop indices [-]

L : $L = E_{kin} + E_{pot}$ (Lagrange's formula)

m, n : Lennard Jones potential parameter [-]

mass : particle cluster mass [kg]

nz : load factor [*g0, Earth gravity]

N_i^{cutoff} : Particles within cutoff- radius [-]

NT : number of quasi-particles [-]

p_x , p_y , p_z : pressure component in x, y and z

Q_{qi} : exterior forces [N]

q_i : generalized coordinates (Lagrange's formula)

$\dot{q}_i$: generalized particle velocity [m/s]

$\dot{q}_i^n$: generalized new particle velocity after re-definition [m/s]

$\ddot{q}_i$: generalized particle acceleration [m/s^2]

r : distance between two particle layers [m]

r_i : radius particle *i* from (0/0/0) [m]

r_{ij} : distance particle *i* to particle *j* [m]

SSP : **S**tore **S**eparation **P**rogram

U_{ij} : Lennard-Jones potential function [kJ]

v : velocity of particle layer [m / s]

V : volume [m^3]

x , y , z : cartesian coordinates [m]

x_{cg} , y_{cg}, z_{cg} : centre of gravity [m]

x_i , y_i , z_i : quasi-particle coordinates [m]

α : potential parameter: $\alpha = f(m, n)$

ε : equilibrium rest potential [kJ]

μ ;dynamical viscosity [kg / m * s]

σ : particle cluster diameter [m]

1.0 INTRODUCTION

The behaviour of liquids in aerospace vehicles like airplanes, rockets or satellites has always been a delicate problem. The fuel provides a significant contribution to the overall mass of these vehicles, and therefore the knowledge of the mass properties of the fuel is extremely important for performance and safety considerations. In the domain of military aircraft, high accelerations occur during flight, where the fuel is forced to slosh within the tanks, especially in partially filled compartments. In order to accurately predict the trajectory of a separating fuel tank in vicinity of an aircraft, it is of paramount importance to represent the correct physical properties of the tank in combination with the ejection and the aerodynamic forces inclusively all interference effects. Thereby the liquid motion becomes the driving parameter for the changing physical properties of the tanks.

This paper deals with an approach that allows a very fast determination and representation of liquid impact effects on the jettison of a partially filled external fuel tank. It is based on the analysis presented in [1] dealing with the inertia and centre-of-gravity change due to fuel sloshing.

2.0 LIQUIDS

In contrast to a solid body, liquid does not keep its shape when it is in motion. The intermolecular forces are weaker than in the crystal grids of a solid, so there is no global order that preserves coherence. In contrast to a gas where nearly no coherence at all exists between the molecules, there are regions where a certain number of molecules are closely coherent. These regions can easily break up and re-connect, and therefore the liquid may take every shape the boundary prescribes. The strength of the intermolecular forces varies from liquid to liquid, dominating a property that is a driving factor for all dynamical analysis: viscosity. Viscosity strongly depends on the liquid temperature and pressure, whereas in a wide range of pressure and temperature, a liquid can be idealized as incompressible. Thus, the volume can be estimated as constant, whereas the shape changes.

3.0 SIMULATION APPROACHES

The modelling of fuel sloshing effects within a tank is a large area for scientific research. Several approaches have been done, analytically and in experiments, to predict the effective sloshing mass and the effective inertia of the liquid, [2], [3], [4], [5]. With a liquid consisting of billions of particles (ions, molecules), molecular dynamics offers in theory the best approach to sloshing effects. But with the extreme big amount of particles and the complexity of solving the governing, partly statistical equations, other approaches have become more and more popular as the computer power has rise as well.

Continuum fluid mechanics, namely Euler- and Navier-Stokes codes, have proved to provide accurate models for gas dynamics and aerodynamic simulation. But in terms of liquids, especially rapidly moving liquids, the codes are extremely time consuming, due to the extreme small time steps required for proper integration. Analytical approaches have been done as well, transforming the physical problem into a mathematical one. These approaches are mostly only valid for idealized liquids (no friction, incompressible, vortex-free, a.s.o.), so they are often limited to special problems [2].

A third way can be considered which deals with macroscopic particle clusters, containing billions of real molecules. The properties of the real molecules are transformed to the macroscopic particles, having dimensions of some 10E-02 meters (instead of 10E-15 meters for real molecules). Although this particle approach provides very good results for slosh predictions, see figures 8 and 9, it still consumes more CPU time than accepted for an effective trajectory analysis. Therefore a special concept based on elements derived from quasi particle cloud models is used within this paper in order to compute trajectories in reasonable computing times and much faster than achievable with the classical approaches.

4 FUEL IMPACT EFFECTS

The dynamics of the overall system of tank structure and fuel volume is a delicate problem due to not-trivial liquid dynamics. The effect of sloshing fuel volumes inside the tank on the mass properties has been analysed in detail in [1]. In order to understand the meaning of fuel impact effects, the tank jettison is now separated into three phases:

Phase 1: During phase 1, the ERU pushes the tank downwards. Only the tank structure is accelerated, the fuel inside the compartments rests quiescent due to its inertia. Dynamically, fuel volume and tank structure move independently of each other.

Phase 2: In phase 2, the structure has moved downwards, and the fuel volume reaches the upper wall of the tank. During this impact, forces are transmitted from the liquid to the structure and vice versa. The two systems are now coupled for a short time, and the tank pitches up.

Phase 3: In phase 3, the fuel has splashed down again, a second impact occurs on the tank bottom. The aerodynamic drag diminishes the free fall of the tank, and the liquid rests on the tank bottom. The effective inertia of the overall tank-fuel system described in [1] are valid in this phase. The initial two phases are subject of this analysis.

4.1 Modelling Strategy

The modelling strategy follows in essential parts the strategy that has been used for the analysis in [1]. The core element is a particle cluster approach developed for the simulation of liquid dynamics in high unsteady conditions. The modelling is based on the geometry of the real 3-compartment tank and typical jettison conditions (angle of attack, ejection forces, ejection speed, a.s.o.). Tank and liquid volume are approximated by a system of finite particle clusters, each containing a fixed number of real molecules. The particle clusters represent the thermo-dynamical and mechanical properties of real liquids in the macroscopic domain. Liquid damping and sloshing can be simulated adequately; therefore this approach has been chosen to simulate the impact forces from the liquid on the tank structure. The forces are computed in dependency of the tank fill level; as the liquid interacts with the tank structure, the computation is an iterative process and the impact forces are computed for every time step of the trajectory.

4.2 Particle Cluster Approach

The particle cluster approach uses a sufficient number of particles that represent the fuel in a partially filled tank. The basic assumptions for the particle connectivity are derived from molecular dynamics; attractive forces between the clusters are considered as well as repulsion if particle clusters approach each other too

close. The equation of motion of the particles is given by Lagrange's formula

$$\left(\frac{\partial L}{\partial \dot{q}_i}\right)^{\bullet} - \left(\frac{\partial L}{\partial q_i}\right) = Q_{q_i} \quad q_i = x\ , y\ , z \quad \text{for} \quad i_T = 1,\ldots, N_T$$

with $L = E_{kin} + E_{pot}$; $E_{kin} = \frac{1}{2} \cdot mass \cdot \dot{q}_i^{\,2}$; $E_{pot} = \sum_{\substack{j=1 \\ j \neq i}}^{NT} U_{ij}$

and the generalised coordinates $q_i = x\ , y\ , z$

The potential energy is given by a Lennard-Jones potential of the form

$$U_{ij} = a \cdot e \cdot \left(\left[\frac{s}{r_{ij}}\right]^m - \left[\frac{s}{r_{ij}}\right]^n \right)$$

where *m* denotes the exponent of the repulsing term and *n* the exponent of the attractive term.

Solving Lagrange's formula, the equation of motion results in

$$mass \cdot \ddot{q}_i - \sum_{\substack{j=1 \\ j \neq i}}^{N} a \cdot e \cdot s^{\,n} \cdot n \cdot \left(\left(s^{\,m-n} \cdot \frac{m}{n} \cdot \frac{1}{r_{ij}^{\,m+2}} - \frac{1}{r_{ij}^{\,n+2}} \right) \cdot \left(q_i - q_j\right) \right) = Q_{q_i}$$

The forces Q_{qi} represent gravity, tank acceleration, a.s.o.

Solving this equation for every particle and integrating the equations with a 6th order Runge-Kutta-Fehlberg formula (table 2), the dynamics of the fuel sloshing can be predicted very accurately.

The following parameters have been used for the computations (each compartment filled at 1/3):

NT = 4900, σ= 0.055 m, mass = 0.2 kg, ε = 0.00005 kJ, m = 3.4 , n = 1.7 , α = 4

The geometry for the particle approach is shown in figures 1, 2 and 3. Figure 1 gives a view inside the partially filled tank, showing the discrete sections set up for the computation in a transparent view. Figure 2 shows particles representing the fuel volume (blue) and the tank structure (black) for a half-filled tank. Figure 3 shows the first Eigen mode for the half-filled tank.

The numerical 3-compartment tank model consists of two kinds of particle clusters. The liquid volume is

approximated by *NT* particles that are connected to each other by a Lennard-Jones potential. The tank structure is simulated by particles that form a rigid body, i.e. they cannot move relatively to each other. These boundary particles are connected to the liquid particles by a special potential function that allows the representation of all relevant wall properties, e.g. wall friction.

4.3 Validation of Viscosity

The dissipation of kinetic energy is physically based on the inter-molecular forces. In contrast to a solid, microscopic liquid particles are able to break up and rebuild inter-particle forces more easily. The permanent breaking and re-arranging is macroscopically not visible. In the microscopic domain, however, the resulting particle motion is known as Brown's molecular motion. Whenever parts of the liquid volume are submitted to exterior forces, the kinetic energy of the liquid particles rises. A part of this kinetic energy is macroscopically visible as liquid flux. Another part of the kinetic energy does not have any specific direction, but contributes macroscopically to the heat energy of the liquid. Consequently, a part of the kinetic energy of the liquid particles does not contribute to macroscopic motion, but is transferred into internal energy (heat). A measure for the amount of dissipated energy is the viscosity of a liquid. Viscosity is a phenomenon that origins from the adherent forces among the liquid particles. In the microscopic domain, these forces have to be overcome whenever one particle layer is moved relatively to the next (figure 4). The strength of these inter-particle forces depends on the bond type among the particles and therefore on the chemical elements involved. The definition of the dynamic viscosity for a Newton fluid that is assumed within this analysis is:

$$m = \frac{F \cdot dr}{A \cdot dv} \qquad \left[\frac{kg}{m \cdot s}\right] \qquad \text{(dynamical viscosity)}$$

The particle cluster approach implicitly contains viscosity; although the equation of motion is conservative, viscosity can be modeled in the following way.

Subject is now a 2-particle constellation. The particle velocity is split off into two parts; the first part is the velocity of the common centre of gravity of the two particles. The second part is the velocity of the one particle relatively to the other. For a 2-particle constellation, the relative velocity is:

$$\vec{v}_{ij,rel} = 0.5 \cdot \left(\vec{v}_i - \vec{v}_j\right)$$

The relative kinetic energy for one particle with respect to an NT-particle system can be written as

$$E_{kin}^{rel} = \frac{1}{NT} \cdot \frac{m_0}{2} \cdot \left(\sum_{j=1}^{NT-1} \vec{v}_{ij}^{\,2} + \sum_{j=1}^{NT-2} \sum_{k=j+1}^{NT-1} \vec{v}_{jk}^{\,2} = \frac{1}{NT} \cdot \frac{m_0}{2} \cdot \vec{v}_{ij}^{\,2} \right)$$

For this part of the overall kinetic energy, dissipation can be applied in the following way:

$$E_{kin,ij}^{rel,n} = d \cdot E_{kin,ij}^{rel} \quad , \quad 0 < d < 1, \qquad d\text{: dissipation parameter}$$

The conservation of momentum implies:

$$\sum_{i=1}^{NT} m_0 \cdot v_i = \sum_{i=1}^{NT} m_0 \cdot v_i^n \quad \Leftrightarrow \quad \sum_{i=1}^{NT} \vec{q}_i = \sum_{i=1}^{NT} \vec{q}_i^{\,n}$$

Also for every two-cluster constellation, the conservation of momentum is required. The new cluster velocities are found to

$$\vec{q}_i^{\,n} = \frac{1}{2} \cdot \left(\vec{q}_i + \vec{q}_j + \sqrt{d} \cdot \left(\vec{q}_i - \vec{q}_j \right) \right)$$

The dissipated energy is now added to the individual heat parameter Q_{ij}

$$Q_{ij} = \Delta E_{kin,ij} = \left(1 - d\right) \cdot E_{kin,ij}^{rel}$$

This is the result for the new cluster velocities in a two-cluster constellation. For a constellation with more than two clusters involved, the new velocities are found to:

$$\vec{q}_i^{\,n} = \left(1 - N_i^{cutoff}\right) \cdot \vec{q}_i + \sum_{l=1}^{N_i^{cutoff}} \vec{q}_i^{\,(j_l),n}$$

The overall dissipated energy in one time step h is

$$\int_t^{t+h} dE_{Q,diss} = E_{pot}(t) + E_{kin}(t) - E_{kin}(t+h) - E_{pot}(t+h)$$

A direct correlation between the cluster system parameters and the thermo-dynamical viscosity is not possible because of the different scales of time and magnitude. The idea is now to determine transformation parameters that allow a proper representation of dissipative forces that result from microscopic phenomena by their macroscopically visible effects. The above-mentioned definition of viscosity is the key to find a correlation between the dissipation coefficient d and the viscosity μ. The macroscopically visible effect of viscosity is a reduction of flow velocity of a liquid when submitted to exterior forces. Regarding a liquid flowing through a channel e.g. gives a velocity profile in radial direction that is not uniform, but different velocity layers can be identified. The velocity profile is of parabolic type with a minimum immediately at the channel walls and a maximum speed that corresponds to the nominal main speed in the channel longitudinal axis. The channel flow is now analyzed in detail to determine the dissipation parameter for the cluster system. Although it is a 3D problem, it is possible to split off the analysis for each direction separately and to use a very simple experiment. For the present example, analytical solutions for the velocity profile and the volume flux are available. The equation to determine velocity and volume flux with respect to channel height and time is:

$$v(y,t) = \frac{r \cdot f \cdot h^2}{2 \cdot h} \cdot \left(\frac{y}{h} - \frac{y^2}{h^2} - \frac{8}{p^3} \cdot \sum_{n=1}^{\infty} \frac{\sin(2n-1) \cdot p \cdot \frac{y}{h}}{(2n-1)^3} \cdot e^{-(2n-1)^2 \cdot \frac{p^2 \cdot h}{h^2 \cdot r} \cdot t} \right)$$

$$\dot{V}(t) = b \cdot \frac{r \cdot f \cdot h^4}{2h} \cdot \left(\frac{1}{6} - \frac{16}{p^4} \cdot \sum_{n=1}^{\infty} \frac{1}{(2n-1)^4} \cdot e^{-(2n-1)^2 \cdot \frac{p^2 \cdot h}{h^2 \cdot r} \cdot t} \right)$$

The simulation of the volume flux is now carried out for a configuration of clusters according to figure 4 in each of the three Cartesian directions. The basic cells contain two particle lines that represent the walls and one line of particles representing the liquid. The liquid particles are submitted to a mass force field that is applied to every liquid particle and that results from a specific exterior pressure difference. Viscosity is now understood as the deceleration of the liquid particles by the channel particles. Without viscosity, the velocity of each of the liquid particles would be proportional to time and the volume flux would be a linear function of time. For a viscous fluid, however, the velocity profile is of parabolic type and the volume flux, after some inflow turbulences, reaches a constant level as the viscous forces dissipate a certain part of the kinetic energy of the fluid particles. The mass field force is defined as follows:

$$\sum_{i=1}^{NT} F = \int_{V_0} f \cdot r \cdot dV \quad , \qquad f = \frac{NT \cdot F}{r \cdot V}$$

The velocity of each particle is time-averaged in time as only the main flux direction is important for the volume flux.

$$\dot{V}(t) = h \cdot b \cdot \dot{x}_i(t) \quad , \qquad \overline{\dot{x}_i(t)} = \frac{1}{NT_t} \cdot \sum_{j=0}^{N_t} \dot{x}_i(t_j) \, , \qquad \dot{V}(t) = h \cdot b \cdot \overline{\dot{x}_i(t)}$$

In the following, the volume flux has been computed for the viscosity of the liquid to be analyzed and the volume flux computed by the cluster system has been adapted until both are in congruency, see figure 5. By varying the viscosity in the analytical solution, a correlation between the dissipation parameter d and the liquid viscosity is obtained (figure 6). This dependency is implemented in the simulation code; it permits the simulation of liquids in a wide range of viscosity and represents the temperature- and pressure dependency of viscosity correctly.

4.4 Impact Force Computation

Liquid impact on structures is not trivial because a lot of dependencies have to be taken into account. The most important difference between the collision of two solids and the collision between a solid and a liquid volume is the damping. In general, two solids collide nearly elastically; the damping of shock energy is very low (depending on the materials). The resulting force on the solid is a sharp peak known as shock (figure 7, top). In contrast to that, during a liquid impact a big amount of the shock energy is dissipated within the liquid (figure 7, bottom), and the resulting forces on the solid are relatively small compared to the hydrostatic forces. Hydrostatic forces are understood here as product of overall liquid mass and maximum particle relative acceleration. The impact forces are forces on the tank structure resulting from the impact pressure of the fuel on the tank surface. Within the particle cluster approach, pressure is understood as the resulting inter-particle force on an elemental volume ΔV per surface unit in x-, y- and z-direction (p_x, p_y, p_z). Immediately at the wall, the surface pressure is identical with the pressure computed for particles close to the wall. If the fuel is in rest, the pressure is identical with the hydrostatic pressure if only mass forces act on the particles. If the liquid is in motion, additional pressure arises due to the inertia of the liquid. The resulting pressure on the walls then

becomes stronger than the hydrostatic pressure. Within the particle approach the resulting force on the wall is computed as the sum of all individual boundary-close particle pulses on the wall. Immediately at the wall, the boundary potential is assumed to have the same physical properties as within the liquid volume. This assumption is justified by the non-slip condition, which states that particles close to the wall have the speed of the wall. Here, the boundary potential is understood as the very first particle layer covering the wall with a thin film. If a liquid volume approaches a solid wall, the repulsing forces of the wall initially only act on the wall-close liquid particles. These particles are repulsed from the boundary, whereas particles away are still moving towards the wall. The repulsing force from the wall now propagates through the liquid volume like a wave until the overall liquid volume has been decelerated (see figure 7). During the force propagation inside the liquid volume, the resulting repulsing force becomes weaker the further it travels because of kinetic energy dissipation inside the liquid. Thus the overall work of the repulsing forces becomes

$$W\left(a_{cg}\ \mathrm{var}\,iable\right)=\int_{x_0}^{x_1}\int_V r\cdot a_{cg}(x)\cdot dV\cdot dx \quad < \quad W\left(a_{cg}\ fix\right)=a_{cg}\cdot\int_{x_0}^{x_1}\int_V r\cdot dV\cdot dx$$

The energy conservation implies that the dissipated energy is transferred into internal energy (heat). This is illustrated in figure 7 where the acceleration peak corresponds to a constant repulsing force applied to every particle. The wider, smaller acceleration level corresponds to the particle-dependent variable repulsing force. The constant force applied to each particle simulates a solid body impact, whereas the variable repulsing force simulates the impact of a liquid.

The location of the impact force maximum can now be computed using the individual wall forces derived before. Multiplying the individual force contribution with the corresponding lever arm with respect to the centre of gravity of the liquid volume gives the resulting momentum.

4.5 Experimental Validation

The liquid viscosity has been validated using a channel flow analogy. For the present analysis where impact forces are the subjects, the liquid modelling has to be validated also for the dynamic pressure modelling described in the section above. Experimental data have been found from NASA resulting from the investigation of liquid impact in a model propellant tank [3]. The test set up is sketched in figure 8. In this experiment, a partially filled model propellant tank is vertically accelerated by a drop mass. The acceleration is suddenly stopped and the tank is decelerated by a spring. Due to the resulting relative acceleration the liquid splashes against the tank dome and the forces and pressure have been measured. The relevant acceleration recordings are relative accelerations between liquid volume and model tank. The particle cluster modelling is sketched in figure 9. The results from the experiment and the corresponding particle cluster simulation are presented in figures 10, 11 and 12.

5 THE STORE SEPARATION PROGRAM (SSP)

The core of store separation modelling at EADS-D consists of the Store-Separation-Program (SSP), a 6 DOF simulation program that computes the motion of jettisoned or launched stores and missiles in any type of interference flow around the carrier aircraft. This approach is based on different mathematical modelling strategies which are utilising computed sectional loads and aircraft flow fields as well as measured installed and on time accurately computed End-Of-Stroke loads in order to represent the aerodynamic effects. The theoretical background is based on Euler solutions successfully in use at *EADS* Deutschland for this special purpose since more than 15 years; see [6], [7]. The slosh subroutine described in [1] has been successfully implemented into the SSP and is the basis for the present analysis. Ejection forces and aerodynamic drag computed by the SSP have been used as input for the particle program. The particle program takes into account the accelerations (translations and rotations) of the tank structure and combines them with the impact forces. The impact forces, however, change the tank accelerations, an interactive process starts resulting in a tank jettison trajectory representing the dynamics of the structure and of the liquid. For the computations, the tank properties in table 1 have been used.

6 RESULTS AND CONCLUSION

6.1 Pitch Characteristic (quiescent)

In figure 13, discrete time steps of the trajectory of a partially filled 3-compartment tank jettison are presented, showing the fuel impact on the tank walls. The pitch angle and the corresponding angular acceleration with respect to the y-axis for a quiescent fuel surface immediately before jettison are presented in figures 14 and 15. The corresponding vertical acceleration is shown in figure 16. In figure 14, the a peak in pitch angle is highlighted representing the time of fuel impact. The overall change in pitch is relatively small compared to the change in pitch due to the ejection forces. The triple-peak in angular acceleration in figure 15 results from the three single impacts of the liquid volumes in the corresponding compartments. the time history of the vertical acceleration in figure 16 shows all relevant features of a trajectory with fuel impact. During the ejection phase, the acceleration due to the ERU is dominating. The first peak results from the fuel impact on the tank top. The second peak is the fuel splash down on the tank bottom. After splash down, the tank is nearly in free fall, only decelerated by the aerodynamic drag. All these results have been obtained for a tank filled to 1/3 in each compartment.

6.2 Pitch Characteristic (modal)

The same jettison parameters used before are now applied to a tank where the fuel volume is oscillating in its first Eigen mode (figure 3). The difference to the examples above is the fuel surface; in the modal case, the surface is not quiescent, but a big mass contribution is located close to one of the compartment walls. The effect on the tank trajectory is a reduction of the impact forces and therefore a slight reduction of the corresponding pitch up momentum. The reason for the slightly lower force peaks is that the fuel can move along the tank walls to the top. This flow process leads to lower impact velocities on the top and therefore to lower force peaks.

6.3 Conclusion and Outlook

The impact damping for the quiescent test case is presented in figure 17. Obviously, the forces due to fuel impact are relatively small compared to the hydrostatic forces that would occur if the fuel volume was accelerated until every fuel particle reaches the tank top at identical velocity. This would be the result for a rigid body impacting on the top. The ratio of impact forces to hydrostatic forces is less than 25 % in most cases, slightly lower for the modal cases . Therefore, it can be concluded that fuel impact forces have an influence on the pitch characteristics of a 3-compartment external fuel tank during jettison. The tank slightly pitches up due to the impact on the tank top in the front compartment, but not to such an amount that the tank completely reverses the pitch-down implied by the ERU. Nevertheless, the temporary pitch-up has to be seen in combination with changing aerodynamics for the new tank position relatively to the free air stream. The trajectories show that risk areas can be identified taking into account the changing mass properties and impact forces of the fuel inside the tank. The combined particle cluster / SSP approach has been validated with experimental data to predict fuel slosh and impact effects on tank jettison trajectories. It is not limited to jettison analysis for clearance aspects, but can also be used for structural analysis in the development phase of tanks.

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8 FIGURES

Empty Tank	
Empty mass	125.0 [kg]
Volume	1.62 [m^3]
Xcg / Ycg / Zcg	2.90 / -0.001 / 0.04 [m]
Inertia Ixx / Iyy / Izz	8.9 / 195.0 / 195.0 [kg * m^2]

Fuel	
Fuel mass (total)	ca. 1180 kg
Rest Fuel mass	ca. 11.7 kg

Empty Tank + Fuel	
overall mass	ca. 1300 [kg]
Xcg / Ycg / Zcg	2.70 / 0.0 / 0.001 [m]
Inertia Ixx / Iyy / Izz (solid)	64.0 / 1890.0/1890.0 [kg * m^2]

Realistic Flight Conditions	
Tank empty with Rest Fuel:	135.0 [kg]
Tank full	1290 [kg]

Table 1: Mass properties of the tank / fuel system for a typical 3-compartment tank

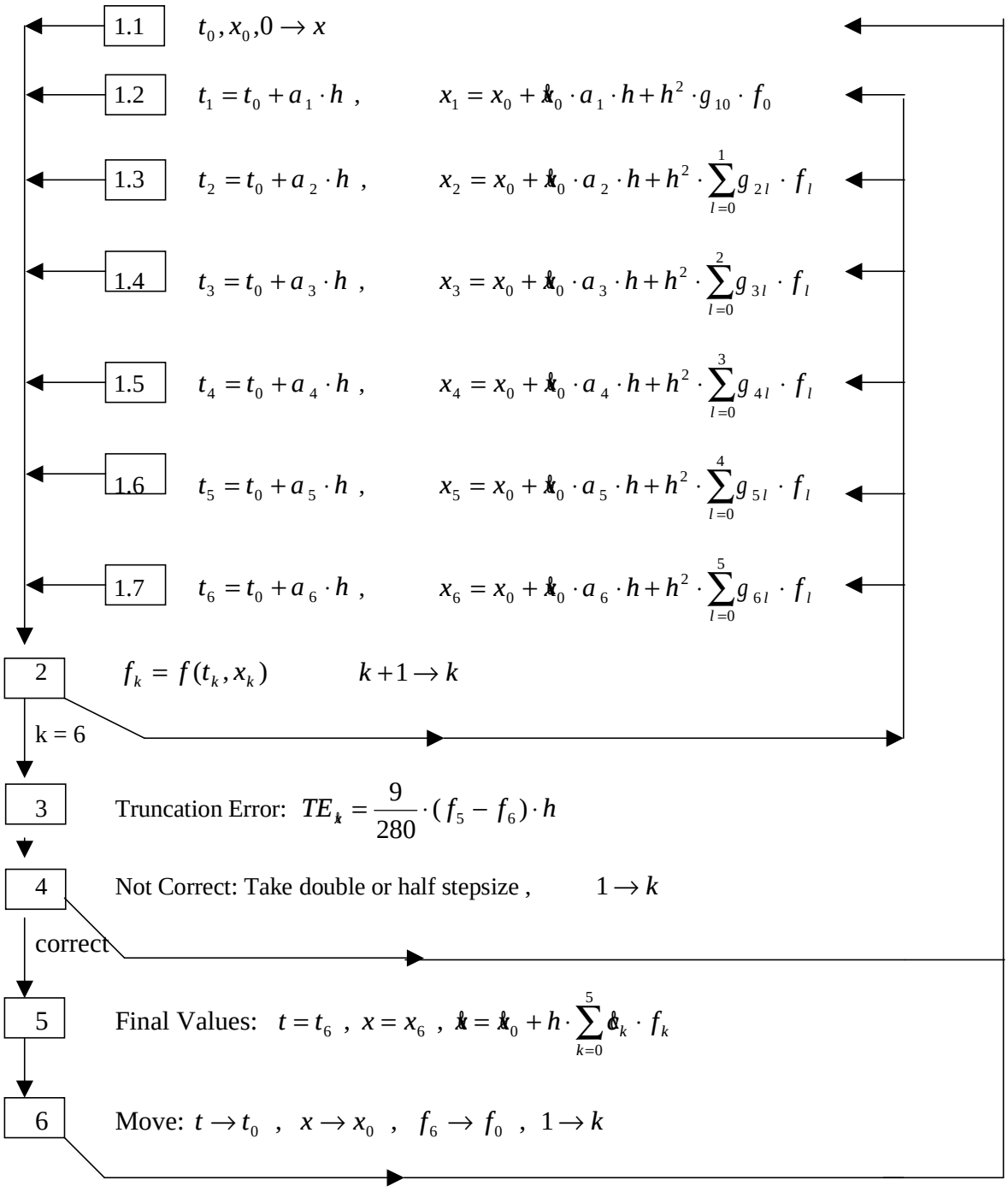

Table 2: 6th order Runge-Kutta-Fehlberg scheme used for the particle approach

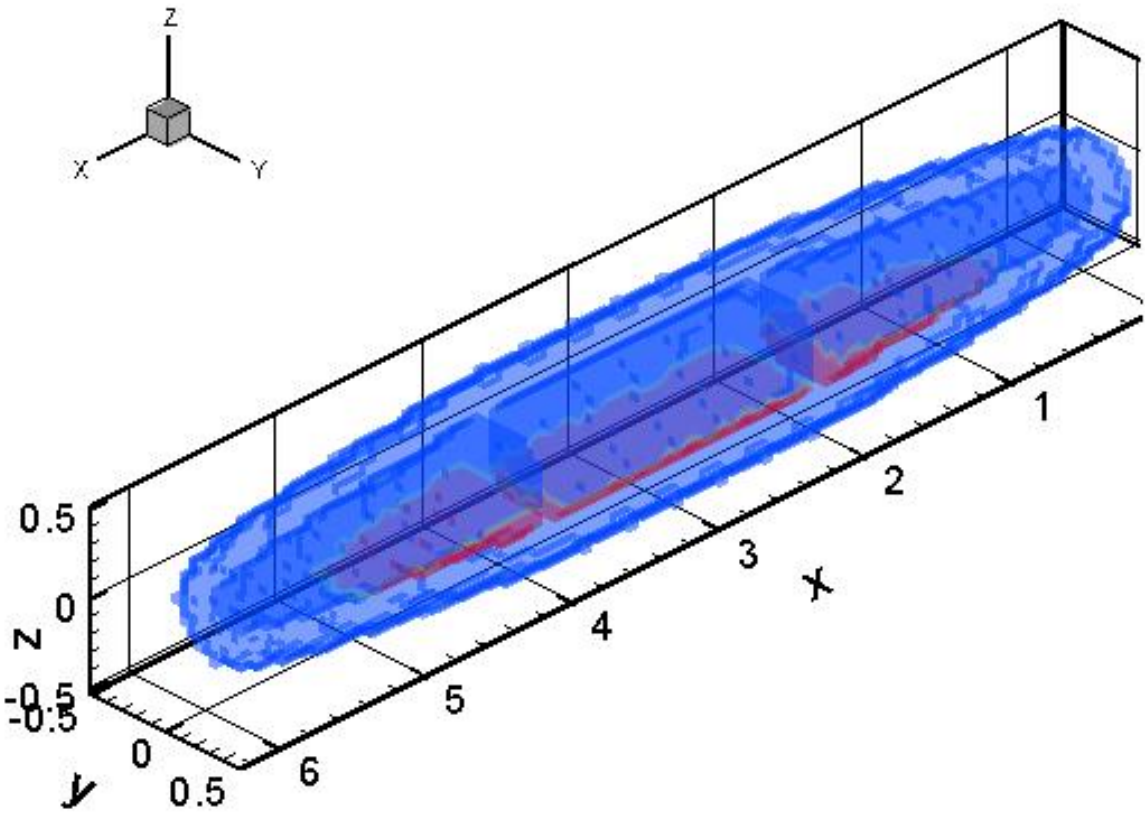

Figure 1: Particle model for 3-compartment tank , 3D-view inside

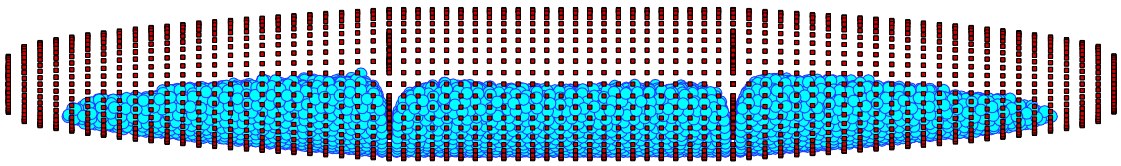

Figure 2: 3-compartment tank, each compartment half filled, nearly-smooth fuel surface

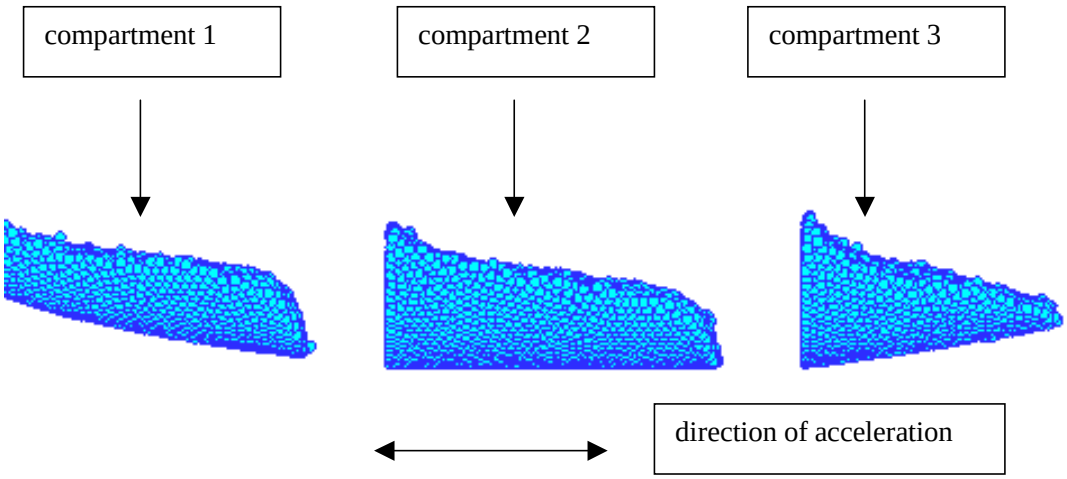

Figure 3: 3-compartment tank half filled, sloshing fuel in first mode

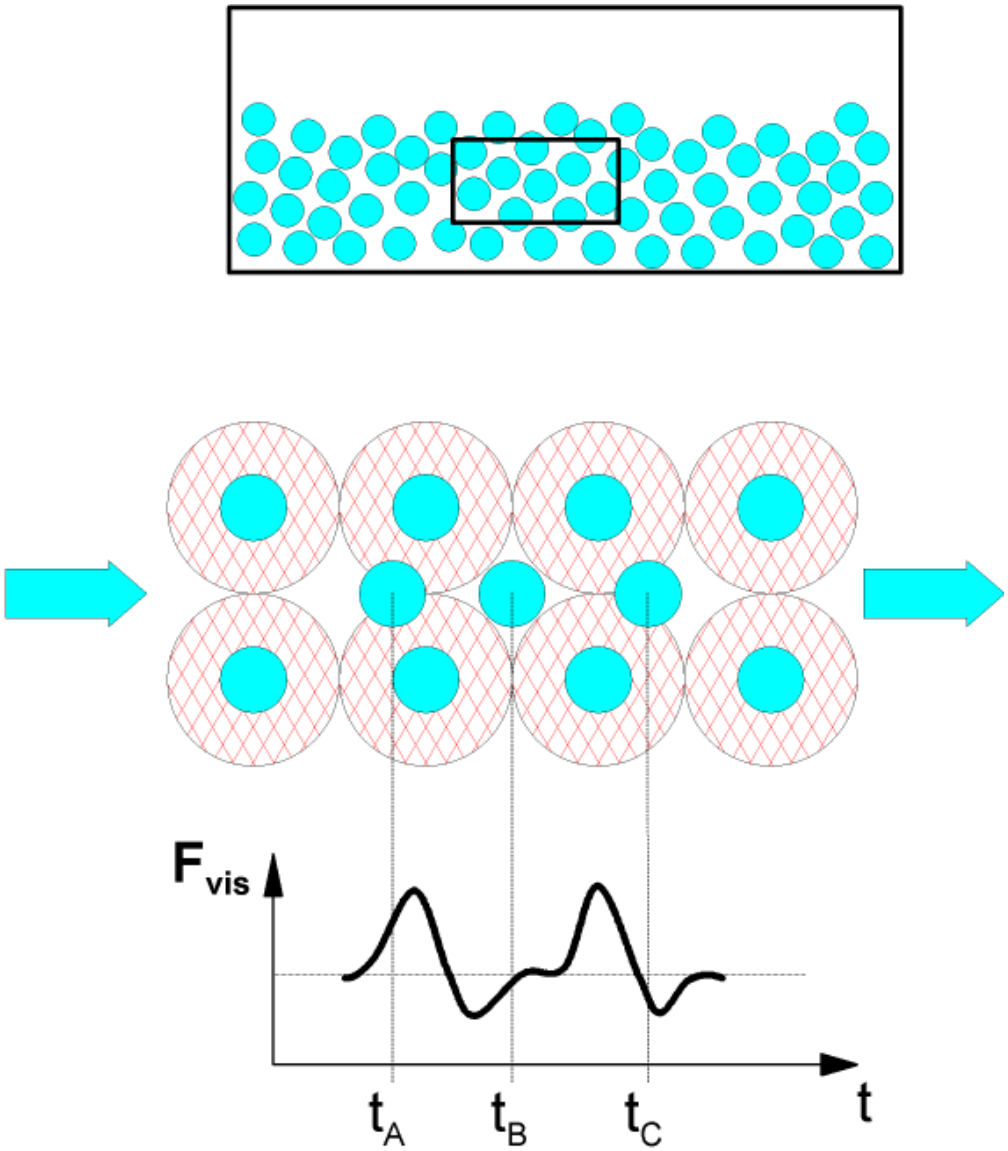

Figure 4: Physical background and particle constellation for viscosity calibration

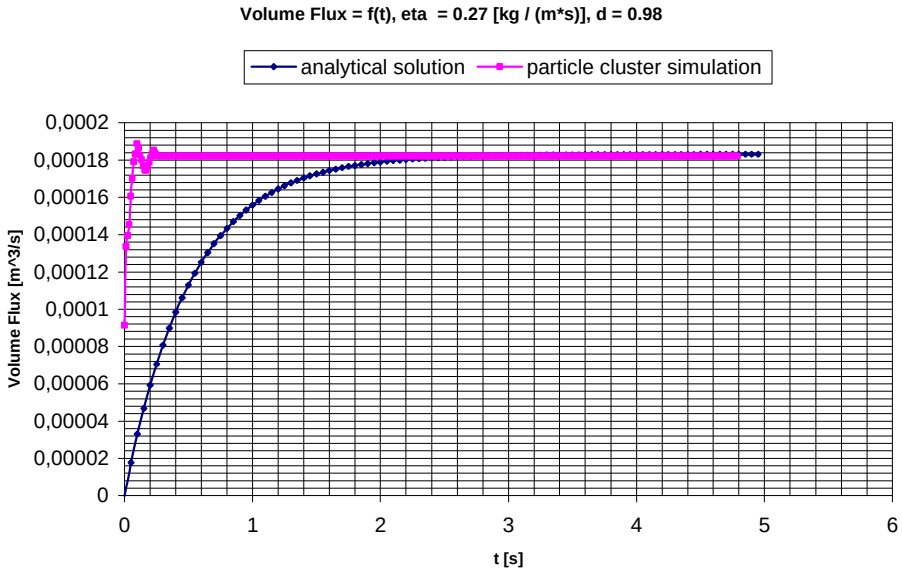

Figure 5: Viscosity validation for the particle cluster approach with analytically derived volume flux

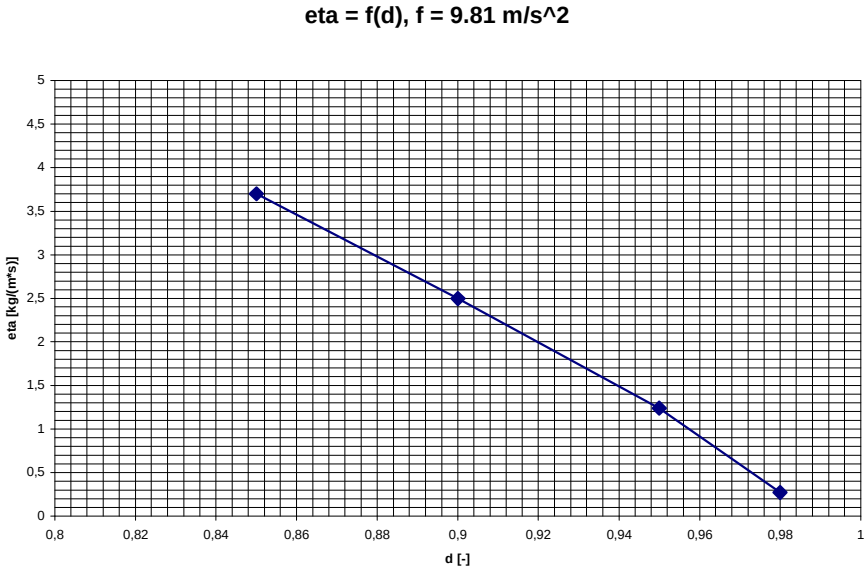

Figure 6: Functional dependency between viscosity and dissipation parameter d

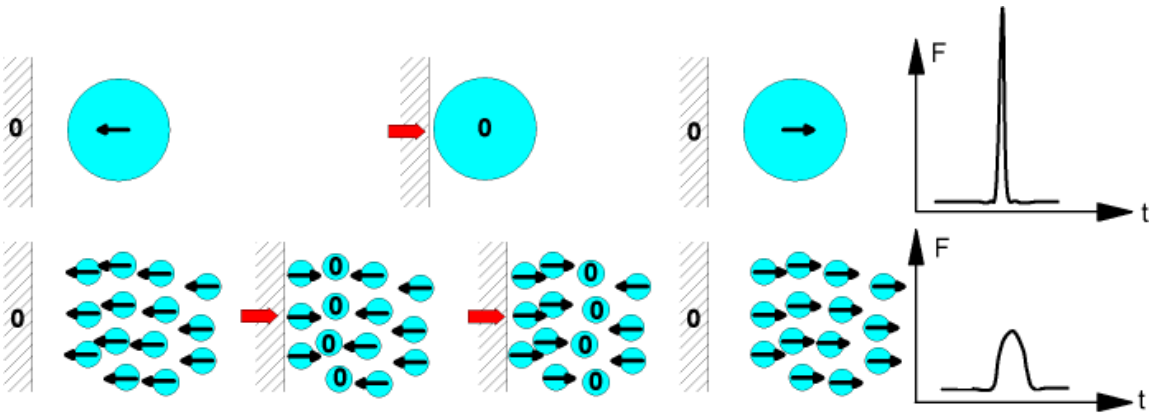

Figure 7: Impact force characteristics of a solid and a liquid

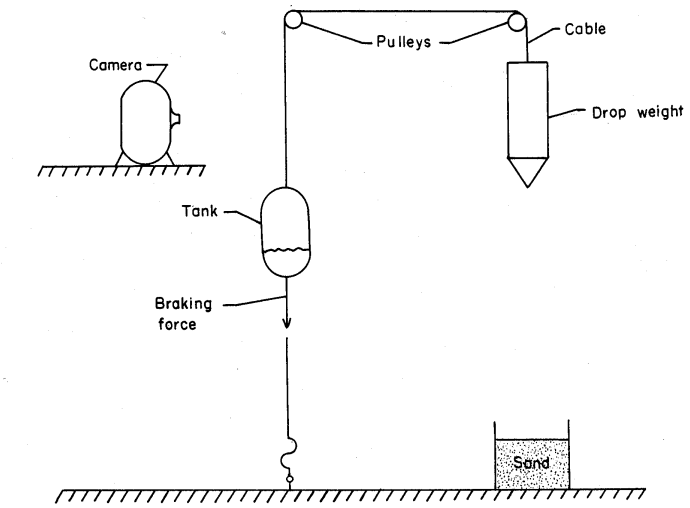

Figure 8: Sketch of liquid impact experiment as described in [3]

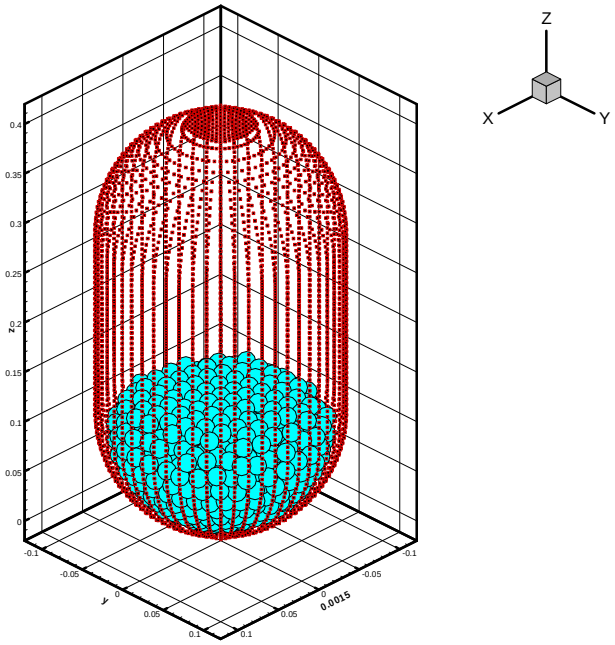

Figure 9: Sketch of particle cluster modelling for the liquid impact experiment as described in [3]

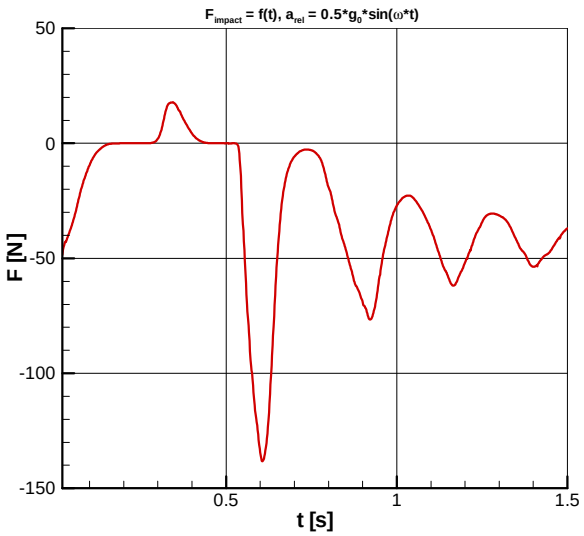

Figure 10: Typical impact force for a sinusoid relative acceleration for the model tank

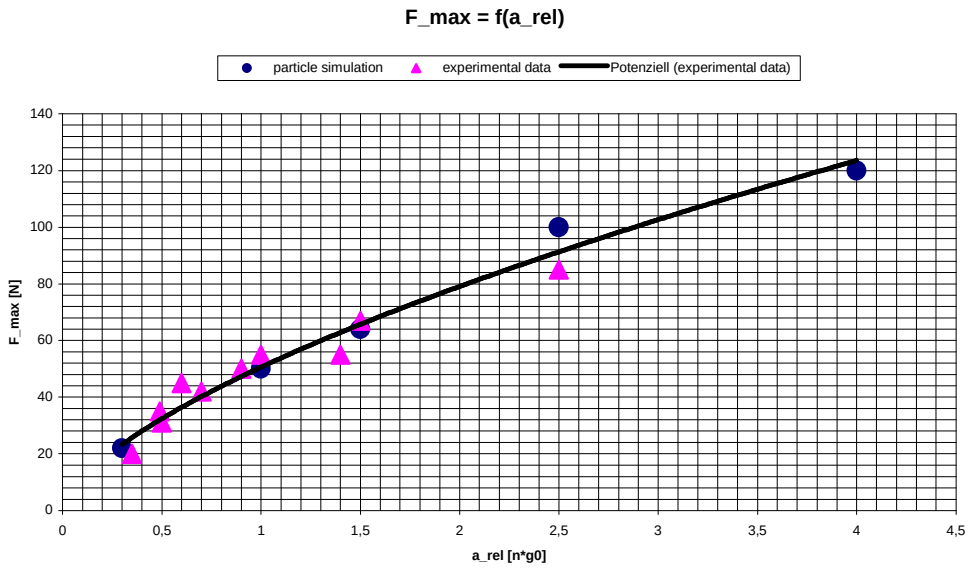

Figure 11: Validation of maximum impact force on the model tank top, experiment / simulation

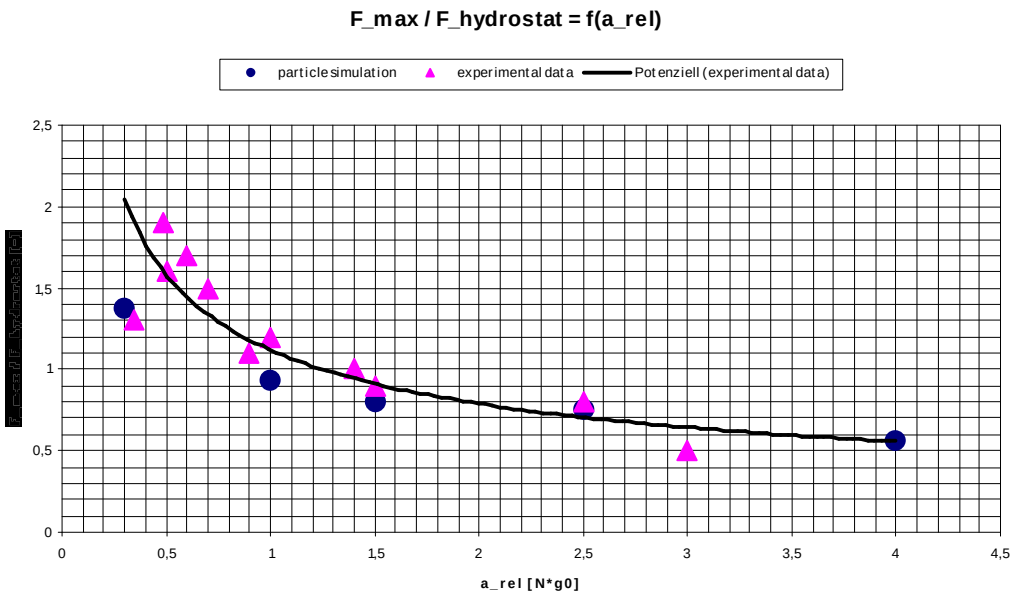

Figure 12: Ratio of maximum impact force to hydrostatic force, experiment / simulation

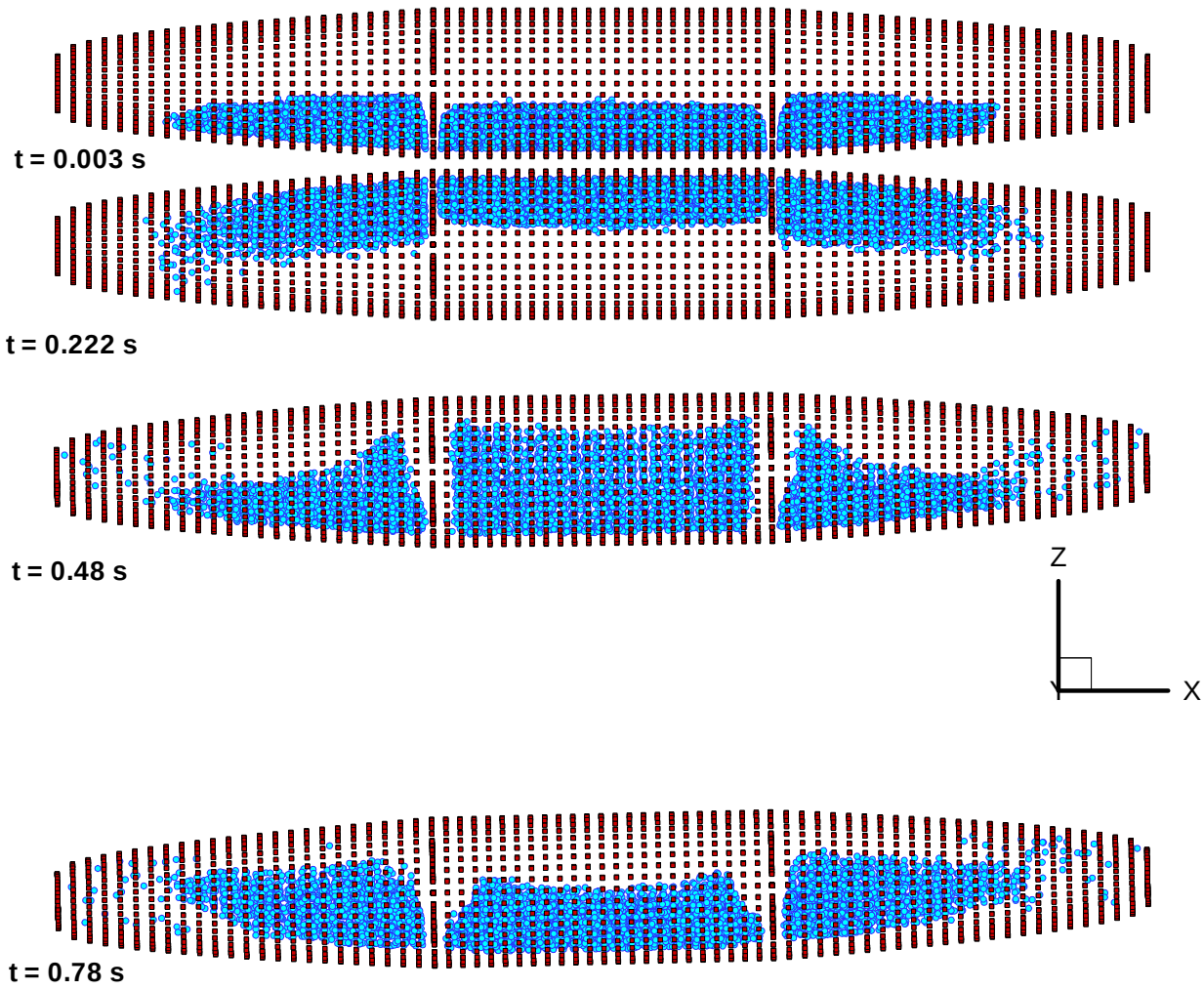

Figure 13: 3-compartment tank jettison trajectory, particle cluster simulation

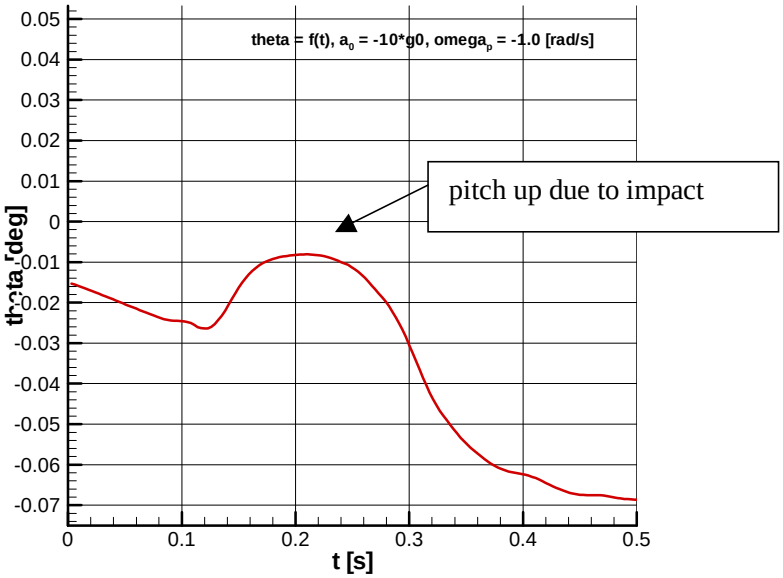

Figure 14: Results of 3-compartment tank jettison analysis, pitch angle with fuel impact

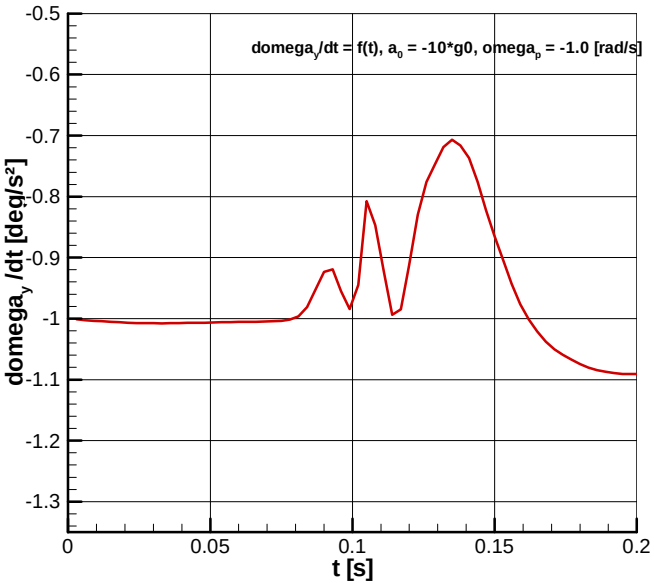

Figure 15: Results of 3-compartment tank jettison analysis, domega_y/dt with fuel impact

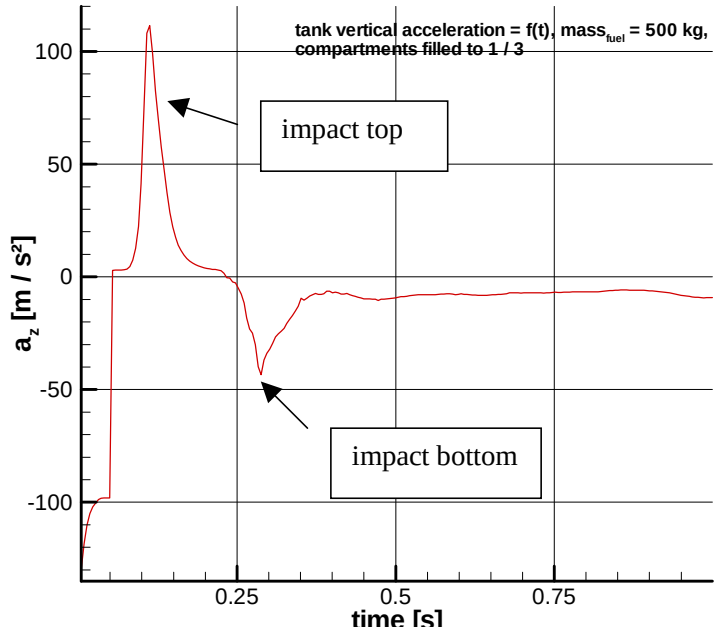

Figure 16: Results of 3-compartment tank jettison analysis, vertical acceleration with fuel impact

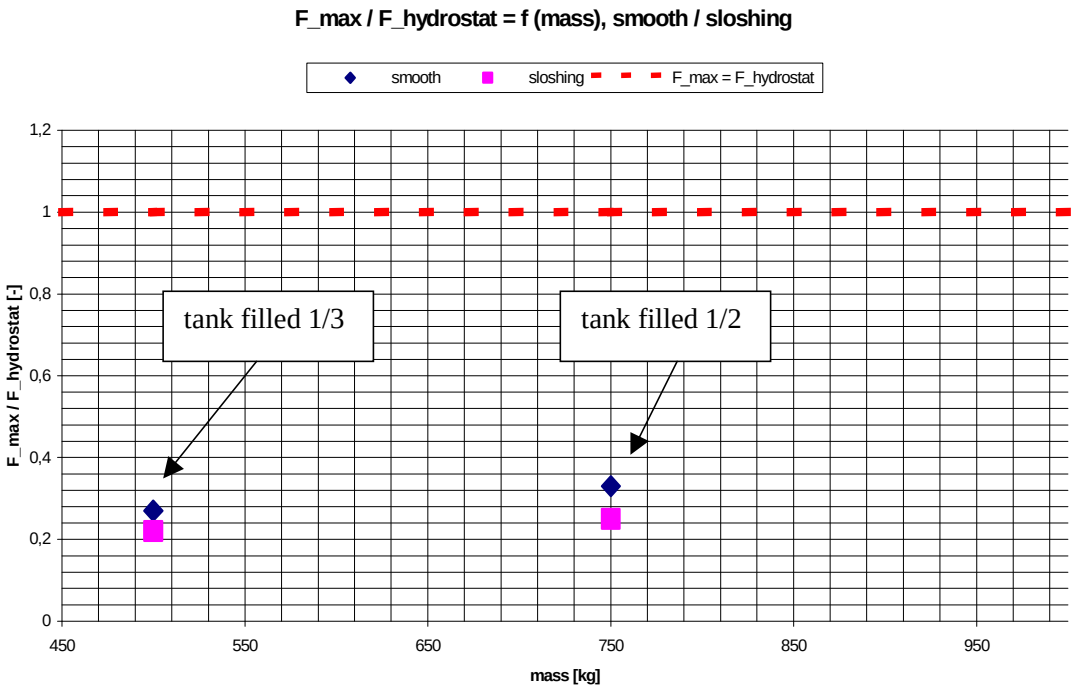

Figure 17: Results of 3-compartment tank jettison analysis with fuel impact

SYMPOSIA DISCUSSION

REFERENCE AND/OR TITLE OF THE PAPER: 10

DISCUSSOR'S NAME: B. Oskam
AUTHOR'S NAME: A. Baeten

QUESTION:
Does your computational time for the particle simulation code scale as N^2 for large number of particles N?

AUTHOR'S REPLY:
The computation is done using a limited-cell list for each particle, defining the number of particles interacting with one specific particle. This list is updated automatically and locally, whenever particles leave/enter the list. This reduces the computation time to a big amount, it scales linear with particle number N.

DISCUSSOR'S NAME: H. Kristou
AUTHOR'S NAME: A. Baeten

QUESTION:
Did you research tank deformation and various cross sections in your cases?

AUTHOR'S REPLY:
Currently, the tank is regarded as rigid body with no deformation. But it is possible to take deformation into account and to predict the critical loads on the tank structure. This is one of the next steps in the research. It is a useful tool for load determination as well; the structure material properties will soon be added to the boundary conditions providing real deformation characteristics.

DISCUSSOR'S NAME: C. Petiau
AUTHOR'S NAME: A. Baeten

QUESTION:
How you manage the fact that particle method "breaks" the isotropy of the fluid? Are you able to compute the static wall pressure distribution resulting from your method?

AUTHOR'S REPLY:
You are right that discrete particles "break" the fluid isotropy. The particle properties are averaged to cell properties and therefore no "hole" in the isotropy occurs. The cell distribution originates from the linked-cell algorithm that reduces the computation time. The cell averaging is similar to continuum mechanics and approaches the continuum values for density and pressure the finer the discretization becomes. The static wall pressure results from the hydrostatic pressure. For the static case, the wall potential has to react to the gravity force of the particle "column" above, and in fact, the wall pressure corresponds to the hydrostatic pressure.

DISCUSSOR'S NAME: A. Cenko
AUTHOR'S NAME: A. Baeten

QUESTION:
Will the Eurofighter have a pivot on the aft end of the tank to ensure it pitches nose down?

AUTHOR'S REPLY:
The Eurofighter has a pivot on the aft end of the tank. It is ensured that the tank pitches down. Nevertheless, the fuel impact in a partially filled tank will not only provide a slight pitch-up, but also a vertical acceleration upwards which results in a tank acceleration opposite to the direction of the ERU forces.