SIMULATION OF AIRBAG DEPLOYMENT USING A COUPLED FLUID-STRUCTURE APPROACH

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ABSTRACT

This paper explores simulation techniques for airbag inflation using a coupled fluid-structure approach. The application is to be seen as an initial study on the phenomena occurring in an airbag during an Out of Position occupant impact.

The application problem is an airbag that is set to impact a head form. The head form is positioned at a very short distance from the airbag. A Multi Material Arbitrary Lagrangian Eulerian technique in LS-DYNA is used for the fluid and it is coupled to the fabric structure using a penalty based fluid structure contact algorithm.

The results of the head form acceleration and velocity show good agreement to the corresponding experimental results. The results also show that at the early stages of the inflation a high-pressure zone is built up between the inflow and the head form. The consequence of this is that the pressure difference between the inflow and the high pressure zone is too low for an a priori assumption of sonic flow at the inlet.

INTRODUCTION

The passive safety of cars has become a very high priority issue for the automotive industry. Today there are not only one or two airbags in a car, certain models have ten times more then that. With the increasing usage of airbags, the number of accidents where the airbag itself can cause an injury to the occupant also increases. Especially in one type of situation this is apparent; the “Out Of Position” (OOP) occupant crash. Several types of OOP crashes exist, but in most cases the occupant is situated close to the airbag as it inflates, possibly causing severe injuries.

In order solve these problems the trend in the automotive industry is to make the airbags gentler and more adaptive to different impact situations. Computer simulations mainly based on the Finite Element (FE) method have for a long period of time been used in a simulation based design process.

Related work

The first airbag modeling efforts can be traced back to the early seventies. Irish et al. (Irish, 1971), King et al. (King, 1972) and Nefske (Nefske, 1972) made considerable contributions to the Control Volume (CV) concept, which is used for most airbag simulations today. The concept was refined by Wang and Nefske (Wang, 1988), and the algorithms defined in their work now serve as the base in all commercial codes of interest for these applications. Nevertheless, these algorithms lack an important feature: a description of the airbag inflator jet. Several models have been proposed to overcome this problem. Groenenboom et al. (Groenenboom, 1993) have constructed a model that accounts for turbulent diffusion in a conical jet originating from the gas generator. Similar models are found in other codes: (Lupker, 1993) in MADYMO and (Hallquist, 1998) in LS-DYNA.

Jetting models have been tested by Fredriksson (Fredriksson, 1996) for OOP problems, where an airbag inflates against the chest of a Hybrid III dummy. His study shows that chest acceleration values for the dummy model tend to be too large when using a CV model with jetting. He concludes that one reason may be that these models are not capable of predicting the redirection of the gas when it hits an obstacle.

This causes the prediction of a too severe injury to the occupant. Recently, a number of conference articles on coupled fluid-structure analysis has been presented. Mestreau (Mestreau, 1996) uses a remeshing technique for the modeling of the fluid. Thereby the fluid mesh is kept inside the structure throughout the simulation. Similar techniques are applied by Zhu (Zhu, 1999) and the simulation of the deployment of a simply folded bag is carried out. Neither of these articles offers any experimental verification.

Ullrich et al. (Ullrich, 2000) invokes a meshless particle method, the Finite Point Method, to solve an OOP airbag inflation problem. Experimental verification is here supplied through a pendulum test where an airbag is deployed against a flat surface. Verification is also supplied by Kamiji et al. (Kamiji, 2001), who have simulated an OOP airbag inflation problem involving a 5th percentile Hybrid III dummy. There is however no theoretical description of the method used in their study.

It is the intention of the authors of this article to investigate the potential for coupled fluid-structure simulations of OOP airbag inflation problems using a structured fluid mesh coupled to the airbag mesh with a penalty contact algorithm.

APPROACH

Experimental Setup

The experiments carried out have been kept simple in order to rule out as many sources of errors as possible. The bag used is a specially sown bag with a square geometry, and inflation is achieved by using stored pressurized Nitrogen from a gas tank. Propellant gas generators have been avoided in favor of stored gas due to measurement reasons. Pressure and temperature in the gas bottle can be measured along with the pressure at the airbag inlet and the pressure at a given point inside the airbag.

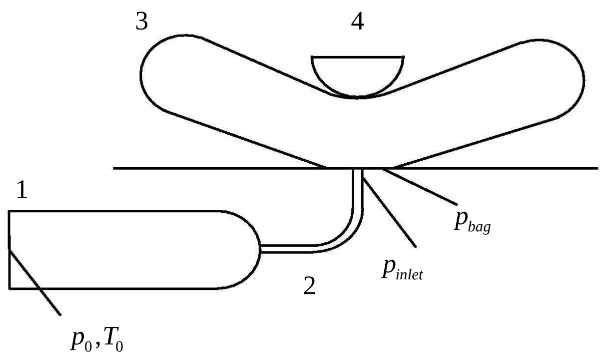

Figure 1. Schematic figure of experimental setup

The experimental setup consists of four major parts, which can be viewed in Figure 1. The gas tank, 1, is filled with Nitrogen. The hose, 2, connecting the bottle with the airbag, has a total length of 1.2 meters, including all connecting parts, and a minimum inner diameter of 15 mm. At the airbag inlet the diameter increases to 21 mm. The airbag, 3, is square in plane with a side length of 0.643 m. It is made of Polyamide 66 and it is covered with a silicon liner, preventing gas from leaking out through the fabric. A Head Form, 4, which is a representative model of the human head, usually used for head to car interior impact tests, is placed just above the airbag before inflation. It has a 0.16 m diameter and its mass is 4.8 kg.

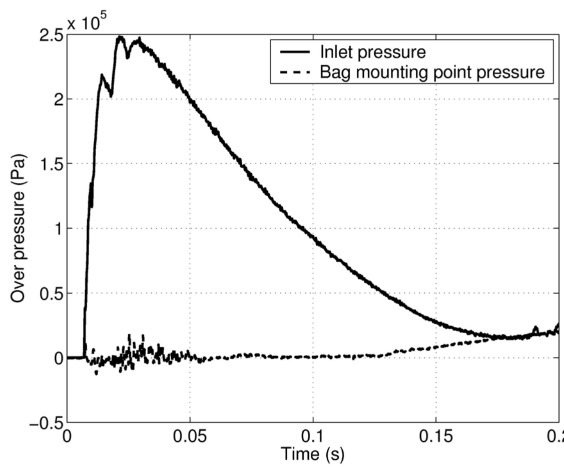

Figure 2. Inlet and bag mounting point pressure

Interpretation of results

As the airbag is inflated, pressure and temperature in the gas bottle, as well as the pressure at the mounting point between the bag and the foundation is registered at a frequency of 10000 Hz. Two tests were made consecutively in order to rule out any measurement errors.

With the assumption that the gas follows the ideal gas law

$$p = \rho RT, \qquad (1)$$

it is possible to calculate the thermodynamic state at the inlet. ρ is the density, T the absolute temperature and $R = c_p - c_v$ where c_p and c_v are the specific heat at constant pressure and temperature, respectively. The simplifications and assumptions being made are as follows

1. The flow is quasi-steady, i.e. the flow at $t=t_1$ is independent of the flow at $t=t_1+\Delta t$.
2. The transition between the gas tank and the hose is considered to be adiabatic.

3. In the hose, friction is added (Fanno frictional flow) due to the length of the hose. This type of flow is also adiabatic.

As the pressure at the inlet is known from measurements, the temperature (or density) must be supplied as boundary condition, see Equation (1). Due to the high flow velocities at the inlet, temperature measurements are very difficult to conduct. Thus, approximations through calculations are necessary. Taking the assumptions 1-3 above into account, one can calculate the temperature at the inlet as

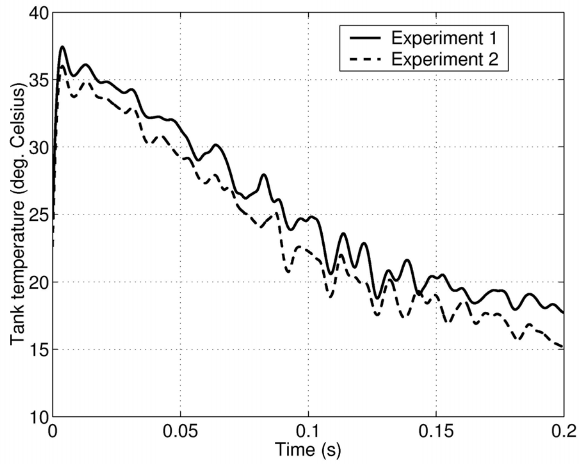

Figure 3. Gas tank temperature

$$T_{inlet} = T_0 \left(1 + \frac{\gamma - 1}{2} M^2 \right)^{-1} \qquad (2)$$

see (Anderson, 1982). T_0 is the temperature for the fluid at rest, $\gamma = c_p / c_v$ and M is the Mach number. As the Mach number at the inlet at this point is not known, temperatures corresponding to M=0, M=0.5 and M=1 are tested. If no major difference in the results is found, the temperature can be considered to play a minor role in the results of these simulations. Excerpts from the high-speed film of the airbag deployment are shown in Figure 8

Fluid-structure coupling
In order to transfer forces between the inflated gas and the airbag structure a fluid-structure coupling algorithm is needed. An algorithm developed by Olovsson (Olovsson, 2000), has proven to be accurate in e.g. metal forging applications, where a Multi Material Euler approach has been used. It was therefore decided that this algorithm should be used in this project as well. This algorithm couples a point, on the structure to a material point in the fluid by a penalty algorithm. The penalty stiffness is based on the mass assigned to the structural coupling point and the nodal masses of the Eulerian element.

Airbag inflation simulations
The airbag studied here is a special purpose sown bag, which is square in the plane with a side length of 643 mm. This bag is modeled with membrane shell elements, as the airbag fabric cannot support bending stresses. Both isotropic and orthotropic conditions have been tested in the modeling process, but only minor differences could be observed in the results. For In Position (IP) problems, the difference in results can be larger, since the tensile stresses in the fabric is considerably larger when the airbag is fully deployed.

The structural model of the airbag is covered with a 30x30x15 block of Eulerian fluid elements. In the *x* and *y* directions the size of the elements are fixed, whereas in the *z* direction the elements are allowed to expand as the inflation process progresses. The expansion can be controlled either by predefined load curves or by adjusting the boundary of the fluid mesh such that it always stays outside a number of given points on the structure.

In each Eulerian element two types of materials are allowed, the surrounding air and the entering pressurized Nitrogen. The inlet conditions are set in an 'ambient element', see Figure 4. The ambient element has a top surface area, which corresponds to the area of inlet in the test. Pressure and temperature are given as functions of time. For efficiency reasons the inlet is not modeled as a circular hole, as the size of the elements would be too small. Standard tabular material data has been used for the Nitrogen, see Table 1.

Table 1. Gas properties

c_p	1040 J/(kg K)
c_v	743 J/(kg K)
ρ (T=273 K, p=1.013 bar)	1.25 kg/m^3
p_∞	1.013 bar

The last component in the setup, the Head Form, is modeled as a rigid body. It is constrained to move only in the *z* direction. This constrained motion does not correspond to the test, but is enforced in the simulations of stability reasons. Thus, it may provide differences in the results at late stages of the process.

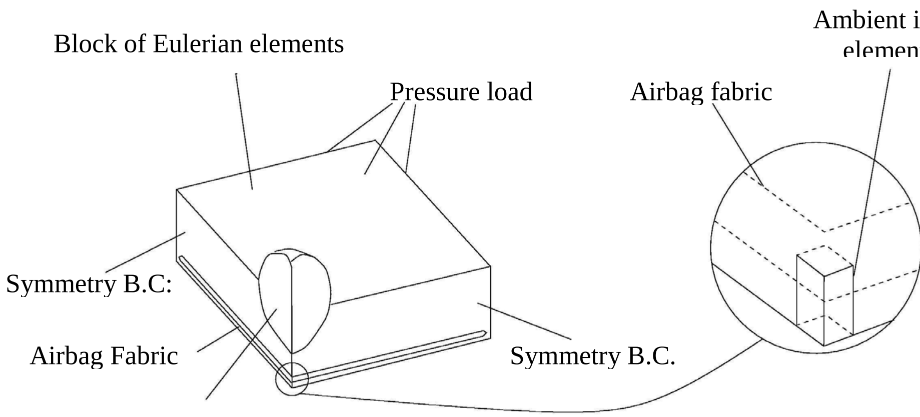

Figure 4. FE-model setup

In each structural element, 10x10 equally spaced coupling points are defined. Using a low number of coupling points increases the efficiency of the simulation but may lead to artificial leakage of the fluid.

DISCUSSION OF RESULTS

The correspondence between the test and the multi-material ALE simulation is good, except for one detail, which is the acceleration peak at 70 ms, see Figure 5. A velocity comparison is found in Figure 6. All experimental and simulation results have been filtered with a low pass filter at 60 Hz.
In airbag inflation simulations it is often assumed that the inlet velocity is sonic. This is however not the case in the present setup. As can be seen in Figure 7 a high-pressure zone is built up between the inlet and the Head Form at the very first milliseconds of the process, making the pressure drop significantly smaller than what is needed for sonic flow at the inlet. However, since the pressure further out in the bag is considerably lower, the flow is accelerated to a sonic level at the boundary of the pressure zone.

If the Head Form was to be situated further away from the inlet, the above stated phenomenon would not occur and a sonic inlet can be assumed as long as the inlet pressure is high enough. For sonic flow to occur the pressure ratio between the inlet pressure, p_{inlet} and the bag pressure just inside the bag, p_{bag}, must be

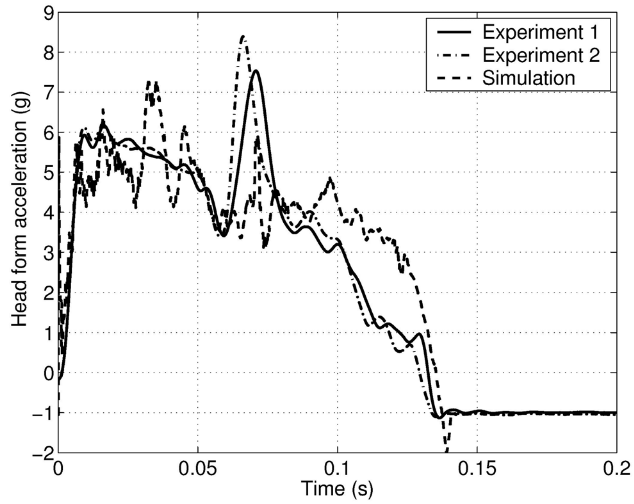

Figure 6. Comparison of Head Form velocity from test and Multi Material ALE simulation

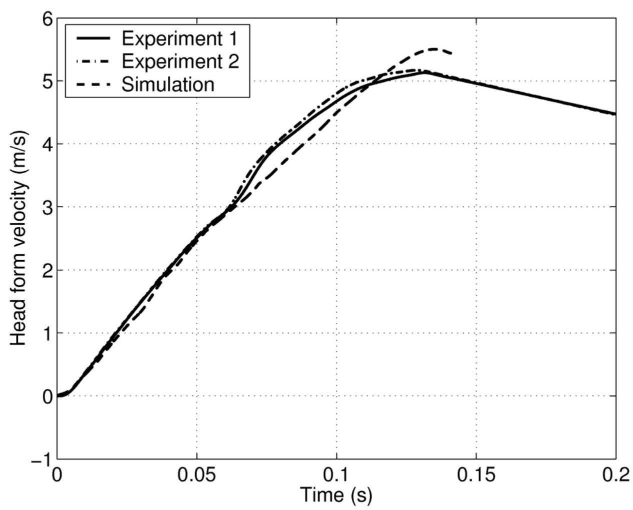

Figure 5. Comparison of Head Form acceleration from test and multi-material ALE simulation

$$\frac{p_{inlet}}{p_{bag}} = \left(\frac{\gamma+1}{2}\right)^{\frac{\gamma}{\gamma-1}} \qquad (3)$$

The deformed configurations of the airbag during the simulated deployment process are shown in Figure 8. Based on the results the following observations are made:

1. Until about 60 ms the Head Form seems to be affected only by the jet itself.
2. After 60 ms, tensile stresses start to build up in the fabric, creating a "trampoline effect", where the stretching fabric accelerates the Head Form.
3. The fluid pressure inside the bag varies a lot with time and spatial position. At certain points in space and time, it is even lower then the atmospheric pressure.
4. The pressure values are quite low until the airbag is fully deployed. Here it happens after the Head Form loses contact with the bag.

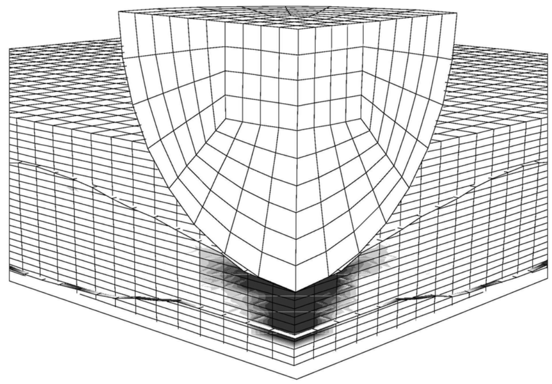

Figure 7. Pressure zone between inlet and Head Form

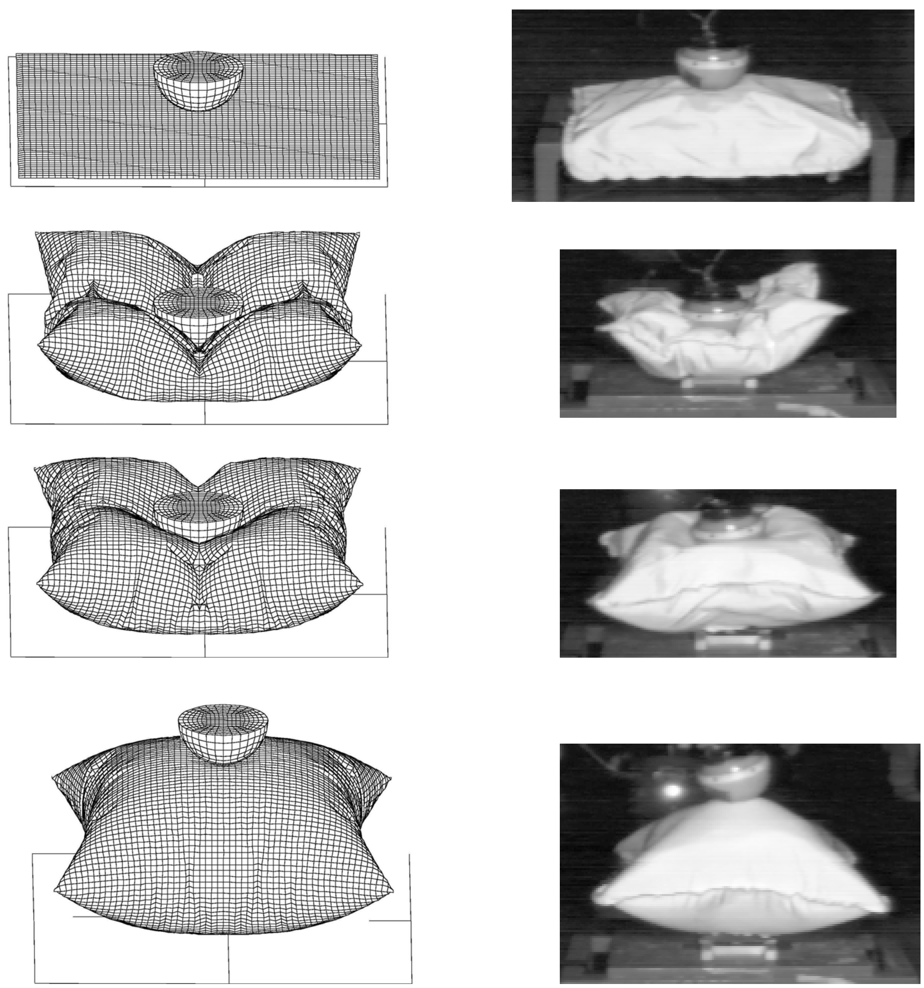

Figure 8. Deformed states from simulation and test at t=0, 40, 80, 120 ms

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