Issues on Gas-Fabric Interaction in Airbag Simulation Using LS-DYNA ALE

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Abstract

Computer Aided Engineering (CAE) has been deployed to help developing effective occupant restraint systems, such as airbags, in automotive industries for decades. Until recently, control volume method, which assumes a uniform pressure and density inside airbag, is still widely adapted in most airbag applications. Control volume method allows use of simple thermodynamic equations to efficiently model airbag. Using control volume method to simulate fully deployed airbags interacting with crash dummies, such as In-Position (IP) simulation, is appropriate. However, with the stringent safety regulations for protecting occupants with widely distributed sizes and sitting positions, as well as the implementation of side and knee airbags, Out-Of-Position (OOP) simulation becomes more and more important for airbag suppliers and OEMs. In OOP simulation, airbag starts to interact with occupants long before it is fully deployed. The non-uniform distribution of gas pressure inside airbag and the highly dynamic characteristics of airbag cushion invalidate the control volume method. To address this issue, fluid-solid interaction (FSI) is implemented in various codes in different forms. The very high speed gas interacts with soft fabric in airbag simulation is quite a challenge for conventional Computational Fluid Dynamic (CFD) codes, and special treatment to deal with this FSI problem should be carefully planned and developed. Arbitrary Lagrangian Eulerian (ALE) approach from LS-DYNA provides a possibility to model this multi-phrase highly dynamic problem.

For OOP simulation, the ALE should be computationally efficient with acceptable accuracy. Normally, gap between layers of airbag is about the same order of magnitude of fabric thickness for flat or folded airbag model. To be computationally efficient, the size of Eulerian elements should be much larger than the fabric gap. This introduces the difficulty for code to handle gas-fabric interaction properly. Larger Eulerian element size slows down the gas propagating speed and causes discrepancy between simulations and testing for airbag deployment. Properly use of initial volume fraction definition from LS-DYNA to introduce gas into cushion fabric gap at time zero, can improve the results without using ultra small Eulerian elements for flat airbag model. However, for folded airbag, the application of initial volume fraction is not so successful. In present study, issues using ALE for airbag simulation will be investigated using several simple test cases. Recommendations for further improving the ALE code for airbag OOP simulation are presented.

Introduction

Airbags are widely adapted in current automotive industry and has saved thousands of lives and reduced the serious injuries since implemented (NHTSA, 2004). However, design of airbag system through prototype testing is very costly and time consuming. Numerical tools were developed to simulate airbag deployment and accelerated design process.

Control volume approach (Tawfik et. al., 1991) is widely used today for numerical simulation of airbag. The airbag fabric is modeled as membrane elements and the volume inside of airbag fabric is calculated numerically. The gas dynamic parameters such as pressure, density and temperature are assumed to be constant inside the control volume. Inflators are modeled with mass flow functions, inflator temperature functions and gas properties (Wang and Nefske, 1988). Control volume methods have been proved to be very efficient and accurate when airbag is fully inflated. However, without information of gas density and pressure distribution inside of airbag during deployment process, the prediction of partial filled airbag using control volume approach is unreliable.

With the stringent safety regulations for protection of occupants in wide ranges of sizes and sitting positions, airbag behaviors during the deployment process becomes more and more important for Out-Of-Position (OOP) occupant protection as well as airbag applications where space is limited between airbag and its protected subject . The non-homogeneous gas density and pressure distribution inside a partially deployed airbag are required to accurately predict the interaction between dummy and airbag. The process of airbag deployment is a very difficult fluid structure interaction problem, since highly dynamic gas is constantly coupling with soft airbag fabric which serves as the boundary and also moves highly dynamically. LSTC provides an arbitral-Lagrangian-Eulerian (ALE) approach to address this problem. ALE formulation contains the Eulerian formulation as a subset (Hallquist, 1998). Cubic or rectangular Eulerian cells need to be defined in the space where fully deployed airbag occupies. Inflators can be modeled using the same empirical approach as that of uniform pressure methods. A penalty based coupling method is adapted to solve interaction between gas and airbag fabric. Some preliminary results using this method for airbag applications have been reported (Lian and Bhalsod, 2004, Haufe and Weimar 2005).

In practice, for a folded or flat panel airbag, the typical gap between two layers of fabric is around 1 mm or even smaller. To run the airbag simulation with ALE cost effective under current computer hardware, normally the dimension of Eulerian cells is around 5-10 mm, which is much larger than the dimension of gap. This low resolution in Eulerian space compared to structural characteristic length in Lagrangian space can cause difficulties for LS-DYNA to predict gas-fabric interaction behavior near the area of gas wave front. This inappropriate coupling not only slowed down the wave propagation speed, but also predicted an erroneous leading wave front shape that was different from experiments. Refining of Eulerian meshes could improve the result; however, the computational time would dramatically increase also. To demonstrate the above phenomena, several simple test cases were presented in the current study. The alternative way to solve the problem and the further expected code improvement for practical airbag simulation with ALE were discussed.

Methods

1. Airbag

A rectangular shape flat panel airbag was constructed and attached to a rigid cylinder as showed in Figure 1. The middle transition portion between inflator and bag was also modeled as fabric material. A nozzle was placed at the center of cylinder to prevent gas leaking. The baseline airbag model was meshed with 5 mm quadrate elements. Inflator portion was assumed to be rigid and fixed without any movement; while fabric portion was defined as membrane elements with fabric material properties. Two corner nodes of airbag fabric were fixed. Generic inflator mass flow and temperature curves were used. A control volume airbag model was built to test the inputs, and the result showed the bag was filled within 5 ms.

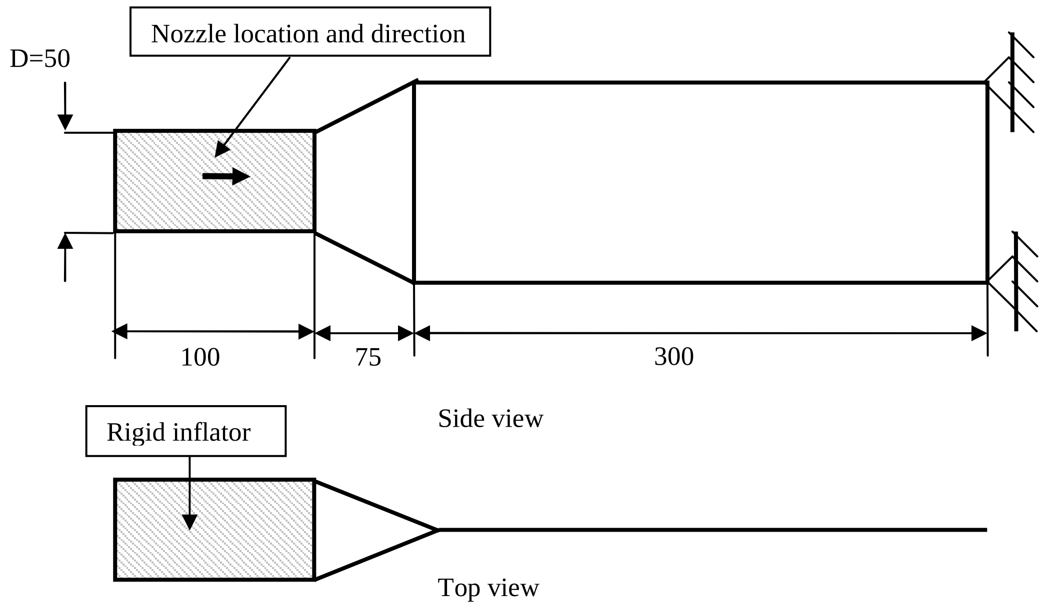


Figure 1. Schematics of the simplified airbag, dimension in mm.

2. ALE model

An Eulerian cell block with dimension of 100 mm by 120 mm by 500 mm was constructed around the simplified airbag. Each cell was a 5 mm cube for the baseline model. An ALE multi-material group contained both environment air and gas exited from inflator. Coupling between Eulerian cells filled with gas and Lagrangian airbag fabric elements was defined by penalty method with a penalty function. The threshold volume fraction of gas for Eulerian cells to start coupling was set at 0.1. The inflator properties were defined using keyword *SECTION_POINT_SOURCE_MIXTURE. Cross section area of nozzle was 95 mm^2, and speed of exiting gas was 377 M/s. The direction of the nozzle was along the long axis as showed in Figure 1.

To improve the accuracy, the Eulerian cell was further selectively refined in the direction perpendicular to airbag panel while cell density of other two directions was unchanged (see Figure 2). Three layers of cells with thickness of 0.3 mm were placed inside of gap of airbag fabric, and 1 mm thick cells next to airbag. The thickness of cells was gradually increased to 3 mm with an exponential distribution. Accordingly, meshes for areas of airbag model which coupling with fine Eulerian cells were refined to prevent gas leaking.

For comparison, a coarse mesh model with 10 mm size of both Eulerian cells and airbag fabric mesh was calculated using the same input parameters as baseline model.

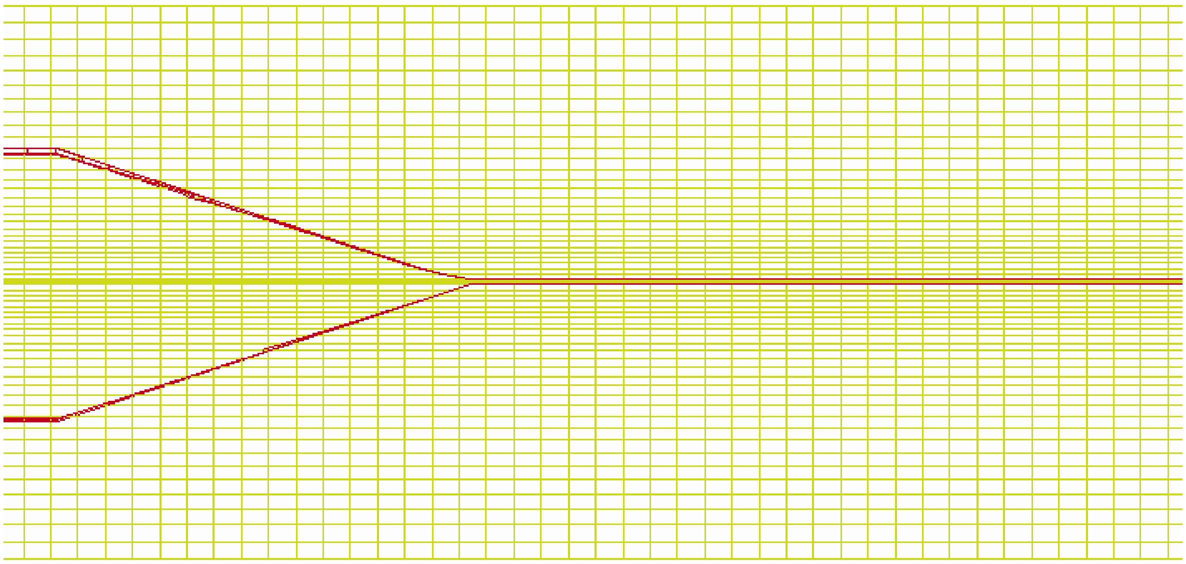


Figure 2. Cross section cut of the model showed how selectively refined mesh was constructed.

3. Initial volume fraction approach

LS-DYNA version 970 rev. 6571 and later introduced a new approach to improve gas-fabric interaction for this type of problems. Using the keyword *INITIAL_VOLUME_FRACTION_GEOMETRY, gas was pre-filled inside the gaps of airbag fabric at the beginning of simulation. The initial volume fraction of Eulerian cell for gas was estimated from the volume of gap occupied inside this cell. This pre-filled gas established coupling with airbag fabric even before gas wave arrives. This approach was implemented with baseline model mesh.

4. Computation environment

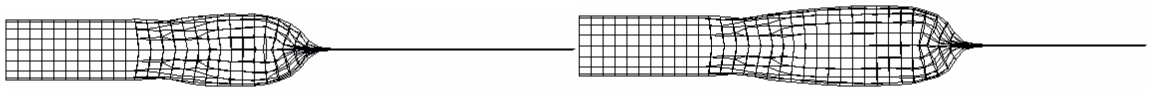
Calculations were carried under an IBM UNIX server using a single CPU. LS-DYNA version 970 rev. 6571 and later was used and Ls-post was selected for post-processing.

Results

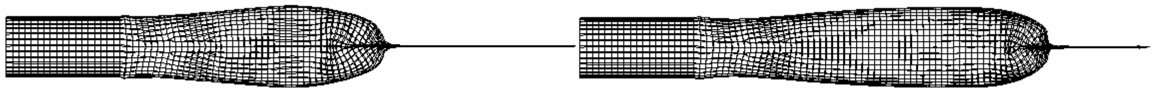
1. Airbag deployment kinematics

Figure 3 showed the predicted deformation of airbag fabric when gas wave propagated inside the airbag at 4 ms and 5 ms, respectively, for each model. When mesh size was uniformly refined from 10 mm (Figure 3a) to 5 mm (Figure 3b), an increased in wave speed was found, however, the round shape of wave front was predicted instead of the wedge shape wave front found in the test of similar tube-like airbag (Figure 4). The discrepancy between model and test suggested that gas-fabric interaction at wave front region was not properly calculated with uniform size Eulerian cells. With further refined Eulerian cells (Figure 3c), the wedge shaped wave front was predicted and wave speed was further increased. However, there was a more than 30-fold increase in calculation time due to the smaller cell dimension (see table 1 for comparison of CPU usage of different cases). When initial volume fraction was defined (Figure 3d), the gap between two layers of fabric was pre-enlarged before gas wave arrived and allowed more Eulerian cells inside fabrics. The similar wedge shaped wave front was predicted in this model.

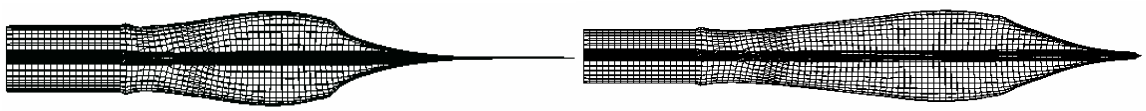
(a) Model with 10 mm uniform size of mesh



(b)Model with 5 mm uniform size of mesh



(c)Model with selected refined mesh



(d)Model with initial volume fraction defined (5 mm uniform mesh)

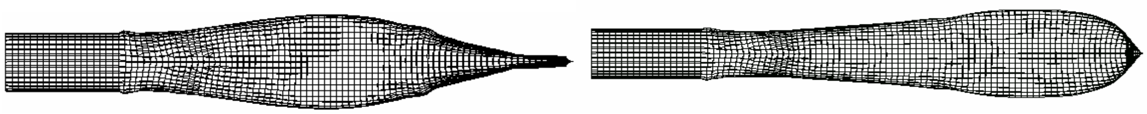


Figure 3. Top view of airbag fabric deformation at 4 ms (left) and 5 ms (right). A round shape wave front was predicted from uniform Eulerian cell models with cell size of 10 mm (a) and 5 mm (b). A wedge shape wave front was predicted from the refined mesh model (c) and model with initial volume fraction defined (d). An increase in gas wave propagation speed was found when Eulerian mesh size was reduced.

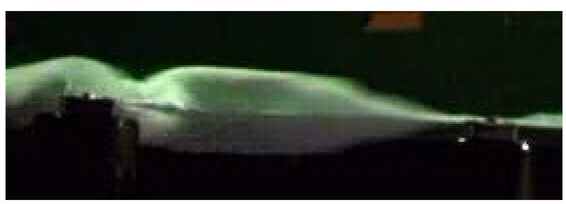


Figure 4. The wedge shape wave front found in the test.

2. Pressure distribution in airbag

When pressure contours were plotted, a high pressure zone was found at wave front region for model with 5 mm element size (Figure 5a). This higher than normal resistant force at the gap region of wave front showed that large size of Eulerian cells (5mm) were unable to solve the gas-fabric interaction at the gap area where the dimension of gap was 1 mm. With refined model (Figure 5b) which included 3 Eulerian cells inside the gap and more Eulerian cells closed to gap, gas propagated faster and without a pressure build-up at the same region. There was a similar effect for model with initial volume fraction defined (Figure 5c). In this case, since gap was enlarged to around 10 mm before gas arrived, more than two layers of Eulerian cells were included inside the airbag and there was no pressure built-up at the wave front of gap region.

Note that at the region near inflator nozzle, the pressure distribution of model with selectively refined mesh was significantly different from these of other two cases. A high pressure zone was found at boundary of rigid inflator wall. A further investigation of velocity vector plots between two models (Figure 6a and 6b), showed different shooting directions of exiting gas: for 5mm uniform element model, gas exited inflator and shot along axis direction as defined, while for selective refined mesh, gas shooting direction was not uniform and a portion of the gas shot perpendicular to the defined jetting direction. This clearly showed that different density of Eulerian cells at nozzle area could affect the behavior of nozzle.

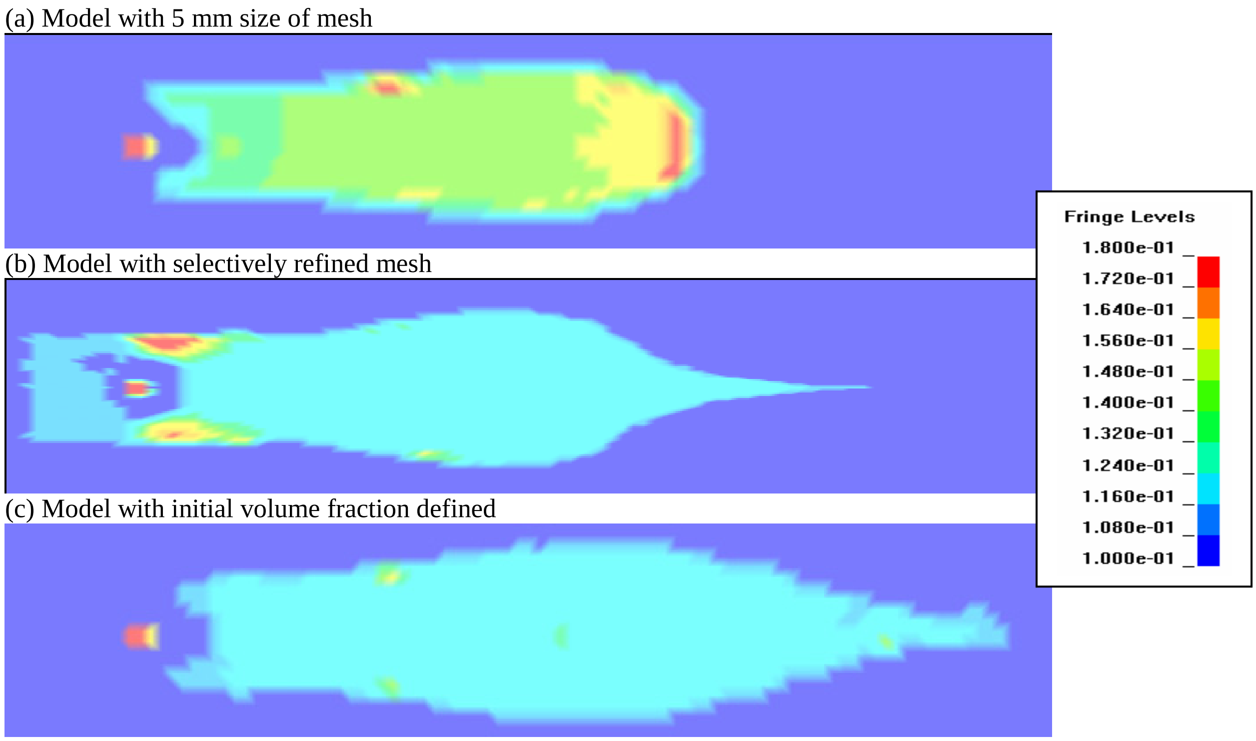


Figure 5. Pressure contour of middle cross section at 4 ms. High pressure zone found at wave front region for 5 mm size Eulerian cell model (a) when compared with model with selectively refined mesh (b) and model with initial volume fraction defined (c).

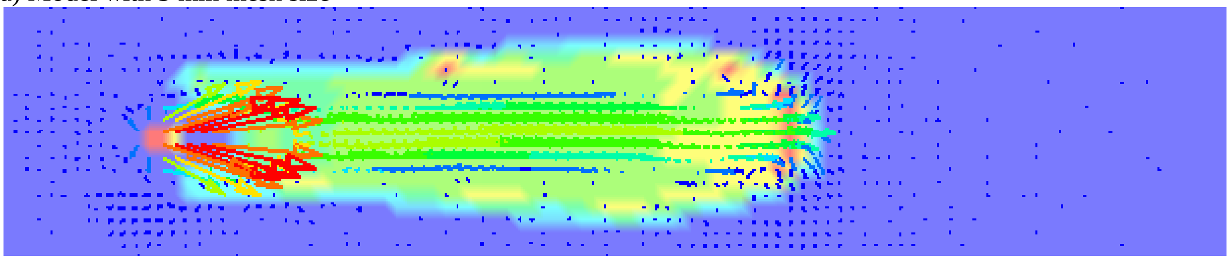
Eulerian cell density	5mm (baseline)	5mm (initial volume)	10 mm	Selectively refined
Normalized CPU time	1.0	1.1	0.1	31

Table 1. Comparison of CPU time for four ALE models.

Discussion and Conclusion

To demonstrate LS-DYNA ALE capability for airbag applications, a simple airbag model was constructed and calculated with different sets of Eulerian cells. The results showed that the density of Eulerian cell had a significant effect on gas wave propagation speed and shape of wave front in a tube-like airbag. Low density Eulerian cell models predicted round shaped wave front and slower wave speed, while high density Eulerian cell model predicted wedge shaped wave front which agreed with test results. However, high density model dramatically increased the calculation time. Initial volume methods pre-filled gas inside the airbag gap at time zero. The pre-filled gas interacted with fabric and enlarged the gap to improve the results without dramatic increase of calculation time.

(a) Model with 5 mm mesh size



(b) Model with selective refined mesh

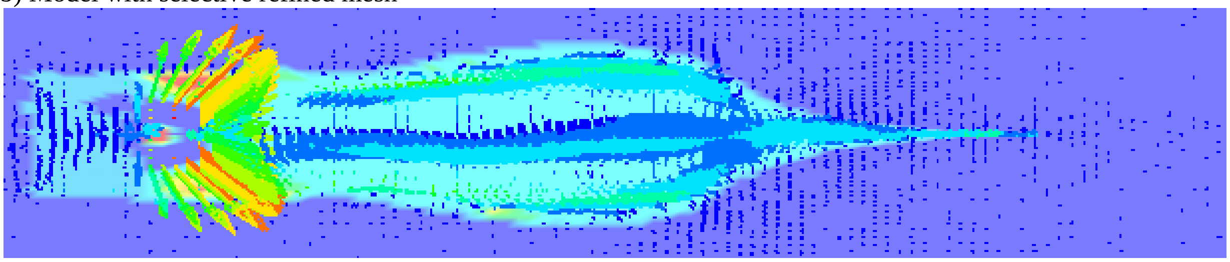
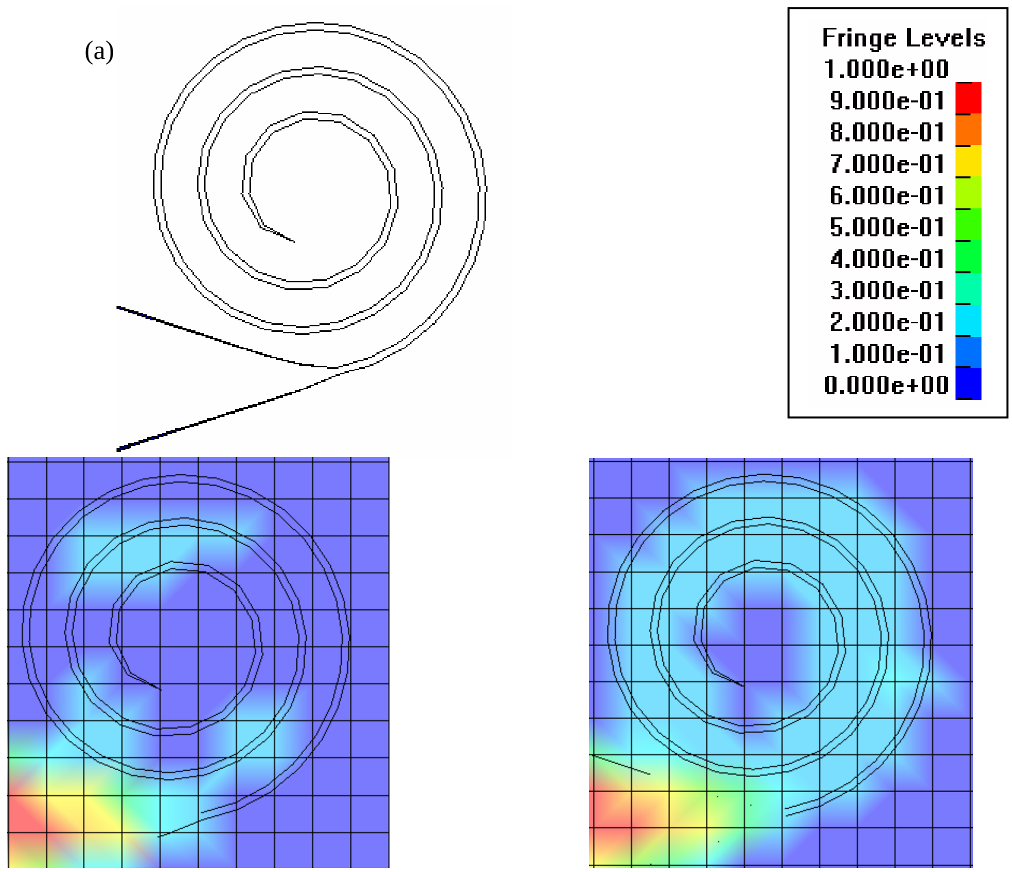


Figure 6 Velocity plots at middle cross section of Eulerian cells over pressure contour. The different of jetting directions were found between two models.

For certain airbag applications, dimension of gaps between fabric layers should be considered as characteristic length for construction of Eulerian cells in order to properly predict the wave front behavior. When coarser cells were used, gas entered the gap was numerically diffused to space perpendicular to the fabric. Therefore, unreal interaction between these Eulerian cells and fabric elements caused the round shape of wave front and local pressure build-up near the wave front. This phenomenon is less problematic for driver and passenger airbag, since a significant portion of gas shooting perpendicular to fabric surface to open up the gap during the inflation. However, for certain airbags, such as curtain airbags, because gas shooting direction is mainly parallel to the fabric surface, filling through the gap must be solved numerically.

The present study demonstrated a strong effect of Eulerian cell construction on the ALE result. The current meshing method from LS-DYNA is not very flexible and lack of automation. When cells in gap region were refined, the refined mesh must be extended to inflator nozzle region. This partially refined mesh at nozzle region would change the gas jetting direction and affect the result. Also dense cells at unwanted area increased chance of gas leaking. Therefore, ability to maintain different mesh density at different area, and solve mesh mismatch at the interface should be considered in the future for ALE development.

Initial volume approach could handle flat panel airbag very well without big increase in CPU time by using the relative large size of Eulerian cells. However, when airbag was folded, the algorithm didn't work well with the same level of Eulerian cell density. Figure 7 showed a loose roll-fold bag with a distance of 5 mm between adjacent layers. The gap between bag fabric was kept 1 mm. When LS-DYNA version 970 was used, cells with nodes laying inside airbag gaps were pre-filled with gas, while cells with airbag crossing through but without nodes inside airbag gap were not pre-filled. Therefore, to pre-fill an Eulerian cell where airbag gap occupies, at least one node of Eulerian cell must be inside of airbag gap. This requirement would dramatically increase cell density if airbag is tightly folded. The new LS-DYNA version 971 solved above issue by increase integration points for Eulerian cells. For same cell density, initial gas could be pre-filled for all cells which airbag occupies. Further validation of applying initial volume approach for folded airbag with testing will be conducted in the future study.



(b) Version 970 (c) Version 971

Figure 7. A loosely folded airbag applied with initial volume method. (a) The schematics of fold pattern. (b) Initial gas distribution contour from LS-DYNA 970. (c) Initial gas distribution contour from LS-DYNA 971.

In conclusion, Eulerian element density can significantly affect the airbag deployment behavior with ALE. For certain airbag application, gap size between fabric layers should be considered as the characteristic length for meshing. Initial volume method was proven to be effective for flat panel airbag without dramatically increase mesh density. Practical and accurate airbag simulation with ALE is still not materialized especially for some types of airbags such as curtain and side airbags. It is recommended that the following further improvement of ALE capabilities for airbag applications should be addressed by the code developer: (1) providing adaptive meshing to allow different mesh density for different areas; (2) more stable expandable mesh to allow denser mesh when airbag is folded and coarser mesh when airbag is deployed; (3) further development of initial volume method for folded airbag applications.

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