Method of Simulation of Fuel Sloshing Effects on External Fuel Tank Separation

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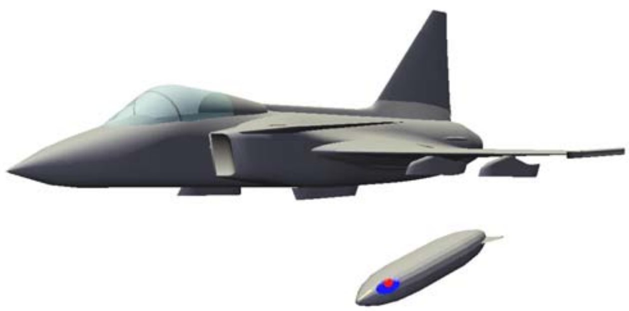
SUMMARY

Fuel sloshing effects have a major influence on external fuel tank separations. To be able to define a safe separation envelope a method of how to calculate the fuel sloshing effects has been developed. The method treats the fuel as a mass point, which can only move inside a bubble shaped limit surface. The limit surface is defined by the possible fuel centres of gravity positions. When the mass point and the limit surface are in contact, forces are arisen to keep the mass point inside the limit surface, e.g. keep the fuel inside the tank. Since the forces also act on the fuel tank the trajectory will be affected during the separation.

To evaluate the sloshing method comparisons to simple CFD calculations have been made. A partly water filled cube was tilted 90 degrees and the centres of gravity motions were studied. The CFD results and the results from the simulation model, based on the sloshing method were similar.

When a partly filled fuel tank is separated from the aircraft it is pushed down by pistons in the pylon. What will happen when the tank accelerates downwards is that the fuel will hit the upper surface in the tank and change the fuel tank motion due to the collision. This behaviour is clearly seen in the simulations and the motion of the sloshing fuel looks natural.

The possibility to implement a more exact model of sloshing fuel affecting the motion of an external fuel tank during separation is today very small. The complexity of the fuel shape inside the compartment is so high that possible CFD models will be too slow to be useful in production simulations.



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1.0 INTRODUCTION

Store separations of empty or partly filled external fuel tanks are critical due to the low weight and high aerodynamic influence. To minimize the risk of collisions between the fuel tank and the aircraft a good simulation tool is needed to analyse and define the release envelope. To be able to simulate a separation of a partly filled fuel tank a method of how to calculate the fuel sloshing effects has been developed.

2.0 METHOD

The fuel is treated as a mass point in the fuel centre of gravity. The positions where the mass point can be located depend on the tank geometry and the amount of fuel. The outermost cg positions will describe a limit surface in which the mass point is free to move. In figure 1 a half filled forward compartment of an external fuel tank with three compartments is shown.

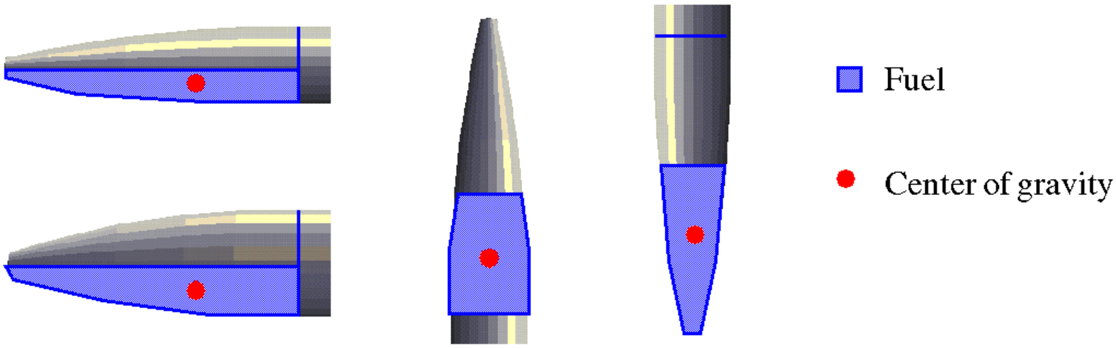

Figure 1: Example of centre of gravity positions depending on orientation

Calculations of the different possible cg positions results in a limit surface best described as an ellipsoid (see figure 2).

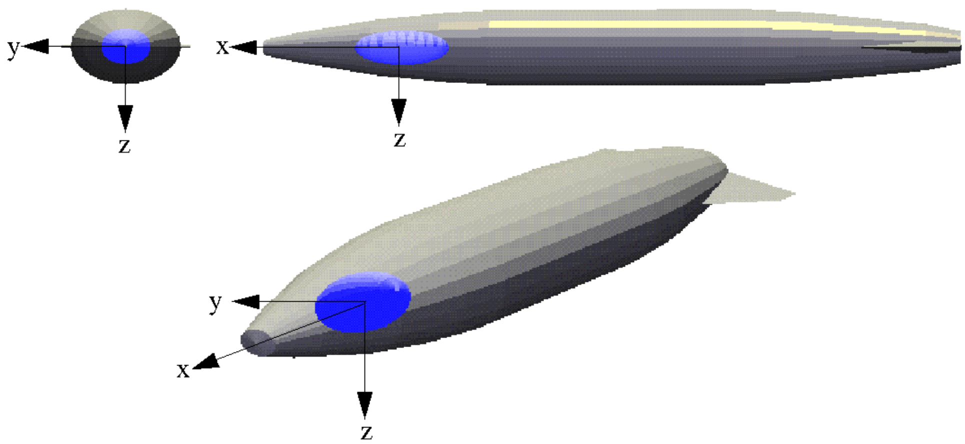

Figure 2: The limit surface for the forward compartment

When the mass point during the simulation hits the limit surface a spring force will be created which will move the mass point back into the ellipsoid. A damping force in the opposite velocity direction also has to be introduced to prevent too much of rebounding. When the mass point is inside the ellipsoid but not located on the surface it is not affected by any forces except by gravity. Figure 3 describes the different forces acting on the mass point. The spring and the damping force only act in the normal direction of the limit surface. The reaction forces affect the tank in the opposite direction.

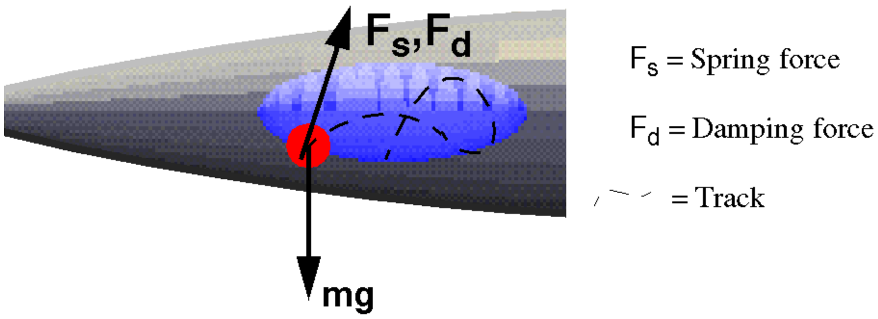

Figure 3: Description of forces acting on the mass point

3.0 LIMIT SURFACE CALCULATION

To be able to calculate the centre of gravity for the fuel the geometry of the fuel tank has to be known. By analysing drawings and by using a curve fitting program the fuel tank contour curves can be found. The external fuel tank used in this example has three compartments. The definition of the coordinate system and the contour curves for the forward compartment are illustrated in figure 4.

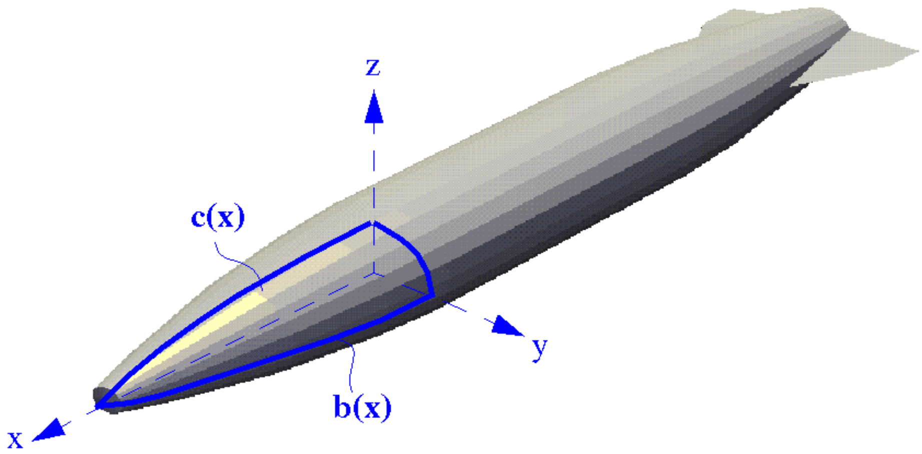

Figure 4: The definition of the coordinate system and the contour curves

The equations of the contour curves b(x) and c(x) are:

$$b(x) = -0.0666 \cdot x^3 - 0.0809 \cdot x + 0.4075 \qquad (1)$$

$$c(x) = -0.0648 \cdot x^3 - 0.0047 \cdot x + 0.2775 \qquad (2)$$

The cross section shape for each x-value is best described by the following equation:

$$\frac{y^{2.5}}{b(x)^{2.5}} + \frac{z^{2.5}}{c(x)^{2.5}} = 1 \quad \text{(Def. for y > 0 and z > 0)} \qquad (3)$$

The position of the fuel centre of gravity depends on the tank geometry and the amount of fuel. Figure 5 shows a half filled forward compartment when the fuel is located in the negative z direction.

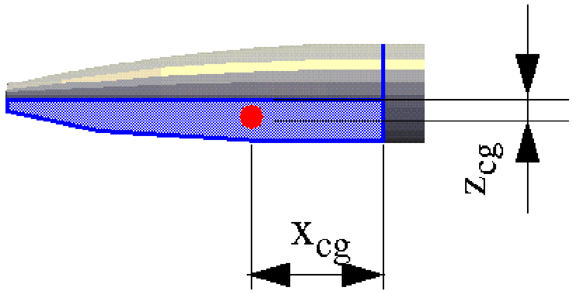

Figure 5: Half filled forward compartment

For this condition the centre of gravity in the x direction, x_{cg}, is calculated by using the following equation:

$$x_{cg} \cdot Vf_{fuel} = \int_0^{x_{length}} (x \cdot A(x))dx \qquad (4)$$

where x_{length} is the total length of the compartment and the fuel volume Vf_{fuel} and the half cross section area A(x), shown in figure 6, are calculated as:

$$Vf_{fuel} = \int_0^{x_{length}} A(x)dx \qquad (5)$$

$$A(x) = 2 \cdot \int_0^{b(x)} z(y)dy = 2 \cdot \int_0^{b(x)} \left(\left(1 - \frac{y^{2.5}}{b(x)^{2.5}} \right) \cdot c(x)^{2.5} \right)^{\frac{1}{2.5}} dy \qquad (6)$$

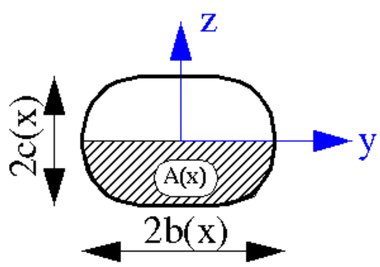

Figure 6: The half cross section area A(x)

A numerical solution is used to solve the integrals. The length of the forward compartment in the x direction is divided into n elements of same length. For each x, b is calculated according to the contour curve (equation 1). The length b is then divided into n elements along the y axis, which gives a z value for each y by using equation 3 and equation 2. The surface (one fourth of the whole compartment) is then described by $(n+1)^2$ nodes, which locations (x, y, z) are known (see figure 7 and figure 8).

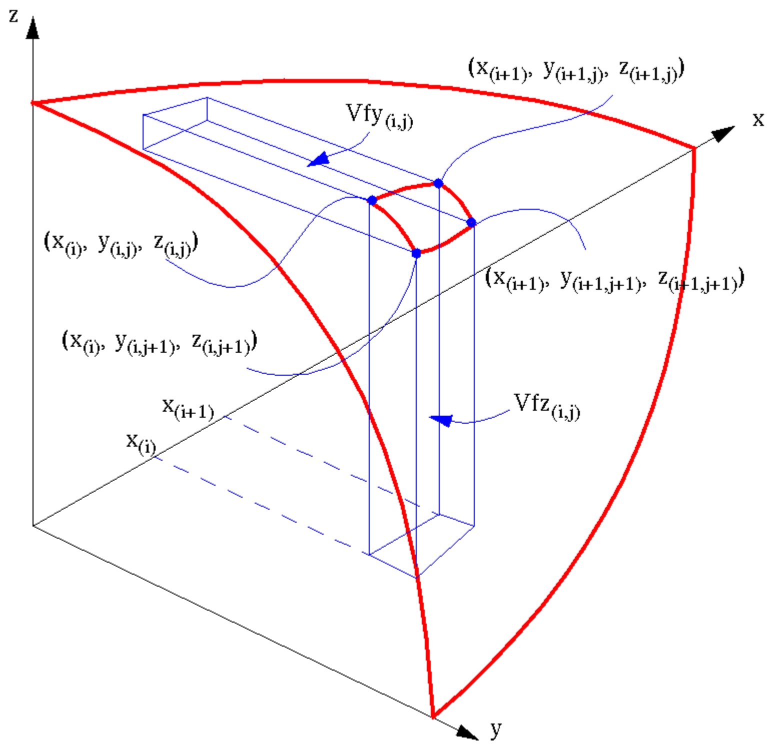

Figure 7: Explanation of nodes

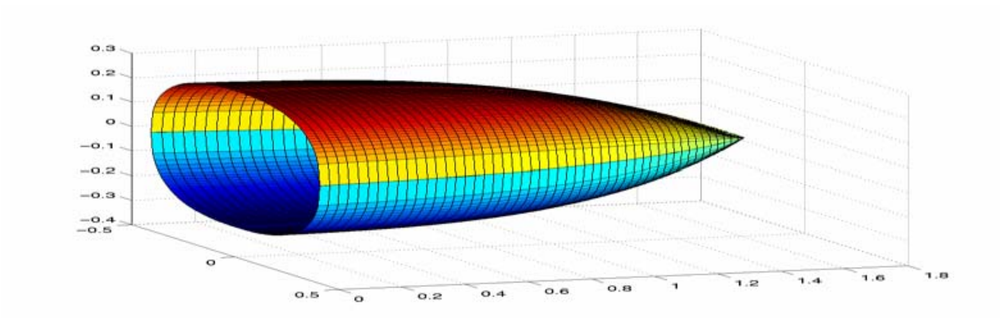

Figure 8: By using the nodes the entire compartment can be plotted

Each volume part in the z direction is calculated as:

$$Vfz_{(i,j)} = \frac{z_{(i,j)} + z_{(i,j+1)} + z_{(i+1,j)} + z_{(i+1,j+1)}}{4} \cdot \frac{y_{(i,j+1)} - y_{(i,j)} + y_{(i+1,j+1)} - y_{(i+1,j)}}{2} \cdot (x_{(i+1)} - x_{(i)}) \qquad (7)$$

The total volume for the fuel in the half filled compartment is:

$$Vf_{fuel} = 2 \cdot \sum_{i=1}^{n} \sum_{j=1}^{n} Vfz_{(i,j)} \qquad (8)$$

By using the following equation the centre of gravity in the x direction is calculated:

$$x_{cg} \cdot Vf_{fuel} = 2 \cdot \sum_{i=1}^{n} \sum_{j=1}^{n} Vfz_{(i,j)} \cdot \frac{x_{(i)} + x_{(i+1)}}{2} \qquad (9)$$

To calculate the centre of gravity position in the z direction the following equation is used:

$$z_{cg} \cdot Vf_{fuel} = 2 \cdot \sum_{i=1}^{n} \sum_{j=1}^{n} Vfy_{(i,j)} \cdot \frac{z_{(i,j)} + z_{(i+1,j)} + z_{(i,j+1)} + z_{(i+1,j+1)}}{2} \qquad (10)$$

where $Vfy_{(i,j)}$ is calculated as:

$$Vfy_{(i,j)} = \frac{y_{(i,j)} + y_{(i,j+1)} + y_{(i+1,j)} + y_{(i+1,j+1)}}{4} \cdot \frac{z_{(i,j)} - z_{(i,j+1)} + z_{(i+1,j)} - z_{(i+1,j+1)}}{2} \cdot (x_{(i+1)} - x_{(i)}) \qquad (11)$$

When the fuel filling condition and tank orientation are as described in this example, the centre of gravity position in the y direction is zero.

By using this method the outermost cg positions in the positive and negative direction of x, y and z are calculated. The six cg positions together with an assumption of an ellipsoid shape of the surface, define the limit surface equation.

4.0 FORCES

The forces that can act on the fuel mass point are the spring force, the damping force and the gravity.

4.1 Spring force

The spring force is calculated as:

$$\overline{F}_s = k_s \cdot \delta \cdot \hat{n} \qquad (12)$$

where k_s is the spring constant, δ is the spring compression distance and $\hat{n}$ is the surface negative normal direction.

With a local origin located in the centre of the bubble the limit surface equation for a half filled compartment is:

$$G(x, y, x) = \frac{x^2}{a_{\lim}^2} + \frac{y^2}{b_{\lim}^2} + \frac{z^2}{c_{\lim}^2} \qquad (13)$$

where a_{lim} is the major axis and b_{lim} and c_{lim} are the minor axes in the limit ellipsoid.

When G(x, y, z) > 1 the mass point is outside the bubble and the spring force starts to act.

The direction of the spring force shall be in the surface normal negative direction (in the collision point).

The negative gradient vector is:

$$-\nabla G(x,y,z) = -\begin{pmatrix} G'(x,y,z) \\ G'(x,y,z) \\ G'(x,y,z) \end{pmatrix} = \begin{pmatrix} -\dfrac{2x}{a_{\lim}^2} \\ -\dfrac{2y}{b_{\lim}^2} \\ -\dfrac{2z}{c_{\lim}^2} \end{pmatrix} \qquad (14)$$

The normalized negative gradient vector is:

$$\hat{n} = \begin{pmatrix} norm_x \\ norm_y \\ norm_z \end{pmatrix} = \frac{1}{\sqrt{\left(-\dfrac{2x}{a_{\lim}^2}\right)^2 + \left(-\dfrac{2y}{b_{\lim}^2}\right)^2 + \left(-\dfrac{2z}{c_{\lim}^2}\right)^2}} \cdot \begin{pmatrix} -\dfrac{2x}{a_{\lim}^2} \\ -\dfrac{2y}{b_{\lim}^2} \\ -\dfrac{2z}{c_{\lim}^2} \end{pmatrix} \qquad (15)$$

With the collision point coordinates inserted in the normalized negative gradient vector, the spring force direction is given.

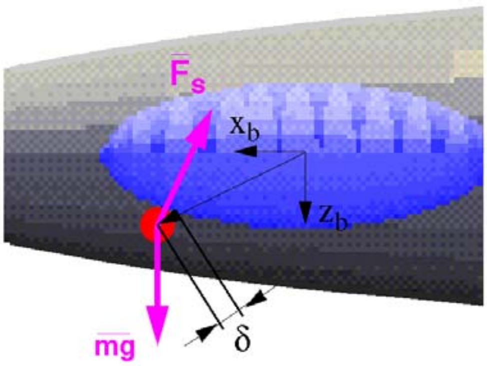

Figure 9: Description of the spring compression distance δ

The spring compression distance δ is calculated as the fuel mass point position subtracted with the collision point (see figure 9). The collision point is defined as the point where the fuel position vector intercepts the limit surface. The linear equation of the mass point position vector combined with the equation of the limit surface give the collision point location.

4.1 Damping force

To prevent too much rebounding when the mass point hits the limit surface a damping force has to be introduced. A damping force usually acts opposite the velocity direction but in the sloshing model the surface normal direction also has to be taken into consideration. The damping force shall not work against streaming fuel over the surface but still reduce rebounding. Therefore, the direction of the damping force will only be in either positive or negative surface normal direction depending on the difference between the collision point velocity and the mass point velocity.

The damping force vector is calculated as:

$$\overline{F}_d = -k_d \cdot \sqrt{\frac{k_s}{m}} \cdot \begin{pmatrix} u_{diff} \cdot |norm_x| \\ v_{diff} \cdot |norm_y| \\ w_{diff} \cdot |norm_z| \end{pmatrix} \qquad (16)$$

where k_d is the damping factor, k_s is the spring constant and u_{diff}, v_{diff} and w_{diff} are the mass point velocity relative the collision point in the three directions. $norm_x$, $norm_y$ and $norm_z$ are the components in $\hat{n}$.

4.2 Forces on the external fuel tank

Additional forces on the tank due to sloshing are the spring force and the damping force acting on the tank in the opposite direction as on the fuel mass point.

5.0 EVALUATION

Results from two CFD calculations of sloshing water in a cube have been used to evaluate and calibrate the sloshing method. Figure 10 shows the limit surface of the cube, the initial positions of the water centre of gravity and the body fixed coordinate system in which the results are presented. In case 1 the cube was tilted 90 degrees during 0.8 s. In case 2 it was tilted 90 degrees during 0.4 s.

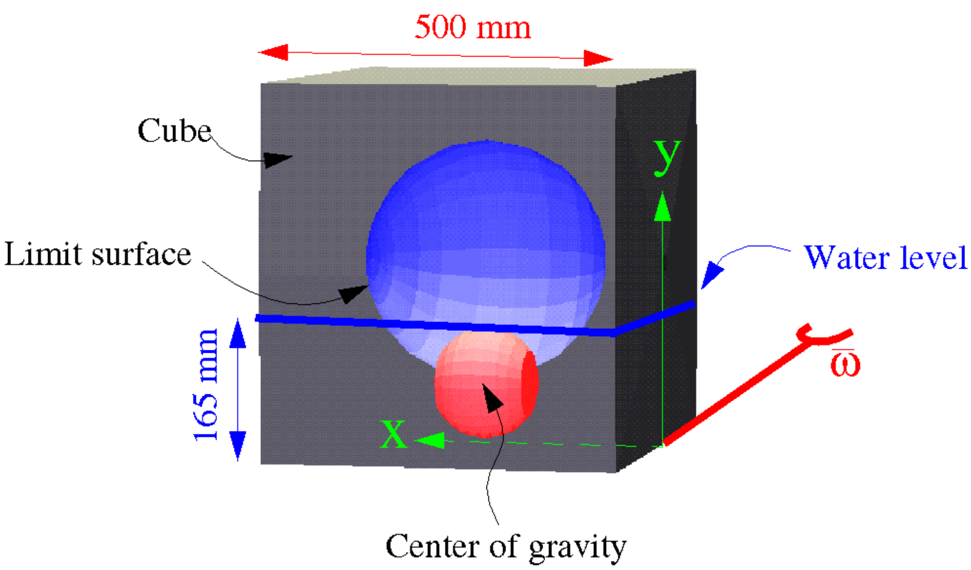

Figure 10: The cube and the body fixed coordinate system in which the results are presented.

A graphical visualization of the simulation of case 1 is shown in figure 11.

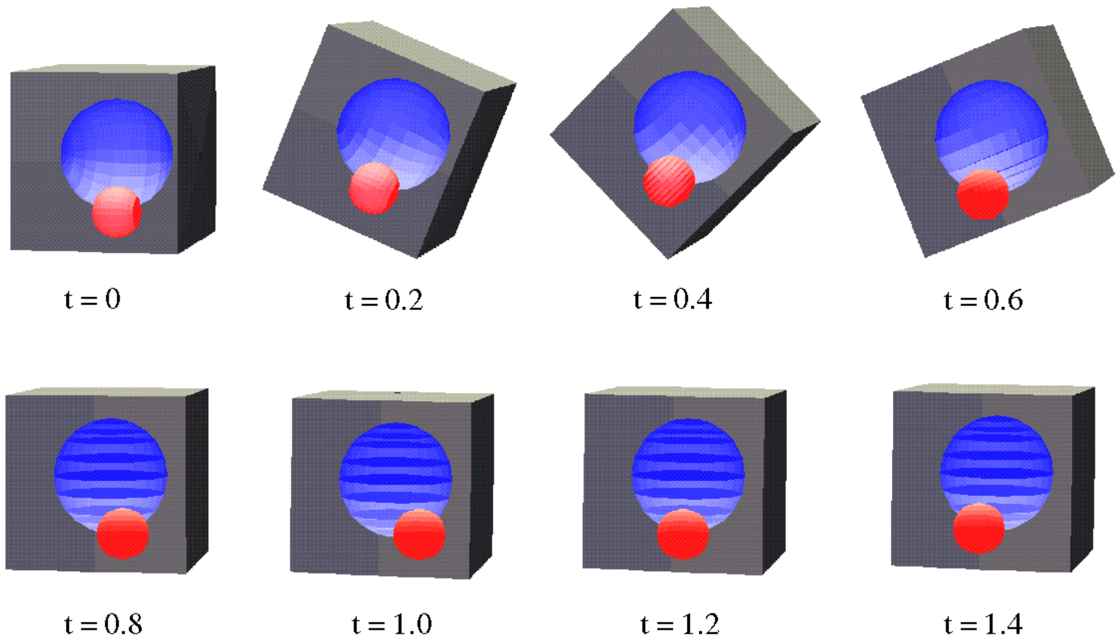

Figure 11: Cube tilt visualization

Comparisons of the centre of gravity positions (x and y coordinates) between the CFD calculations and the simulation model, are presented in figure 12 to figure 15.

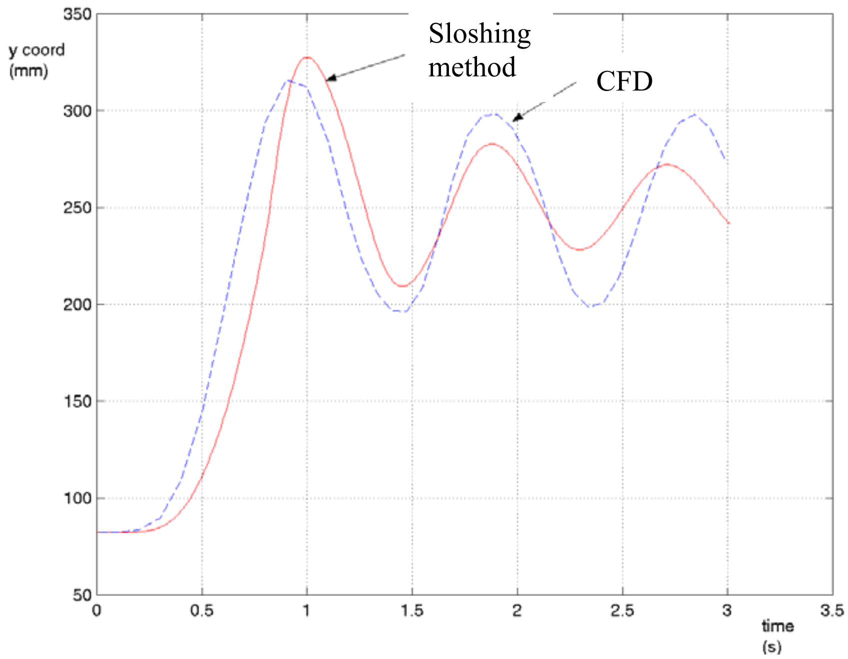

Figure 12: Case 1, comparison of y positions of CG calculated by CFD and by the simulation model

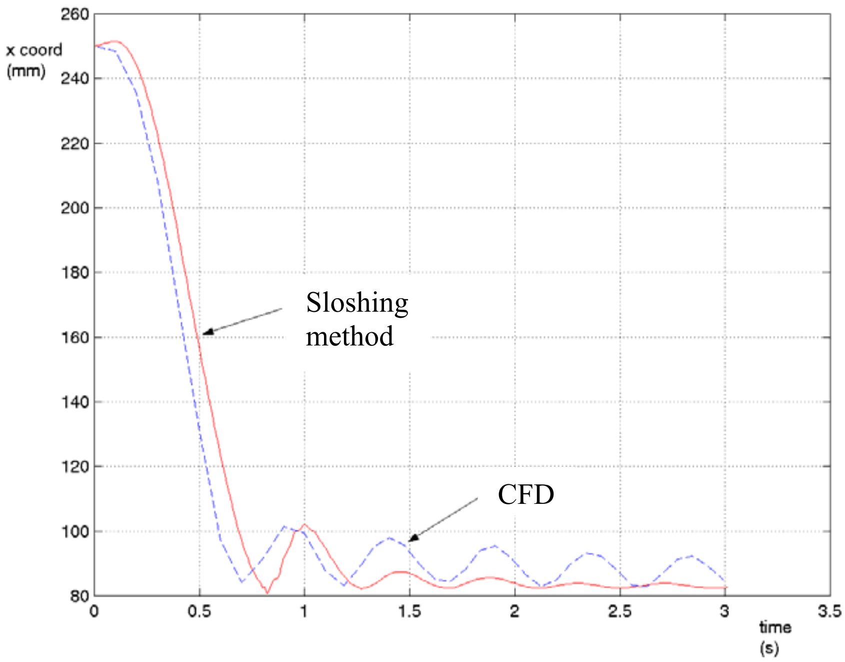

Figure 13: Case 1, comparison of x positions of CG calculated by CFD and by the simulation model

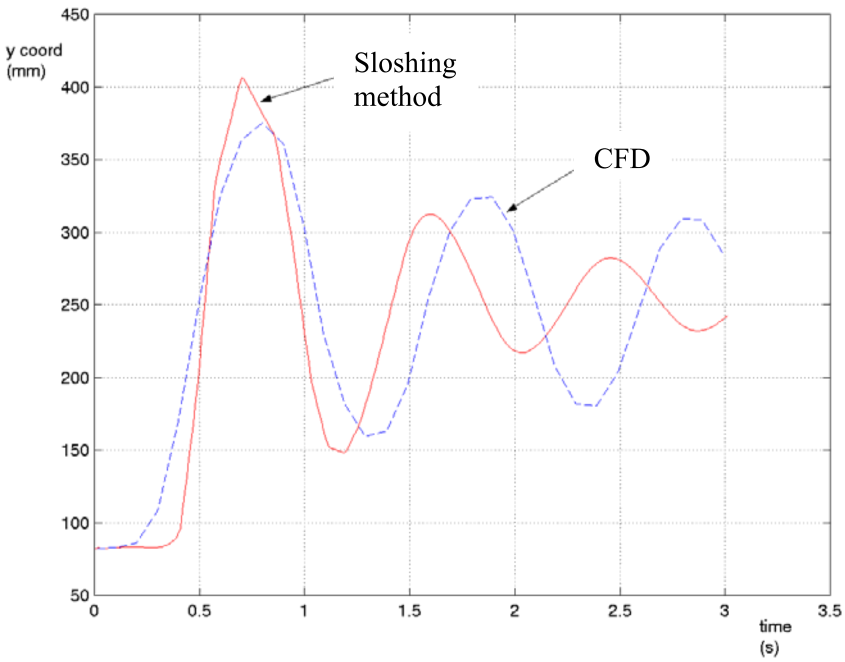

Figure 14: Case 2, comparison of y positions of CG calculated by CFD and by the simulation model

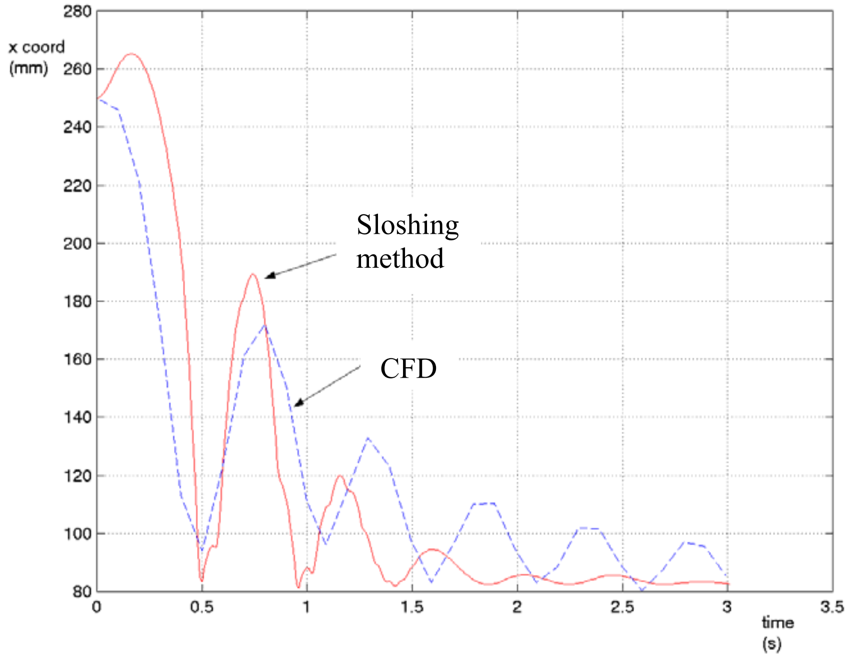

Figure 15: Case 2, comparison of x positions of CG calculated by CFD and by the simulation model

As seen in the graphs, the motions calculated by the simulation model are more damped than the results calculated with CFD. The frequencies are also slightly different but keeping in mind that the simulations take about a second to calculate, compared to the three hour CFD calculations, the results are good. Additionally, the first part is most important when it comes to a tank separation.

6.0 RESULT

Figure 16 shows an example of a separation simulation with the forward compartment half filled (middle compartment full). The sloshing influence on the tank is seen in the graphs where the pitch rate and the pitch angle relative the aircraft are presented.

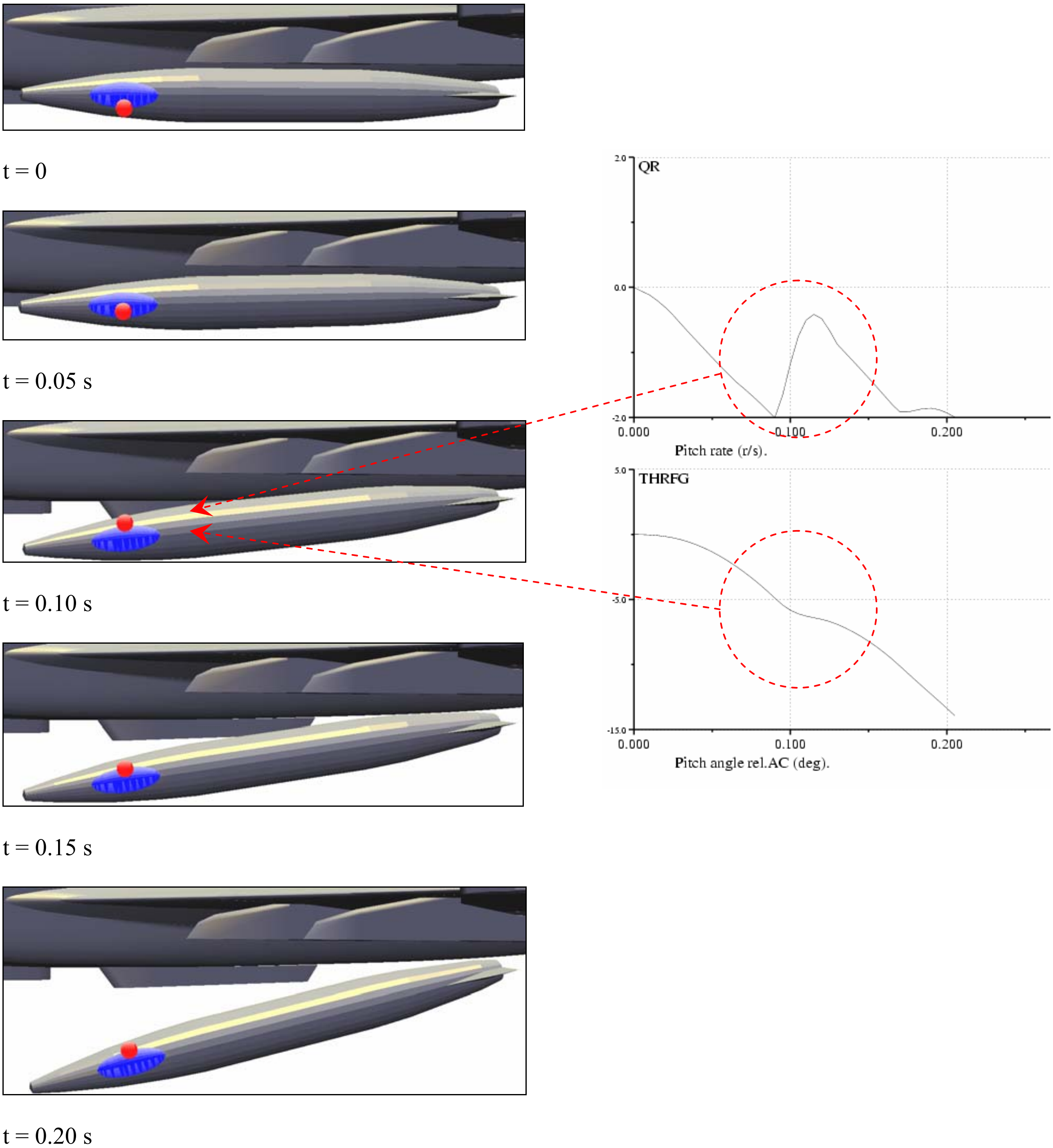

Figure 16: Result of a separation with sloshing fuel

When the fuel tank is released and pushed down by the pistons of the ejection release unit, the fuel in the half filled forward compartment is not affected until it hits the top of the compartment. The reaction force affects the motion of the fuel tank as seen in the graphs.

7.0 CONCLUSION

The possibility to implement a more exact model of sloshing fuel affecting the motion of an external fuel tank during separation is today very small. The complexity of the fuel shape inside the compartment is so high that possible CFD models will be too slow to be useful in production simulations.

This new approach with the simplified model seems to work very well. The motion of the fuel and the tank look natural and the good agreement with the simple CFD model gives confidence to the method. In addition, the simulation model works fast and it is possible to examine the effect of many combinations of remaining fuel quantities on the tank trajectory.

DISCUSSION EDITING

Paper No. 14: Stores Method of simulation of fuel sloshing effects on external fuel tank separation

Authors: Bertil Eronn, Anders Lindberg, Fredrik Ljungberg

Speaker: Bertil Eronn.

Discussor: Mr. Baeten

Question: 1. To what point do you refer when computing the rotations of the partially filled tank?

2. Do you consider the tank and the fuel to have mass properties of one unique body at same time during the trajectory?

Speaker's Reply: 1. The rotations are computed around the primary body´s center of gravity, in this case the empty tank.

2. No. They are treated as separate, interacting bodies.

Discussor: Graham Akroyd

Question: How were the spring and damping constants determined?

Speaker's Reply: The constants we are currently using are not final but were derived from comparisons with CFD results.

.Discussor: G. Moretti

Question: 1. Is the size of the ellipsoid dependent on fuel constant?

2.Is the ellipsoidal shape an assumption that should be reviewed?

Speaker's Reply: 1. Yes. Both size and shape are dependent on fuel fill rate. Currently we are only accounting for the size change though.

2. The ellipsoidal shape of the limiting surface is in the current model a simplification due to numerical computation reasons. The exact shape is dependent on the tanks internal geometry. We have not investigated how a different shape will affect modelling results.

Discussor: Alex Cenko

Question: 1.Is the tank pivoted on the aft end to constrain the pitch motion?

2.Since the pilot does not have any idea of the fuel distribution in the tank, how would you issue a flight clearance for a partially filled tank?

Speaker's Reply: 1. No, the tank is not pivoted or hinged.

2. We are only looking to make sure that the current clearance for releasing thanks that still have fuel in them is valid.

Discussor: Kit Eaton

Question: As the method only looks at reaction forces normal to the wall presumably the roll damping and inertia changes are neglected?

Speaker's Reply: Currently yes. We will do further work to implement friction between the wall and the fluid and hence get roll inertia properly in the model.

Discussor: Andre Baeten

Question: 1. Does your lagrangian method models the actual surface tensionand capillarity that determines the free surface of the sloshing fuel?

2.Have you built a transparent model to visualize the sloshing liquid´s free surface?

Speaker's Reply: 1. Don´t know??

2. We haven´t yet.