Testing and verification of the new CPG method for complex internal structures in airbags

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1 Introduction

Airbags are essential lifesaving components in passive occupant safety systems and are being used more and more frequently with the help of advanced technology. They are also being developed for pedestrian protection systems. As the applications of airbags become more diverse and their safety performance more important, both the hardware and simulation methods have evolved to meet the new requirements.

In the last few decades airbag simulations in LS-DYNA faced significant developments. The earliest simulation method in the 1980s was the Uniform Pressure Method (UPM), also known as the Control Volume (CV) method. In this approach, a uniformly distributed pressure is applied to all airbag segments, which is based on the calculations of the equation of state for ideal gases. As this method assumes equal pressure everywhere in the airbag, it leads to some inaccuracies during the deployment of an airbag. This can especially be an issue in out-of-position (OoP) load cases where local effects on the occupant injury values are important. In the early 2000s, the Arbitrary Lagrangian-Eulerian (ALE) method was applied to airbag simulations. A special keyword, *AIRBAG_ALE, was dedicated to this already existing method to simplify airbag definitions. This method allowed local flow fields to be represented more realistically during the deployment of complex geometries. However, the ALE method encountered some challenges when simulating very tightly folded airbags, where it was difficult to separate multiple gas layers and contact interactions which could cause some leakage and locking problems.

The Corpuscular Particle Method (CPM) was introduced approximately 20 years ago to overcome those limitations from previous airbag simulation methods [1]. CPM, based on kinetic molecular theory, proved to be faster than ALE, more accurate than UPM and robust for many applications [2][3]. It became widely used in standard crash simulations and has been continuously improved [4]. Nevertheless, CPM has some limitations due to its fundamentals like capturing gas flow characteristics, which has been lately one of the main focuses for complex designs with internal structures such as tethers or chambers.
In response to an increasing demand for local accuracy and realistic gas behavior, a new approach was developed, the Continuum-based Particle Gas (CPG) method [5]. This method uses the compressible Navier-Stokes equations together with the ideal gas laws and offers the capability to simulate accurate gas flow fields during airbag deployment as well as minimum reliance on empirical tuning parameters, making the calibration process more straightforward, thus enabling robust simulation outcomes.
In this work a generic tube-shaped airbag has been modeled and simulated using the CPG method to predict its flow simulation time-history against hardware deployment test results.

2 Tank test

In computational gas dynamics, for the CPG method as well, an accurate definition of initial boundary conditions is essential for reliable pressure development within closed volumes such as airbag systems. In the CPG method, the relationship between gas velocity and the inflation area for the initial boundary conditions, as described in [4], is governed by the following equation:

$$(\rho \cdot v)_{inlet} = \frac{\dot{m}}{A} \quad (1)$$

where ρ is the gas density, $\dot{m}$ is the mass flow rate at the boundary and A is the effective inflation surface.
In compressible gas dynamics, the inlet velocity is physically constrained by the local speed of sound. Consequently, the maximum achievable velocity at the inlet is limited to the sonic condition (Mach=1). When the calculated gas velocity is above this threshold, the flow is so called choked. At this point any increase of mass flow rate causes an increase in gas density rather than velocity increase. After leaving the inlet, the choked flow can accelerate to supersonic velocities (Mach>1) as the gas expands, which results in a corresponding decrease in density due to expansion effects.
Wrong definitions of boundary conditions may result in inaccurate pressure distributions throughout the airbag volume that can lead to wrong design conclusions. To avoid this, traditional tank test methods are appropriate to examine the gas generator's inlet boundary conditions. These tests are performed in a constant-volume tank setup, as illustrated in Figure 1a, where experimental data provides a benchmark for the successive simulation validation, as illustrated in Figure 1b.

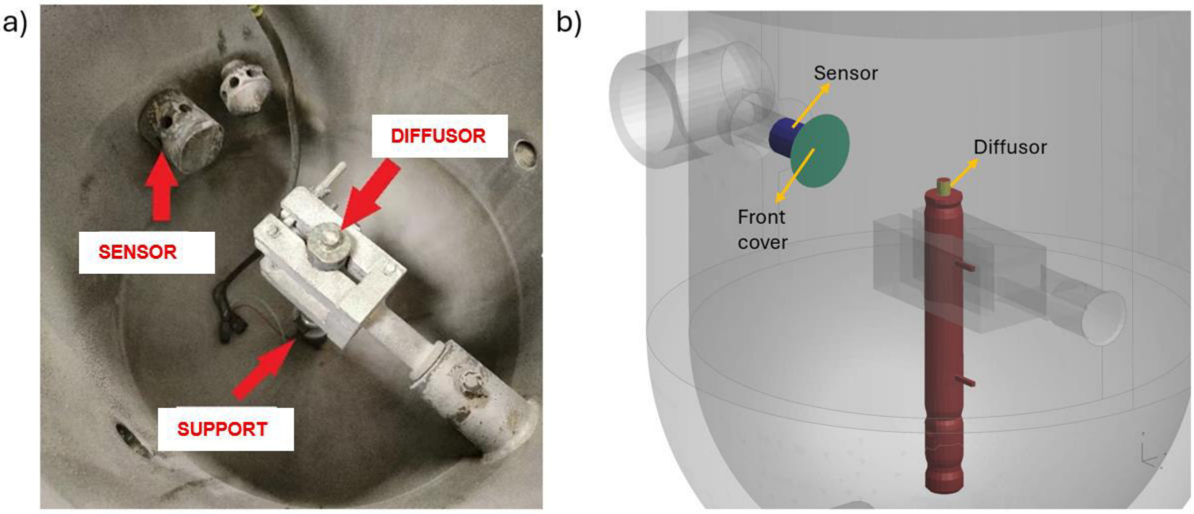

Fig.1: a) Hardware setup of a tank test with a gas generator. b) Corresponding simulation model of the tank test setup in LS-DYNA.

In LS-DYNA, the implementation of the CPG method is carried out via the *AIRBAG_CPG keyword, which requires a shell-based definition of the inflation area, specification of the mass flow rate and gas temperature and a proper interparticle distance.

The inflation area for the CPG model is typically defined using shell elements located around the gas generator nozzle, as can be observed in Figure 2a. The parameter interparticle distance between each CPG particles (HLEN) is defined as a constant value of 5.0mm in this tank model, as illustrated in Fig.2:b.

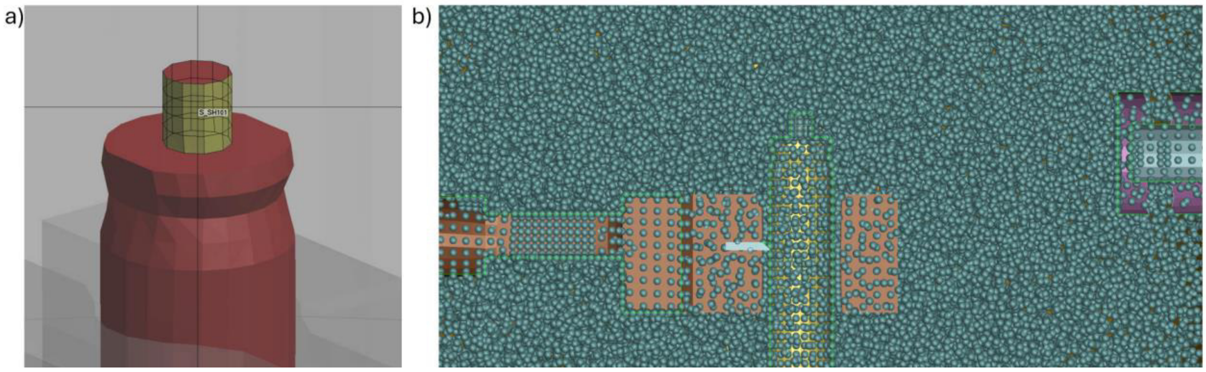

Fig.2: a) The set of shells around the diffusor is used to define the CPG inflation area. b) Generated CPG particles with HLEN=5mm.

In addition to CPG, the CPM model of the same setup is also simulated for the purpose of comparison. In both simulation models the thermal effects between the tank and the gas within the closed volume are not considered. As presented in Figure 3, minor discrepancies in pressure levels between the simulation and the test may be due to this. Local effects of the CPG total pressure output in an early simulation stage can be observed in the fringe plot presented in Figure 4.

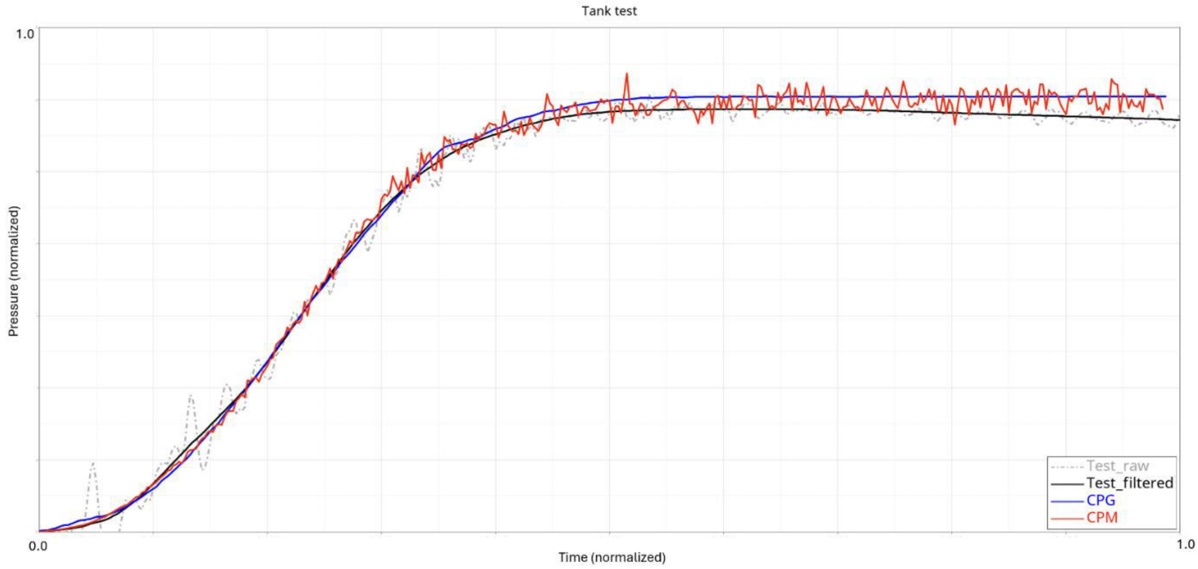

Fig.3: Pressure results of the test, sensor part pressures CPG and CPM simulations in the tank test.

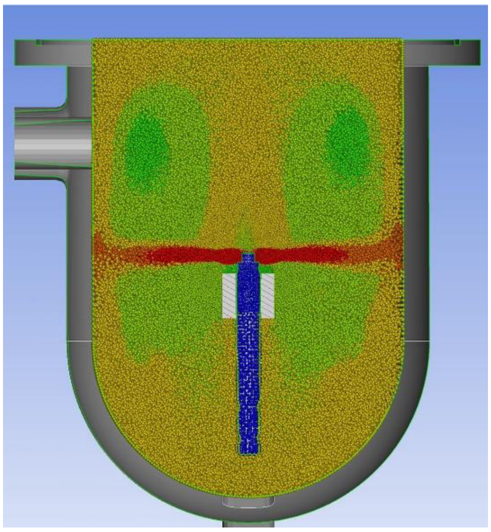

Fig.4: Fringe plot of total pressure output in an early state of the simulation where local flow effects can be observed.

3 Generic bag models

Following the initial tank test verifications for the CPG method, it is essential to take a step further to assess the correlation between experimental and simulation results in an airbag scale. To this end, generic airbag models are developed by Toyoda Gosei Europe NV, providing both hardware tests and simulation models. Within this assessment, various airbag configurations were tested, including a simple tube bag, as well as tube bags with one and four internal tethers, under both flat and rolled initial conditions. Figure 5 illustrates the generic airbag model with four tethers as an example. The developed generic airbag model tries to capture today's challenges in airbag modelling of complex folded airbags, like for example Knee Airbags (KAB) or Curtain Airbags (CAB), having in addition complex internal structures. Simulation results using both CPM and CPG methods were then compared against the experimental test results.

The objective of these comparisons is to incrementally increase model complexity and observe the accuracy of the CPG method, particularly in capturing internal flow phenomena since internal parts like tethers have always caused challenges in simulating flow dynamics, especially in the early phase of airbag deployments. An important point to know regarding CPG modeling for internal tether part is that, unlike CPM, the CPG method does not require explicit definitions of internal vents. Simply modeling the holes of the tethers as they physically exist is sufficient for CPG simulations. This not only simplifies the model setup but also makes the model closer to reality.

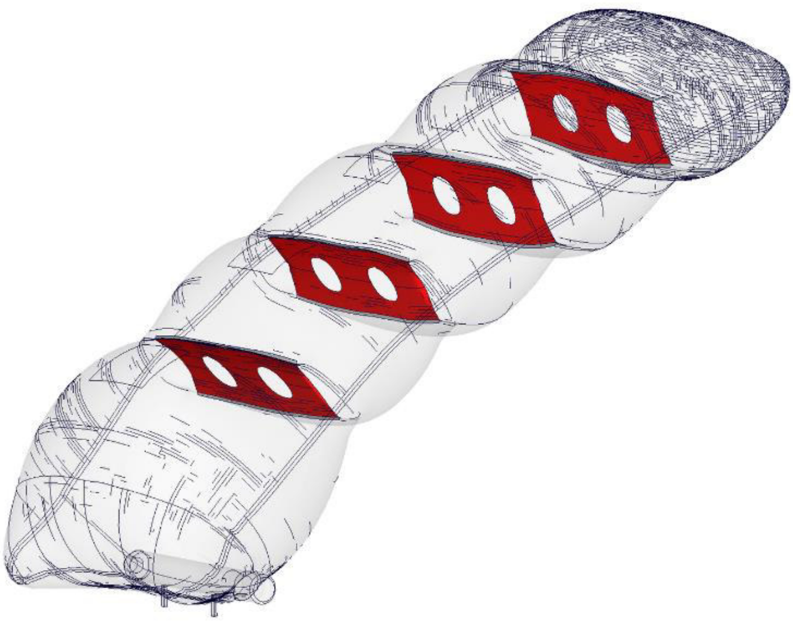

Fig.5: Visualisation of internal tether parts in deployed state.

Deployment and timing of the CPG method simulation should show that the mass flow through internal tethers closely matches the hardware results. This is intended to confirm the ability of the CPG method to accurately capture complex internal flow characteristics in airbags without requiring adjustments to the models. Since the flat versions of the airbags already showed good agreement with the experimental results, this study presents comparisons of the rolled airbag models in the following section.

3.1 Simple tube bag

In this subsection the visual results comparisons of the simple tube bag – CPM, hardware and CPG are presented in Figure 6, while Figure 7Fig.7: presents the comparison of the obtained pressure results.

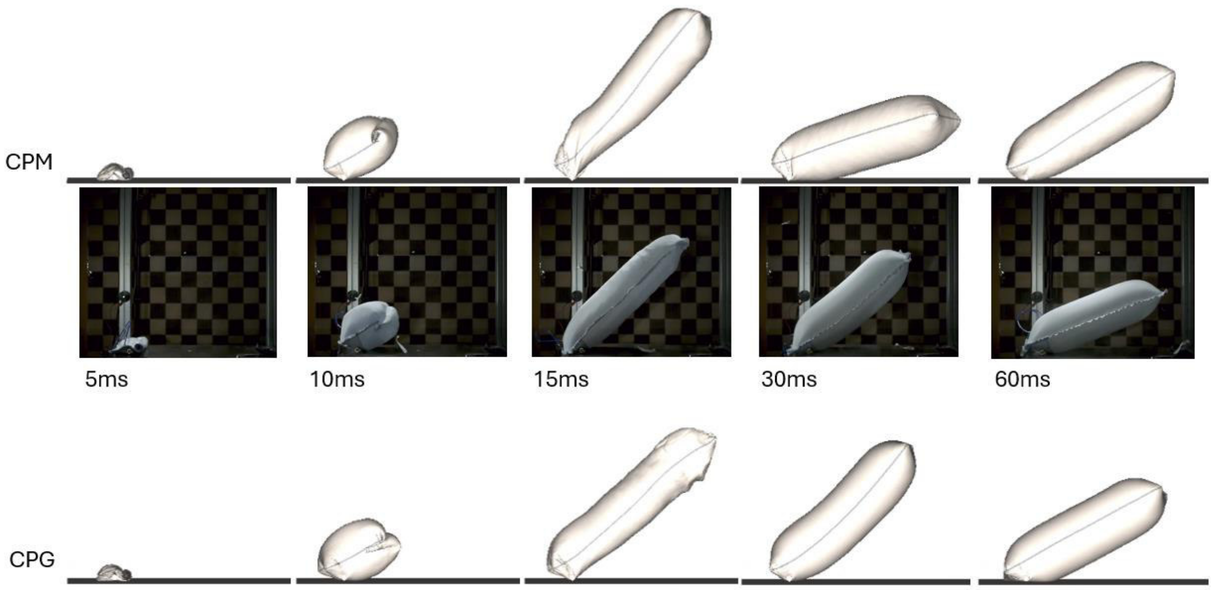

Fig.6: Simple tube bag comparisons with the experiment at t=5, 10, 15, 30 and 60ms from left to right respectively.

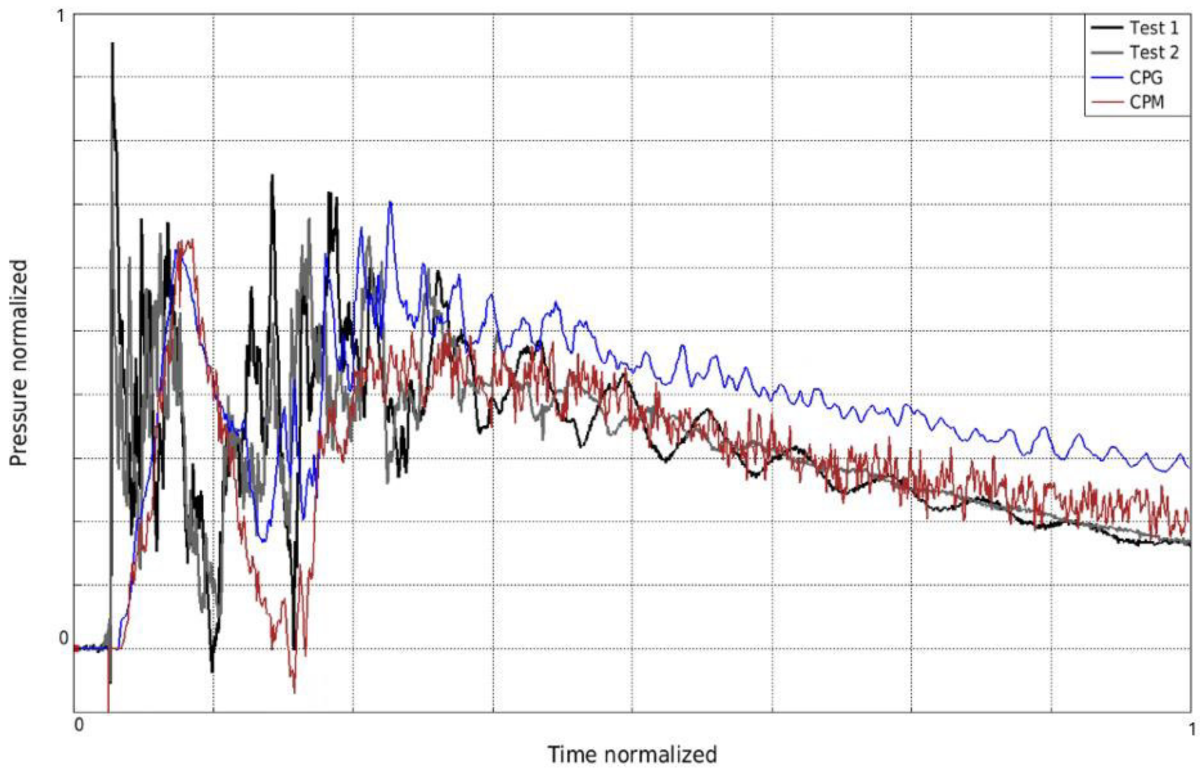

Fig.7: Simple tube bag pressure output comparisons with CPM, CPG and experiment.

3.2 Tube bag with one-tether

In this subsection the visual results comparisons of the simple tube bag with one tether – CPM, hardware and CPG are presented Figure 8, while Figure 9 presents the comparison of the obtained pressure results.

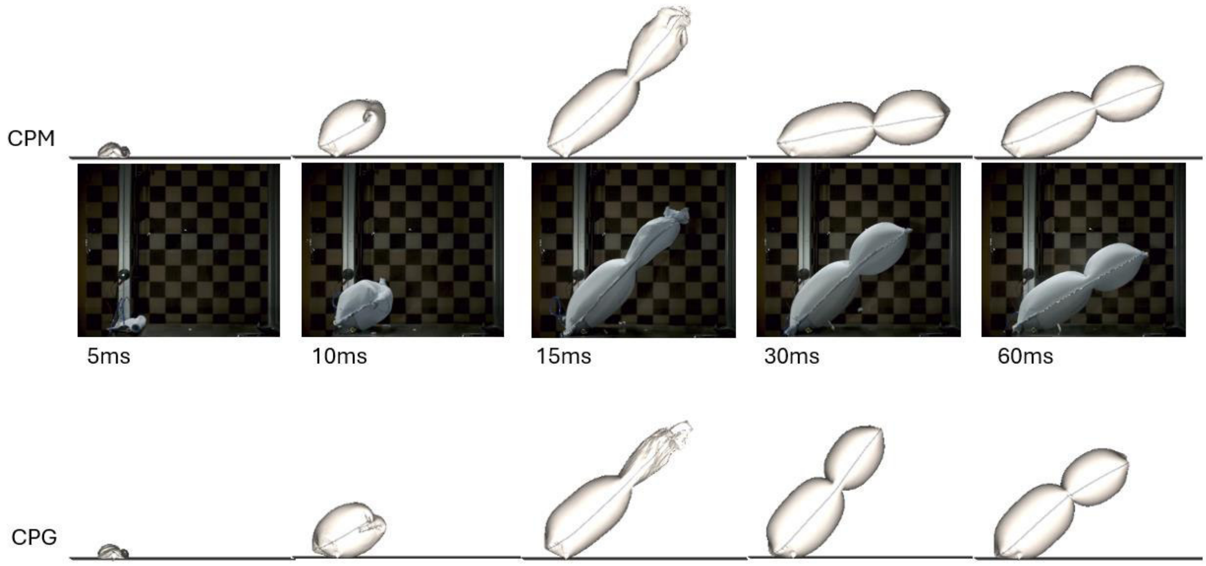

Fig.8: One-tether tube bag comparisons with the experiment at t=5, 10, 15, 30 and 60ms from left to right respectively.

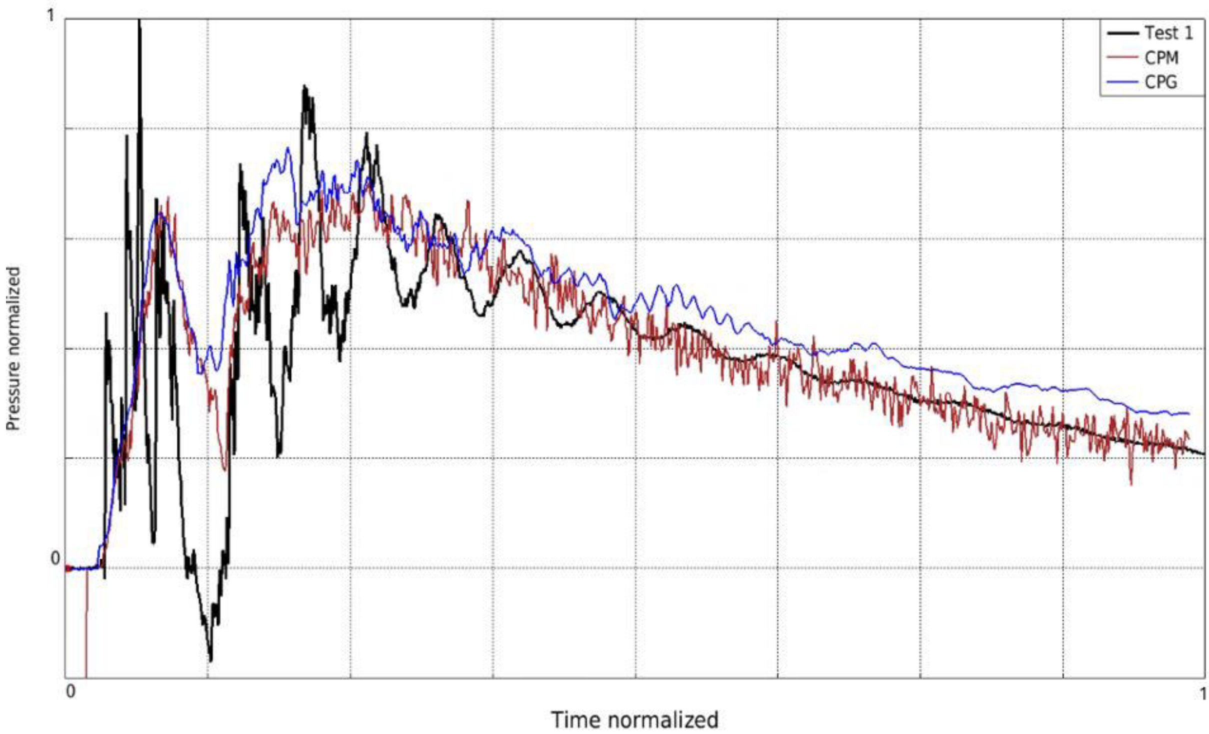

Fig.9: One-tether tube bag pressure output comparisons with CPM, CPG and experiment.

3.3 Tube bag with four-tether

In this subsection the visual results comparisons of the simple tube bag with four tethers – CPM, hardware and CPG are presented in Figure 10, while Figure 11 presents the comparison of the obtained pressure results.

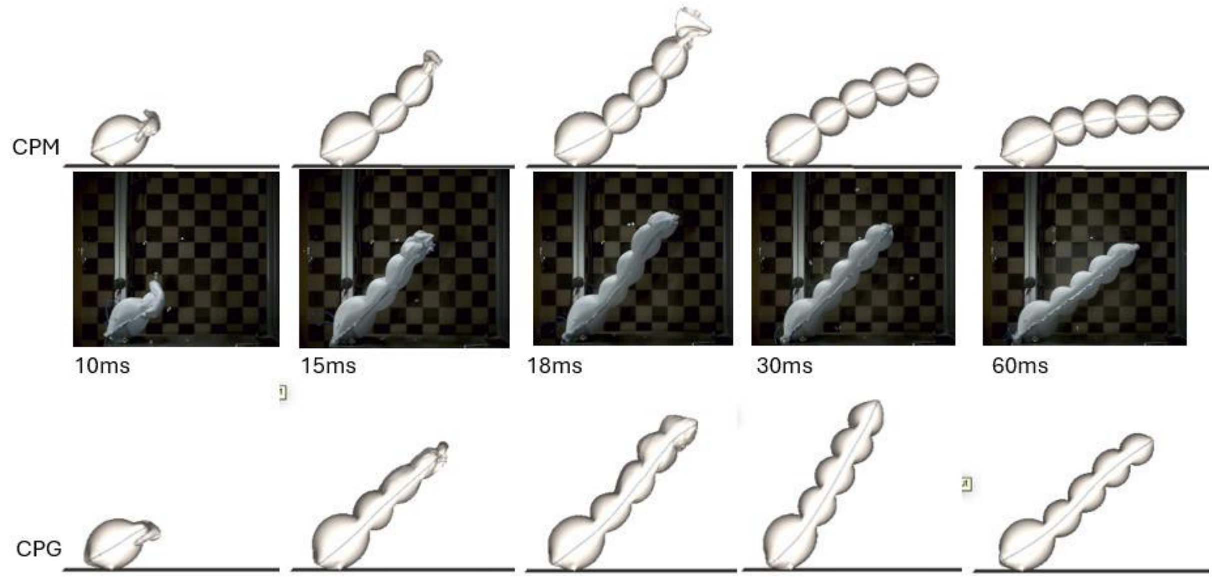

Fig.10: Four-tether tube bag comparisons with the experiment at t=10, 15, 18, 30 and 60ms from left to right respectively.

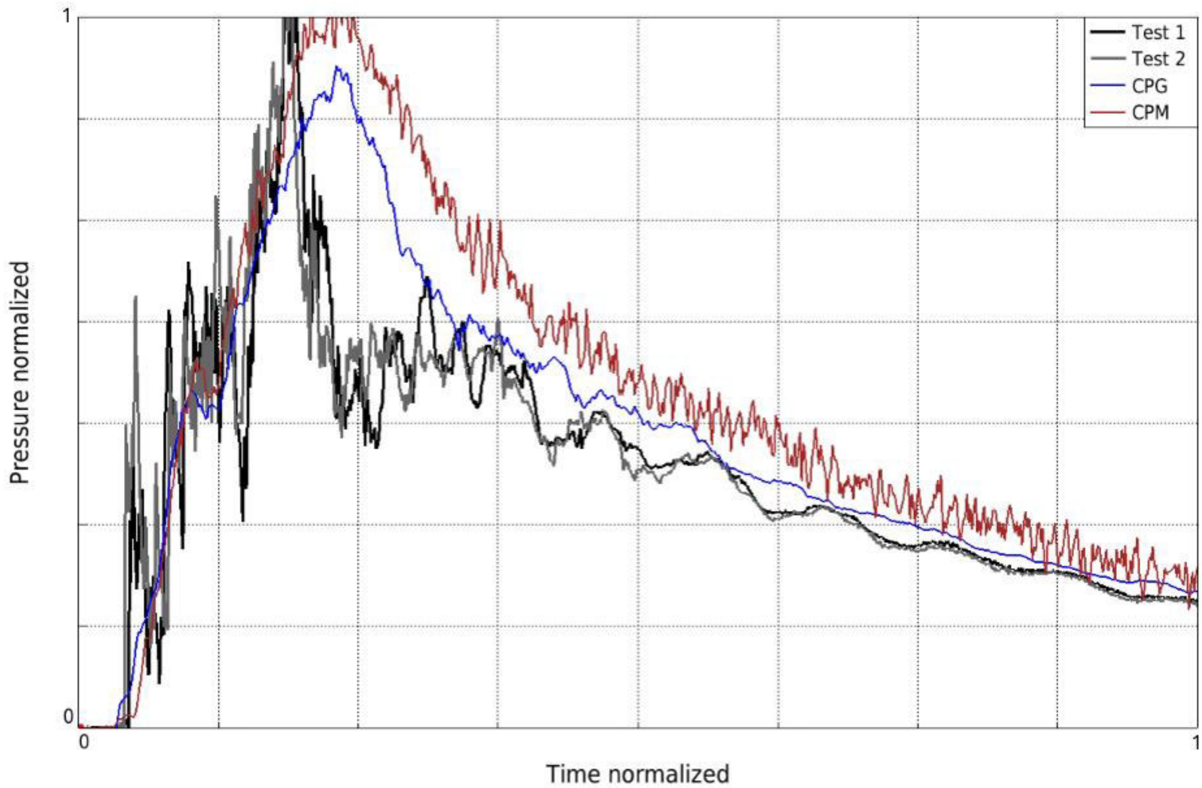

Fig.11: Four-tether tube bag pressure output comparisons with CPM, CPG and experiment.

4 Discussion

Both methods capture well the kinematics of the rolled generic airbags, as illustrated in Figure 6, Figure 8 and Figure 10. However, the CPG method shows improved kinematics in comparison to the test results, especially in terms of roll unfolding and overall airbag filling time. Figure 12 illustrates the improved unfolding kinematics of CPG over the CPM for the generic model with four tethers, 5 chambers respectively, as an example. As can be observed, the model using the CPG method is closer to the results obtained in the test.

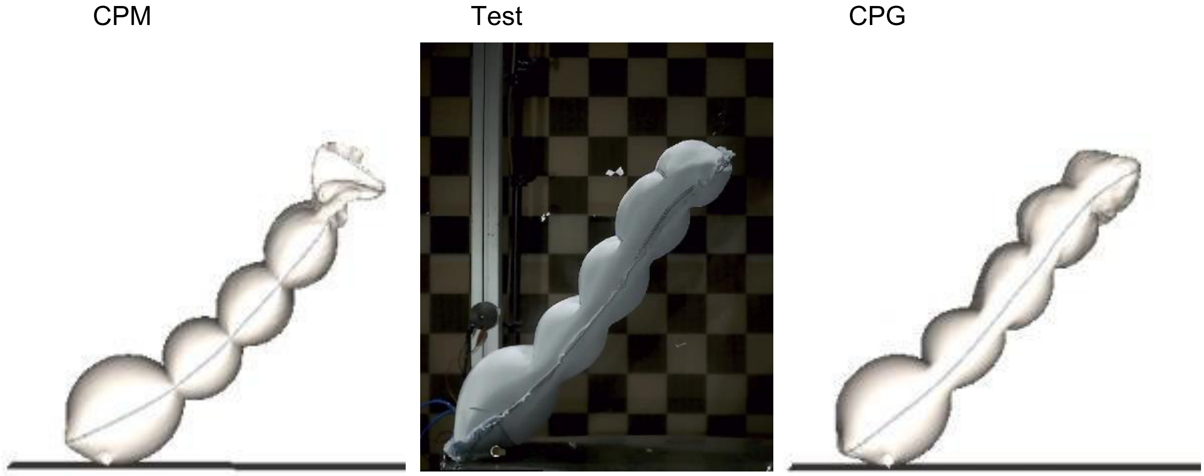

Fig.12: Kinematics comparison of the four-tether generic airbag – CPM, Test and CPG for 18ms.

From that, applying the CPG method improves the gas transport through the chambers over the CPM method. In the four-tether generic airbag model the fifth chamber is filled at 18ms, as in the test.

The obtained pressure signals, illustrated in Figure 7, Figure 9 and Figure 11, show a good correlation in terms of overall shape, phase and amplitude towards the test results. However, it must be noted that heat losses are not considered in the simulations for CPG and CPM, which can explain the minor differences obtained. In addition, the local pressure measurement in the test has been carried out using a tube connector, while the pressure in the simulations has been measured in the area of the pressure connector, directly on the airbag surface (CPM: particle interaction with the boundary, CPG: directly calculated – average over points). Considering that small scale venting (in the inflator region) is not yet taken into account in CPG, the pressure curve correlation may improve further in the future.

5 Conclusion

The CPG method represents a significant advancement in LS-DYNA to simulate gas flow characteristics accurately. Due to its foundation on continuum-based equations internal flow dynamics can be captured correctly, making more precise models in complex airbag designs with internal tethers and chambers.

The simulation results presented in this study demonstrate that CPG can closely replicate experimental behavior, particularly in terms of gas flow timing through the internal tethers and kinematics correlation throughout the overall airbag deployment. Figure 13 illustrates the simple tube bag in flat condition in an early stage of the deployment, Top View a) and Side View b). From that it can be observed that gas transport and kinematics (pressure wave) correlate well even in early stages of the simulation time history and test response. This method also reduces dependency on manual tuning to meet behaviors more realistically, without requiring internal vent definitions or approximations.

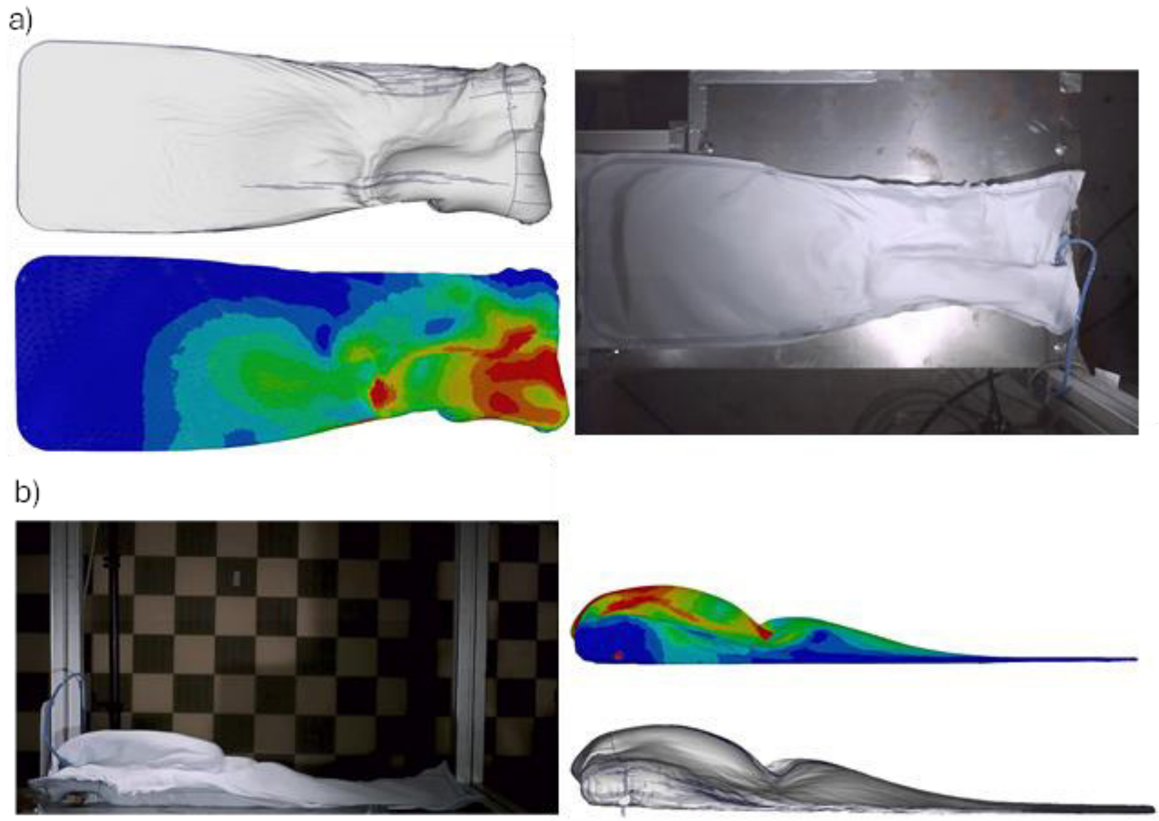

Fig.13: CPG gas flow representation with fringed velocity components during deployment of the simple tube bag in flat condition, a) top view b) side view.

However, some discrepancies in pressure results were observed, as presented in Figure7, Figure 9 and Figure 11. These deviations are likely due to the exclusion of small-scale vent modeling in the gas generator region. External vent modeling is an important topic since correct estimations for mass outflow require accurate modeling of the boundary conditions, making it even more important for supersonic velocities on the venting boundaries. Additionally, fabric material calibration for gas leakage through the seam modeling could also be investigated further. These points are considered as future work in this study to improve simulation fidelity.

Despite these limitations, the CPG has shown a good promise as an advanced airbag simulation tool. It enables handling of complex internal geometries with fewer assumptions which makes it a powerful method for both design exploration and validation. It is still being developed for better accuracy without any extra modeling and computational efforts.

The generic airbag utilized in the present study aims to represent with its complexity (tethers and chambers) airbags like for example Knee Airbags (KAB) and Curtain Airbags (CAB). The results obtained in the present study promise that the application of the CPG method may help to further improve simulation predictions for those types of safety devices in the future. Similar conclusions have been made in a study of CPG applied at Curtain Airbags in [6].

6 Acknowledgements

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7 Literature

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