ON THE SIMULATION OF OUT-OF-POSITION LOAD CASES WITH THE ALE-METHOD

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Summary:

Many accidents with children or small adults, where the ignition of the airbag leads to dangerous and even fatal injuries for the passengers, have led to a number of efforts to analyze this so-called „Out-of-Position“ load cases more deeply within the development process of an airbag system. In the framework of simulation systems the fluid-structure interaction between the inflating gas and the airbag fabric has not been taken into account in the past. Recent developments in the LS-DYNA software package allow a fully coupled arbitrary Lagrange-Euler formulation and thus a more exact representation of the airbag deployment process within the simulation system. In the present contribution we will describe the standard procedure, based on the assumption of a uniform pressure distribution in the airbag and the recently achieved advances in LS-DYNA with respect to fluid-structure interaction of the expanding gas and the inflating airbag fabric.

Keywords:

Fluid-Structure-Interaction, airbag deployment, Out-of-Position load case, LS-DYNA

1 Introduction

Scenarios, where the passenger or the dummy is situated not in the standard position, but is situated very close to the airbag-module itself are commonly called “Out-of-Position” (OoP)-load-cases. In those cases a detailed analysis of the inflating gas properties is decisive to get a simulation model with the required accuracy. The very early stages of the airbag deployment process are target of such simulations. Thus the discretized model must incorporate the effects of the inflating gas, the fluid-structure-coupling of the gas with the airbag fabric and the surrounding air. Therefore besides the Lagrangian description of the airbag also an Eulerian description of the fluid processes is necessary, i. e. the gas that inflates the airbag must be discretized in the model. The standard procedure for airbag simulation, however, which is described as *Control-Volume-(CV)*-technique, does not take into account a detailed fluid description. In the present paper a comparison of the standard *Control-Volume*-technique with the Euler-Lagrange-coupled approach is given and the advantages as well as the drawbacks of the latter are discussed.

2 Control-Volume-Technique

The simulation of the deployment process of an airbag system is normally performed with FE-Methods simulating the dynamic behavior of the system by explicit time-stepping schemes. These methods are especially suited for the complex, highly nonlinear systems arising from complicated contact situations in a deploying airbag from the initially folded situation. To get an approximation of the time-dependent behavior of the interior pressure of the bag the so-called *CV*-technique can be used.

In any time step the volume of the airbag is being calculated by applying the Gaussian integral theorem. Assuming an ideal gas law and an adiabatic process, pressure can be determined as a function of density ρ as:

$$p = (k-1)\,\rho\, e \tag{1}$$

Here *k* is the isentropic coefficient $k = \frac{c_p}{c_v}$ and *e* the specific internal energy ($e = E / \rho_0$). For two neighboring states denoted with subscripts 1 and 2 there is:

$$\frac{e_2}{e_1} = \left(\frac{V_1}{V_2}\right)^{k-1} = \left(\frac{\rho_2}{\rho_1}\right)^{k-1} \tag{2}$$

With this equation from a known volume V_2 at a time step $t=t_2$, the volume at the previous time step V_1 and the appropriate internal energy e_1 the actual internal energy e_2 can be determined. From the internal energy the pressure can be calculated and applied as pressure load normal to the entire internal airbag fabric. This concept can basically also be applied for the simulation of tires or gas containers having constant pressure inside the containment.

For the deployment process itself the method must be further extended. The inflating gas is given by a time dependent mass flux $\dot{m}_{12}$ with an appropriate inflow temperature of the gas. Due to Wang & Nefske (see [8]) the total inflating mass flux is split into three components (see figure 1):

$$\dot{m}_{tot} = \dot{m}_{in} + \dot{m}_{out} = \dot{m}_{12} + \dot{m}_{23,vents} + \dot{m}_{23,leakage} \tag{3}$$

Here $\dot{m}_{23}$ stands for the mass loss due to small holes in the airbag (vents) and porosity (leakage) of the airbag. Both mass fluxes are dependent on temperature and pressure difference between inner and outer side of the pressurized surface. The expression for the internal energy increase is:

$$\dot{E} = c_p \dot{m}_{tot} T_{in} \tag{4}$$

The new values for pressure are being determined in a similar way to eqn. (1). The algorithm will determine the pressure values through a half index-shift method.

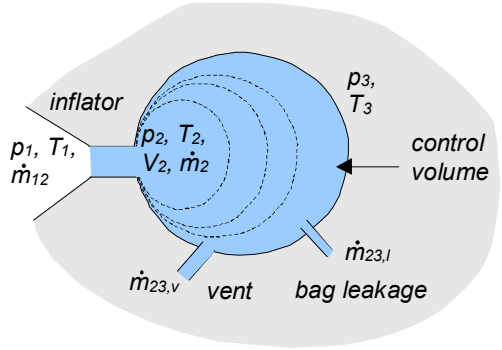

Figure 1: Control-Volume-concept

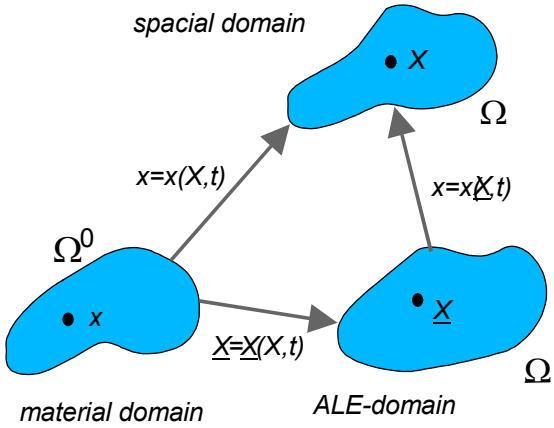

Figure 2: ALE-concept

Summarizing we can note, that in the CV- technique there is no discretization method of the fluid flow. The whole concept is based upon scalar thermodynamic equations. Extensions, which take into account a dependency of the pressure field on the inflow direction (commonly termed jetting) are based on the same simple assumptions. It is also possible, to take into account a gas mixture (so-called hybrid gas generators) or temperature-dependency of the specific heat coefficients. The calculation time can be neglected in comparison to the calculation time necessary for the structural behavior of the airbag. The inflow values (mass fluxes and temperature values over time) are determined by tank tests.

At this point it is important to show two major deficiencies of the traditional airbag models based on *Control-Volume*-technique:

1. It is a strongly simplified model of the gas properties neglecting local fluid effects
2. For the mass loss only very coarsely determined coefficients can be used.

While the influence of the first point is of minor importance in a regular case, where the dummy or passenger is hit by the airbag in a situation, where the airbag is already almost fully deployed, the

situation is different in an OoP-load-case. Here the dummy or passenger is in contact with the airbag in a much earlier stage of the deployment process. A physically correct model of the flow situation is necessary. Concerning the 2nd point, we note, that the values for the mass fluxes $\dot{m}_{out}$ often have been used in an incorrect manner to meet experimentally determined acceleration values. Based on a physically correct model both disadvantages of the *Control-Volume*-technique can be avoided.

3 Arbitrary-Lagrangian-Eulerian description of the Problem

To model the fluid dynamics correctly a discretization of both, the air volume surrounding the airbag and the inflowing gases, and the coupling forces is needed. A very elegant mathematical description of both field equations can be performed through the *Arbitrary-Lagrangian-Eulerian-(ALE)*-concept (compare [3], [4] and [7]). In the present study the simulation system LS-DYNA is being used, which is based on an FEM-approach, both for the discretization of the *Lagrange*- and the *Euler*-domain.

3.1 Conservation laws

In the ALE-method, as indicated by its name, in certain domains a *Eulerian* description of the reference configuration is chosen, whereas in other domains the *Lagrangian* coordinates can be used. In a *Lagrangian* system the observer will move with the material. On the other hand, in a pure *Eulerian* description the observer is fixed in space and the material points are moving through a stationary grid of fixed points. The *Arbitrary-Lagrange-Euler* methodology now allows an arbitrary mixture of both coordinates. This means, that the observation points can follow their own arbitrarily defined curve as outlined in figure 2. By *x* respective *X* mappings in the appropriate domains are denoted. It is obviously seen, that the two extreme cases of the more general *ALE*-method come down to the classical description of the *Eulerian* grid, which is commonly used in pure flow problems and the pure *Lagrangian* description, which is commonly used in structural problems. Mathematically an arbitrary reference region leads to an additional term in the conservation laws. In the numerical algorithm even a new set of equations must be solved, as the dynamics of the moving grid points has an impact on the discretized problem, which is being shown in figure 3.

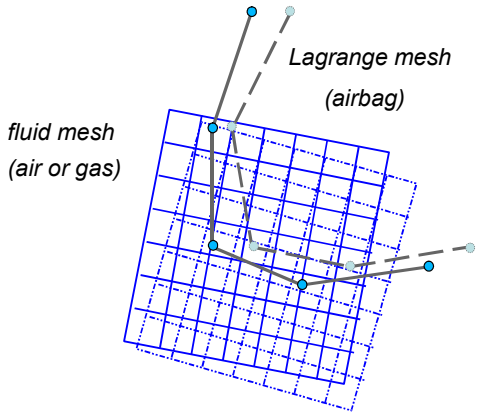

Figure 3: ALE-concept at two adjacent time steps

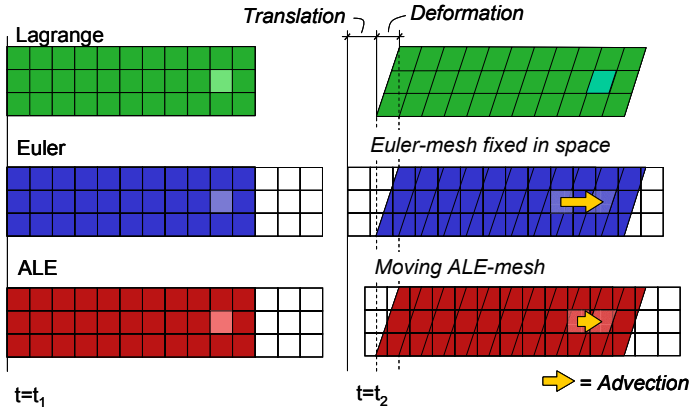

Figure 4: Comparison of Lagrange, Euler and ALE-description

In the following the conservation laws are being given. The whole set of equations is solved inside LS-DYNA by an explicit time-stepping algorithm. The additional terms due to the grid movement are highlighted by a separate color:

$$\text{Momentum conservation: } \rho\ddot{\mathbf{x}} + \rho\nabla\dot{\mathbf{x}}(\mathbf{v}-\dot{\mathbf{x}}) = \rho\mathbf{b} + div\,\boldsymbol{\sigma} \tag{5}$$

$$\text{Mass conservation: } \dot{\rho} + \nabla\rho(\mathbf{v}-\dot{\mathbf{x}}) + \rho\, div\,\mathbf{v} = 0 \tag{6}$$

$$\text{Energy conservation: } \rho\dot{\mathbf{u}} + \rho\nabla\mathbf{u}(\mathbf{v}-\dot{\mathbf{x}}) = \boldsymbol{\sigma} : \mathbf{D} + \rho\mathbf{r} - \nabla\mathbf{q} \tag{7}$$

Within these equations ***v*** denotes the material velocity and $\dot{x}$ the velocity of the grid points. ρ denotes the density, ***b*** external body forces and the last two terms in equation (7) denote heat sources and sinks.

For this simplified description, we must note, that equations (5) to (7) in the case of an *ALE* description are referencing to an *ALE*-coordinate system. If the highlighted terms are deleted, a *Lagrangian* system is referenced. If $\dot{x}$ is set to constant zero the pure *Eulerian* system is referenced. This is also easily shown in figure 4, where an arbitrary domain is moved and deformed. The upper part fits to the classical *Lagrangian* description. For the *Eulerian* description a part of the surrounding space must be discretized, as the Eulerian mesh is fixed in space. In the ALE-Formulation the mesh moves with the domain.

3.2 Advection

As usual in the *Eulerian* approach also in a “moving” Eulerian approach mass transport between elements has to be taken into account. This so-called advection terms must be treated in a special way within the numerical algorithm to ensure stability and accuracy of the numerical scheme. In the airbag simulation a second order accurate flux vector splitting scheme based on Van Leer’s approach is used. In the *Multi-Material-ALE-Formulation* also up to eight different materials with the appropriate history and state variables have to be taken into account by the advection scheme (see [5]). The latter formulation results from the necessity to integrate hybrid gas generator data, commonly used for CV-technique calculations, directly into the OoP-analysis without any change. Another aspect concerning the accuracy of the advection step is related to the time step size. To get a sufficiently accurate and stable method, the material flux within one time step is limited to a quarter of the element size, which means that the mass flux relatively to the grid movement determines an additional time step limiting criterion to the existing *Courant*-criterion arising from the explicit time-stepping scheme.

3.3 Coupling

Besides the gas dynamical effects the unfolding of the airbag itself must be considered also. This part is being discretized in the classical *Lagrangian* approach. The missing link between the two different discretization schemes must be handled by an appropriate coupling mechanism, which solves the

interaction problem between the gas (respectively gas fractions in the *Multi-Material-Formulation*) and the airbag fabric. Here the user has the choice between penalty-based and constraint-based coupling methods – very similar to the treatment of contact problems. In the constraint-based coupling method momentum is, but energy is not conserved. On the other side penalty-based coupling methods also conserve energy, but may have certain stability problems. For airbags a certain adapted version of the penalty-based coupling schemes is recommended. In this method a so-called penetration vector is determined, which represents the intrusion of the gas into the surrounding air volume thereby moving through the airbag fabric. A pressure-penetration-relationship is defined, which determines the penalty-force that will push the gas material back into the inside of the airbag.

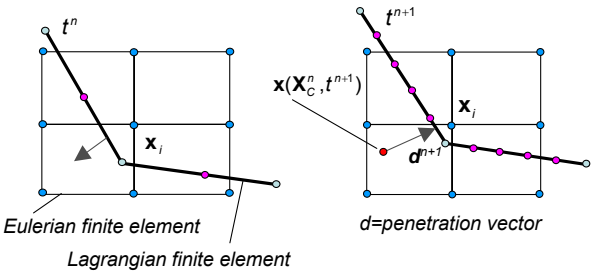

Figure 5: Penalty based coupling concept

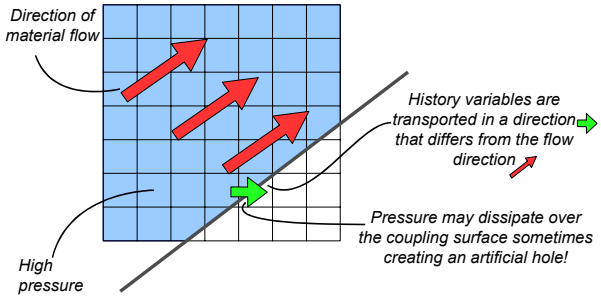

Figure 6: Leakage of gas through fabric

In figure 5 one more necessary condition for a successful *ALE*-analysis is illustrated. To determine the "contact forces" between gas and airbag fabric, LS-DYNA uses besides the element nodes additional coupling points in the airbag element. The local density of these points can be chosen by the user. A high density of the points will result in a additional computation time; too few coupling points will lead to an unwanted artificial leakage effects. This is, certain parts of the gas flow are not being caught by the coupling algorithm and can penetrate the airbag structure. One more reason for this leakage effect can be the advection itself. Figure 6 gives an interpretation of this effect: The flow direction in the airbag differs from the direction in which the state variables are advected. Therefore the algorithm advects mass through the airbag. Within the software the main goal is to suppress unwanted artificial mass loss due to algorithmic or numerical reasons.

3.4 Porosity

Nowadays in a passenger car both coated and uncoated airbags are being used. In the case of uncoated porous fabrics the classical *Control-Volume*-concepts come with special empirically determined terms to account for the mass loss due to the porosity of the airbag fabric. As the *ALE*-concept does not contain the possibility of real (porous) flow through the airbag and the algorithm tries to avoid artificial leakage effects, the wish to account for porosity effects contradicts these goals. Therefore in LS-DYNA the mass loss due to the flow through the airbag will be subtracted from the system. This is being implemented by experimentally determined curves, which indicate the gas velocity through the airbag fabric as a function of pressure difference between in- and outside the airbag volume. In the conservation laws the kinetic energy loss is balanced by an additional heat source.

4 Examples

The following two examples will show clearly the major advantages of the ALE-method with fluid-structure-coupling, when applied to the numerical analysis of OoP-load cases. Both experiments are being used in a similar form by car manufacturers and automotive suppliers for the airbag design. In this paper no measurements from experiments are shown.

4.1 Example 1

A simple test example is investigated to show the principle effects of the impact of an object at a small distance to the unfolding airbag. Comparisons of the acceleration values of a rigid tube (compare figure 7) which is situated in front of the airbag are made. Different modeling techniques for the simulation are applied. The results of a hybrid gas generator based on the Control-Volume-technique (Figure 7a) are compared to results based on an *ALE*-calculation. (Figure 7b and 7c) For the hybrid gas generator a CV-standard model based on the uniform-pressure-assumption and the result of a model accounting for jetting-effects are also compared.

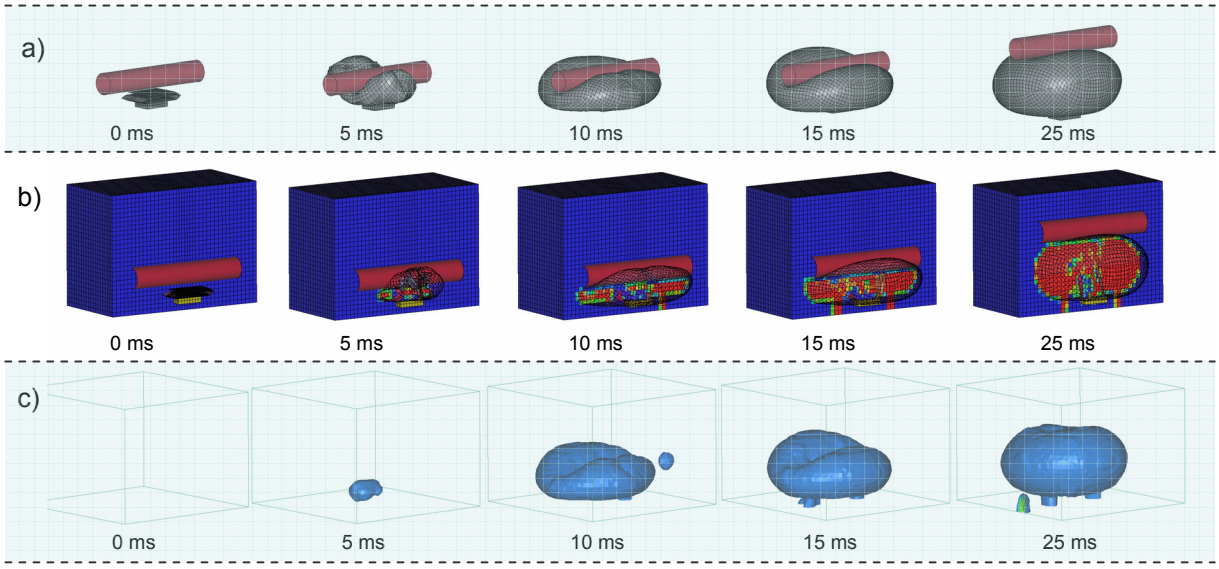

Figure 7: Unfolding of airbag: a) Control-Volume b) Euler-method and c) iso-surface of inflowing gas

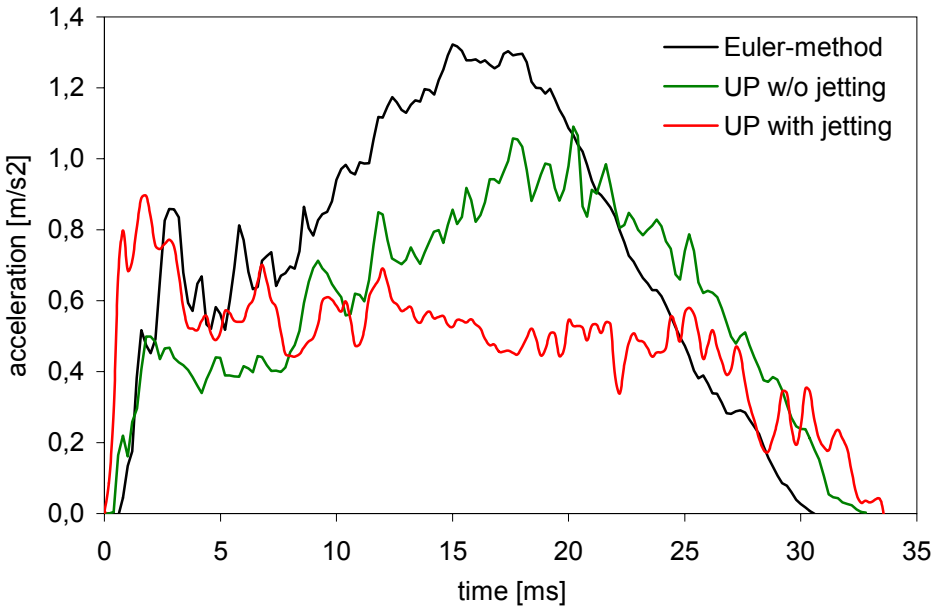

Figure 8: Acceleration of steel pipe in z-direction with different modelling techniques

In this example the uniform-pressure-method with jetting (an outflow angle of 30° has been chosen) leads to a large initial momentum immediately after the start of the simulation. Both uniform-pressure-method without jetting and *ALE*-method accelerate the rigid tube at a later time. We also note, that the flow results from the *ALE*-method lead to a larger absolute acceleration value. The latter is due to the fact, that the flow hits the rigid tube more directly and centrally due to the fact, that the outflow has been directed straight towards the pipe, whereas the uniform-pressure-method without jetting lets the airbag first unfold in all directions without any obligation. The equally distributed pressure load of the fabric geometry in the uniform-pressure-method leads to a faster volume growth in the very beginning. Please note also, that in the uniform-pressure-method with jetting the outflow angle has been chosen arbitrarily. By adjustments of this free parameter – in this case the angle has to be increased – the result can be adjusted to the *ALE*-result with flow effects.

4.2 Example 2

This example will illustrate the problem of OoP-load cases in more detail. For this purpose a three-year-old Hybrid III child dummy is situated at a close distance to the folded airbag. The geometry of the numerical experiment will simulate the real situation of many dangerous accidents in a passenger car. The gas generator data is the same as in example 1. Figure 9 shows the principal experimental setup and the deployment process belonging to this experiment. After ignition of the airbag, child head, thorax and vertebral column will experience extreme loadings, which can lead to severe injuries or even death.

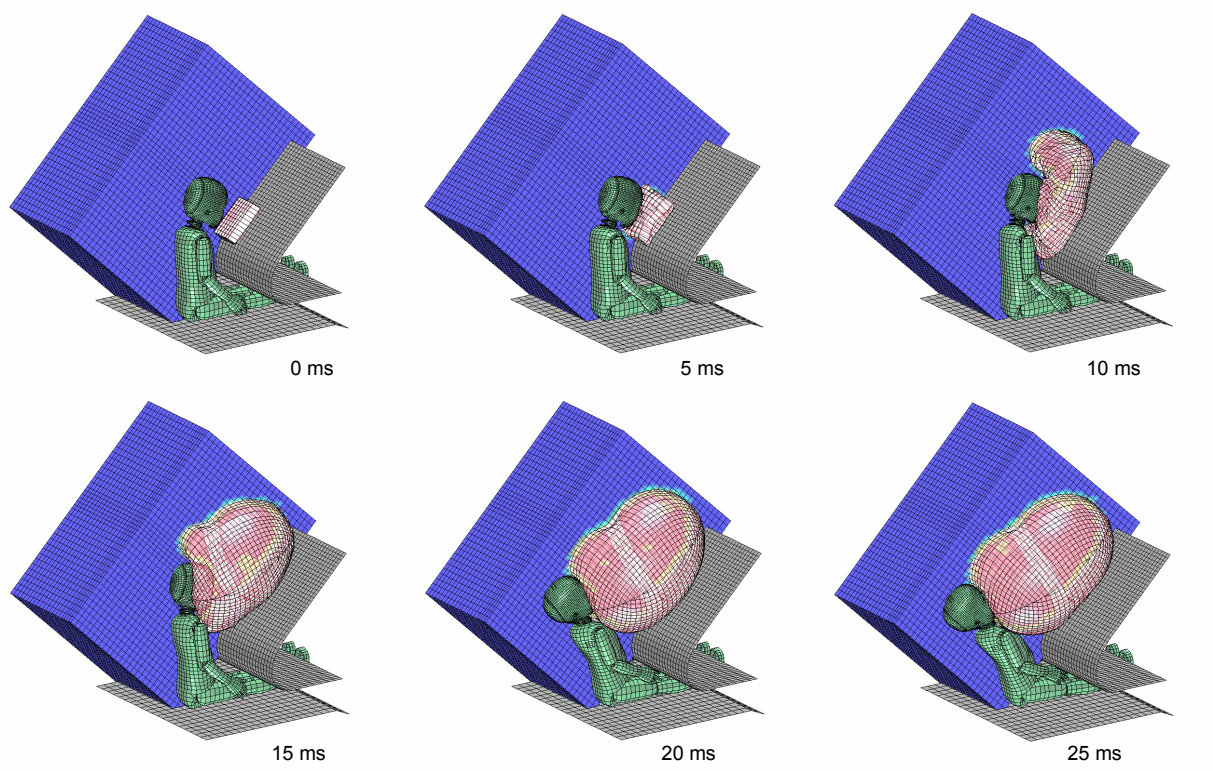

Figure 9: Unfolding of OoP-airbag problem with Euler-method (Euler-mesh cut open)

The extreme high loading of the neck region is recognized in the figures. In figure 10 the accelerations of the head and in figure 11 the appropriate values for the thorax are given. As we have seen already in example 1, the flow analysis leads to higher acceleration values, which have proven to be much more realistic due to experimental work and experience in this area. However, the present airbag discretization and also the fluid mesh has proven to be too coarse to allow justified design decisions. Also, the acceleration effects are very much depending on the inflow data and geometry. In the present study both have been chosen arbitrarily to show principal effects only.

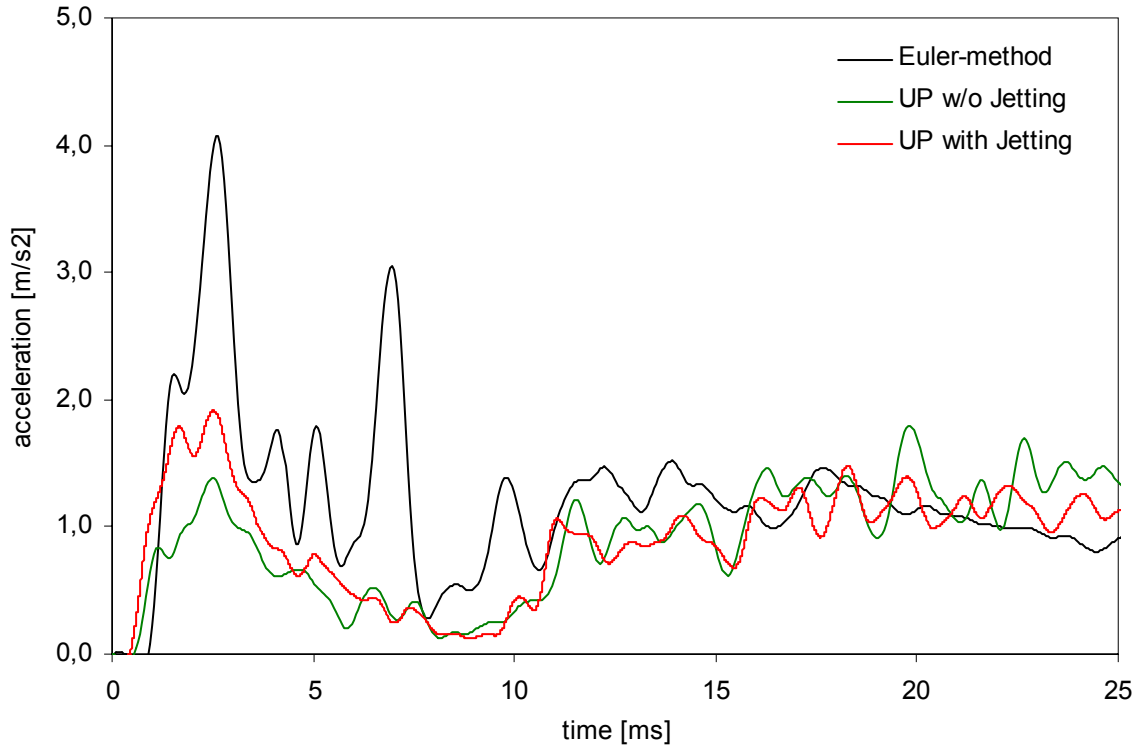

Figure 10: Total acceleration of head with different modeling techniques

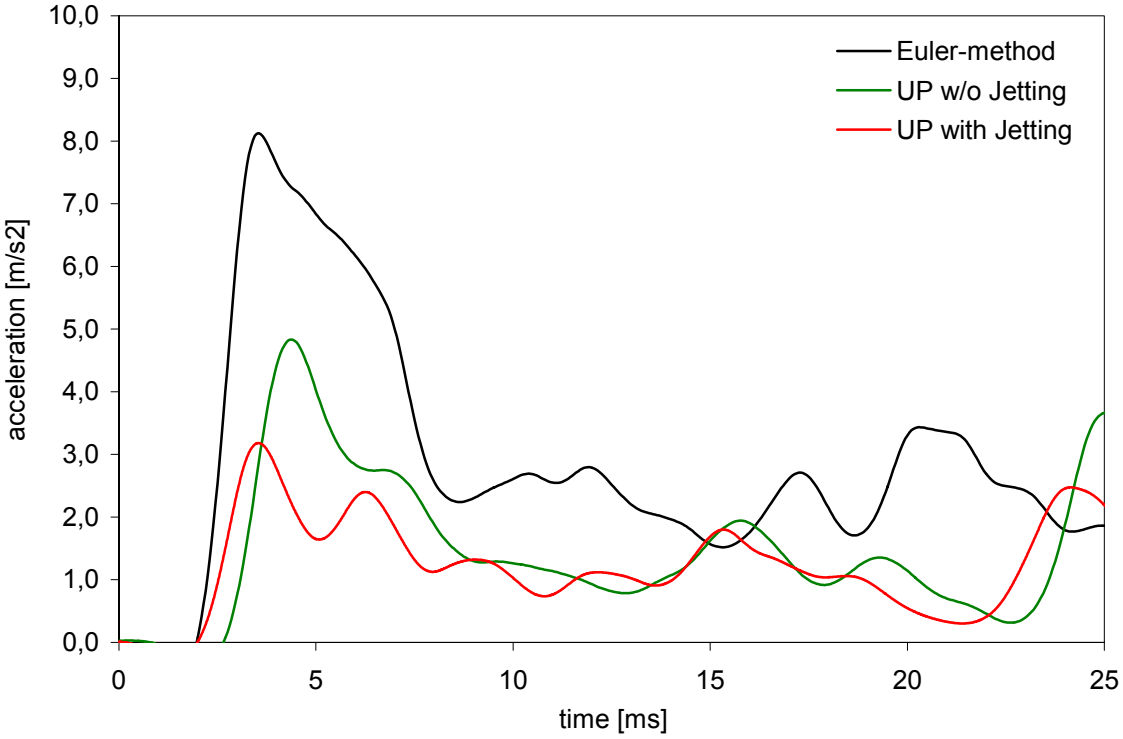

Figure 11: Total acceleration of thorax with different modeling techniques

5 Summary

In this paper an overview of the actual status in simulation methods for the deployment process of an airbag is given. Today the dominating approach is the classical method of uniformly distributed pressure inside the airbag (commonly including hybrid gas generators) based on strongly simplified assumptions. This is compared to a state-of–the–art Multi-Material-Eulerian-Method with fluid-structure coupling.

The advantages of the Eulerian approach especially in the first milliseconds of the airbag deployment process have clearly been seen when “Out-of-Position”-investigations are being made. In this case the more demanding method based on a detailed simulation of the fluid flow effects and the gas-flow-structural interaction gains much more reliable results in case of analyses of variants. Also a more realistic pressure distribution within the airbag can only be achieved by a method, which resolves the flow effects in space and time. The necessary gas generator data can be determined based upon experiments. A fitting of the generator data for airbags with different geometry seems to be unnecessary with this method.

The additional numerical and also the discretization effort and the necessary know-how of the user must not be underestimated. Depending on the geometry and level of detail a factor of five to ten in engineering hours must be considered.

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