Continuum-based Particle Gas (CPG): A New Approach for Airbag Deployment Simulations

Edouard Yreux, Jason Wang, Iñaki Caldichoury

Ansys, Part of Synopsys, Inc

1 Background of Airbag Deployment Simulations

The evolution of automotive safety systems has witnessed a remarkable journey over the past few decades, with airbags emerging as pivotal components in mitigating the severity of injuries during vehicle collisions. Initially conceived as relatively simple passive restraint systems, airbags have undergone a profound complexification in their design and functionality, driven by the relentless pursuit of enhanced occupant protection and regulatory compliance. Today, modern vehicles incorporate a diverse array of airbags strategically positioned throughout the cabin to address various collision scenarios. From front and side airbags to curtain and knee airbags, this proliferation underscores the nuanced approach to occupant protection adopted by automotive manufacturers.
However, from a numerical analysis standpoint, this increased complexity has introduced new challenges. Modeling airbag deployment has been difficult from the outset due to the intricate dynamics of airbag inflation and the complex Fluid-Structure-Interaction (FSI) involving gas, airbag fabric, and internal components. While initial endeavors primarily aimed to accurately depict the interaction between occupants and fully inflated airbags, modern CAE tools must now also predict the entire deployment phase with exceptional precision, necessitating the incorporation of complex physics into the numerical methods.
Early modeling efforts relied on a Control Volume (also called Uniform Pressure) approach where explicit representation of the gas is replaced with a simple uniform pressure model. While the fully deployed geometry is correct, deployment kinematics is notoriously inaccurate. Developed two decades later, the Corpuscular Particle Method (CPM), rooted in kinetic gas theory, quickly emerged as the preferred technique for sophisticated airbag modeling. This method adeptly handles intricate airbag designs and has demonstrated considerable utility. However, the recent trend towards increasingly complex airbag designs, coupled with the growing need for high-fidelity resolution during initial deployment stages, has underscored certain shortcomings in effectively resolving local flow characteristics using this method.
CPM involves numerous numerical parameters that require calibration and tuning to align with experimental tests, which presents challenges in two aspects:

1. Due to the absence of predictive capabilities, airbag design continues to rely on experimental tests, with numerical models being developed retrospectively and calibrated to match these tests. Consequently, simulation cannot be utilized to make design choices in the airbag manufacturing process. This is in sharp contrast to other areas of vehicle design, where predictive numerical simulations are used extensively to inform a wide range of design decisions before the vehicle is constructed.
2. In crashworthiness analysis, numerical airbag models must be meticulously calibrated to align with experimental data. Achieving accurate correlation across all load cases (dummy sizes and positioning) can be difficult, often necessitating the tuning of different models for various scenarios.

To address these concerns, we propose a novel method for simulating airbag deployment known as Continuum-based Particle Gas (CPG), which relies on continuum physics principles. Like CPM, CPG is a particle-based approach that eliminates the need for meshing the airbag's internal volume. However, CPG adopts continuum theory and resolves the compressible Navier-Stokes equation coupled with an ideal gas equation of state. CPG aims to provide precise gas dynamics and eliminate the need for numerical parameter calibration to achieve accurate model correlation. The objective is to elevate the predictive capabilities of airbag deployment simulations to the same standard as other aspects of crash analysis, enabling users to rely on numerical results prior to hardware testing.

2 CPG Theory

CPG is a particle method based on a generalized finite difference framework. The domain Ω is represented by a collection of particles that sample the interior volume as well as the outer and internal surfaces. Each particle is equipped with a kernel function ϕ_h of compact support h (for example, a cubic-B-Spline), and the approximation space is constructed using linear Moving-Least-Squares (MLS) approximation functions $\{\Psi_I\}_I$. For any point $\boldsymbol{x}$ in the domain Ω, a neighbor list $\{J\}$ is constructed containing all the particles whose support h cover the evaluation point. For non-convex domains, special care must be taken to ensure neighbors don't interact through the domain boundary or through internal surfaces. The approximation function associated with particle I evaluated at point $\boldsymbol{x}$ then reads [1]:

$$\Psi_I(\boldsymbol{x}) = \boldsymbol{H}^T(\boldsymbol{0})\boldsymbol{M}^{-1}(\boldsymbol{x})\boldsymbol{H}(\boldsymbol{x}-\boldsymbol{x_I})\,\phi_h(\boldsymbol{x}-\boldsymbol{x_I})$$

with $\boldsymbol{H^T}(\boldsymbol{x})$ =$[1 \quad x \quad y \quad z]$ and $\boldsymbol{M}(\boldsymbol{x}) = \sum_J \boldsymbol{H}(\boldsymbol{x}-\boldsymbol{x_J})\boldsymbol{H}^T(\boldsymbol{x}-\boldsymbol{x_J})\phi_h(\boldsymbol{x}-\boldsymbol{x_J})$.
Our conservative variables read as

$$\boldsymbol{U} = \begin{Bmatrix} \rho \\ \rho u_x \\ \rho u_y \\ \rho u_z \\ \rho E \\ \rho c_1 \\ \vdots \\ \rho c_{n_{sp}} \end{Bmatrix}$$

where ρ is the fluid density, $\boldsymbol{u} = \{u_x, u_y, u_z\}$ is the fluid velocity, E is the total energy, and $\left(c_1, \dots, c_{n_{sp}}\right)$ are the mass fractions of the n_{sp} gas species in the domain. Neglecting viscous terms for brevity, the governing equations can be summarized as

$$\frac{\partial \boldsymbol{U}}{\partial t} + \boldsymbol{\nabla}\cdot\boldsymbol{F} + (\boldsymbol{\nabla}\cdot\boldsymbol{w})\boldsymbol{U} = \boldsymbol{0}$$

where $\boldsymbol{w}$ is the transport velocity and $\boldsymbol{F}$ is the convective flux, expressed as

$$\boldsymbol{F_x} = (u_x - w_x)\boldsymbol{U} + \begin{Bmatrix} 0 \\ p \\ 0 \\ 0 \\ pu_x \\ 0 \\ \vdots \\ 0 \end{Bmatrix};\ \boldsymbol{F_y} = (u_y - w_y)\boldsymbol{U} + \begin{Bmatrix} 0 \\ 0 \\ p \\ 0 \\ pu_y \\ 0 \\ \vdots \\ 0 \end{Bmatrix}\ and\ \boldsymbol{F_z} = (u_z - w_z)\boldsymbol{U} + \begin{Bmatrix} 0 \\ 0 \\ 0 \\ p \\ pu_z \\ 0 \\ \vdots \\ 0 \end{Bmatrix}$$

and p is the fluid pressure, calculated from an ideal gas equation of state in this case.

For a complete description of the CPG theory and the various boundary conditions necessary for airbag deployment simulations (such as modeling of airbag inflator orifices and external vents), as well as a summary of verification and validation studies for this new solver, refer to [2]. The following sections present the latest additions to the solver.

2.1 Heat Exchange and Thermal Coupling

It is possible to model the thermal exchange with external surfaces by assigning a heat transfer coefficient (see `HCONV` in ***AIRBAG_CPG**). The CPG solver will add a heat source or sink term on wall particles based on the choice of heat transfer coefficient, local surface area, the current local temperature and atmospheric temperature T_{atm}.
Coupling between CPG and LS-DYNA's implicit thermal solver is also available for shell surfaces. Heat is exchanged between CPG particles and corresponding shell structures according to

$$\dot{Q} = hA(T_{\text{struct}} - T_{\text{CPG}}),$$

where h is a user-provided heat transfer coefficient. This heat flux is then incorporated in the energy equation of the CPG particles, and imposed as a Neuman boundary condition on the shell elements.

2.2 Particle Size Adaptivity

In order to balance computational cost and simulation accuracy, it’s necessary to adapt the particle size in different regions. Areas with large pressure/velocity gradients, such as around inflators and vents, typically need a finer inter-particle distance to accurately capture the complex flow developing in these regions. Conversely, in large volumes of gas away from any boundary, the gas flow is typically less complex and accuracy requirements are lower, which allows us to employ a larger particle size (Fig. 1).

Various options are available to control this parameter. The more general approach consists of using one or more **`*MESH_SIZE_SHAPE`** keywords in conjunction with **`*DEFINE_FUNCTION`**, as detailed in [2]. Since this approach can be cumbersome, new options in **`*AIRBAG_CPG`** allow the user to simply define a local particle size around vents and/or inflators. The solver will automatically identify a suitable refinement region and define transition regions between different particle sizes. Finally, a refinement/coarsening strategy based on particle distance to wall has also been implemented. A pseudo-distance is calculated by initializing the distance metric to zero for particles generated on surface elements and propagating a geodesic distance function through the nearest-neighbors graph. This distance metric is then used to ramp the particle size from a specified minimum size at the walls to a maximum size at internal particles. The format of the associated **`*DEFINE_CPG_ADAPTIVE`** keyword is provided in Table 1.

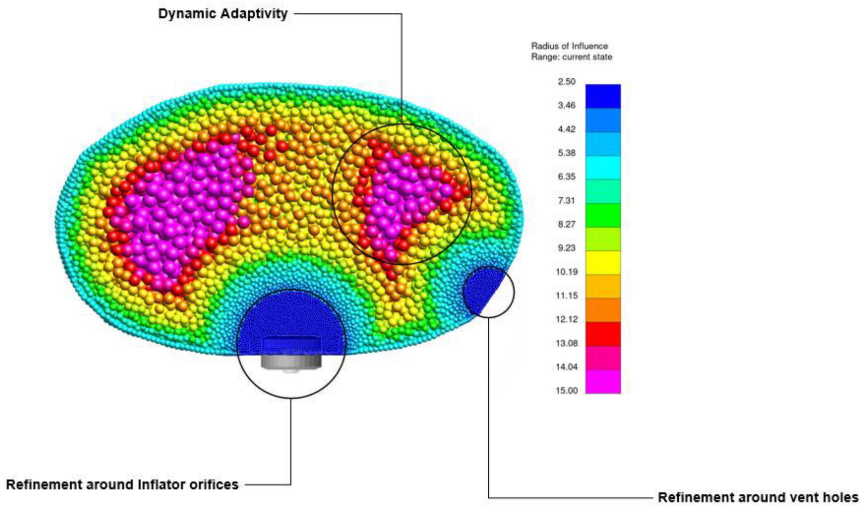

Fig. 1: Adaptive particle size using various CPG options

`*DEFINE_CPG_ADAPTIVE`							
`id`							
`distsw`	`hmin`	`hmax`					

Table 1: Keyword format for adaptive option. `id` *is referenced in* ***`*AIRBAG_CPG`*** *and* `distsw` *is set to 0/1 to deactivate/activate wall-distance-based adaptivity.* `hmin` *and* `hmax` *define the particle size at the wall and away from the wall, respectively.*

2.3 Standard k-eps Turbulence Model

Another new feature recently developed in the CPG solver in an optional k-eps turbulence model. When this option is switched on through **`*CONTROL_CPG`**, two new equations are added to the system outlined in section 2 to track turbulence kinetic energy k and turbulent dissipation rate ε. As the details of this particular turbulence model are widely available in the literature ([3]), we will simply mention a few CPG modeling considerations here:

- While it’s common to ignore the laminar viscosity of the various gas species found in typical airbag deployment simulations, the turbulence model can only be activated if all gas species in the simulation are associated with a laminar viscosity as specified in

***DEFINE_CPG_GAS_PROPERTIES**. This laminar viscosity μ is used a baseline factor to limit the turbulent viscosity: $\mu_t = \min\left(\rho C_\mu \frac{k^2}{\varepsilon}, C_{lim}\mu\right)$, where $C_\mu = 0.09$ and $C_{lim} = 1 \times 10^4$ by default.

- Friction coefficients can be defined for different parts of the airbag through the `NPDATA` lines of ***AIRBAG_CPG**. A shear stress is then calculated at boundaries and incorporated via a law of the wall.
- When the turbulence model is activated, additional variables can be visualized in the result files, see Fig. 2 and Fig. 3.

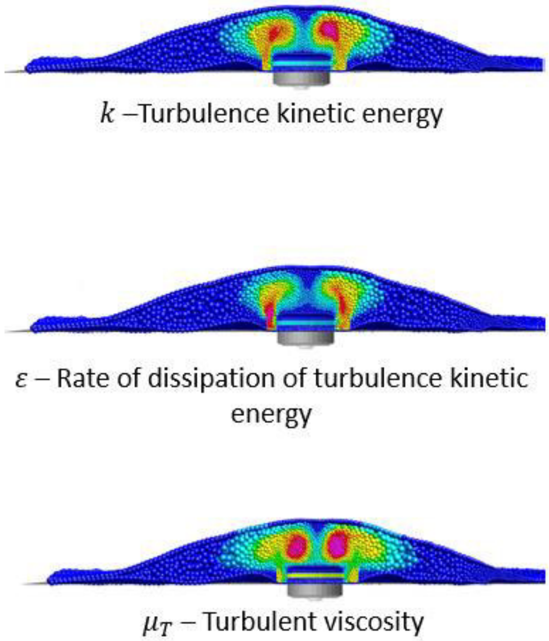

Fig. 2: Additional variables available for visualization when the turbulence model is activated.

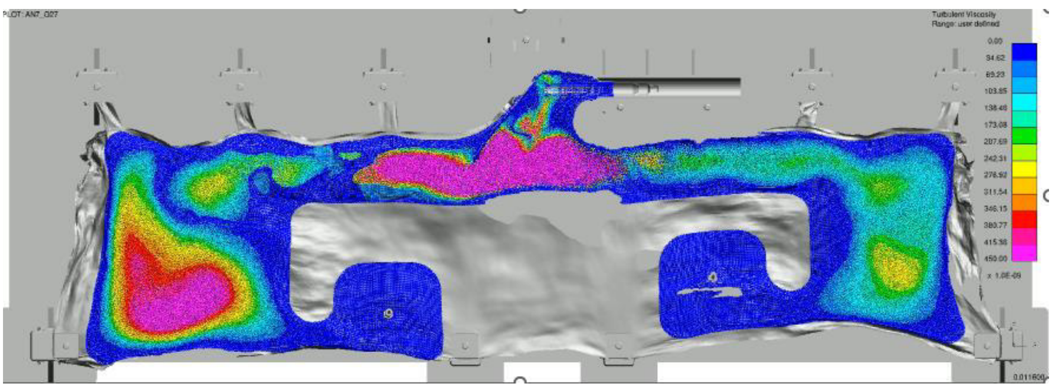

Fig. 3: Turbulence model in action on a demonstration model. Numerical model courtesy of JSOL Corporation, experimental data courtesy of Toyoda Gosei Co., Ltd.

From a practical stand-point it may be worthwhile to remember that the impact of any given turbulence model is to add extra eddy stresses (μ_t) to the fluid solution. Consequently, a simulation result that has included a turbulence model will appear as more diffusive, with a potential reduction in the intensity of recirculation zones. Due to the extreme transient aspect of airbag simulation, the impact of adding a turbulence model is generally thought to be small.

2.4 Coupling with the Discrete Element Method

Another new feature available in the latest LS-DYNA release is coupling between the CPG solver and Discrete Element Method (DEM) spheres. While CPG was mainly developed to address airbag deployment simulations, a few different applications have started to appear, one of which being battery-venting simulations during a thermal run-away. This process typically involves combustion residue (very hot particles) being carried away by the gas. With this in mind, a new ***DEFINE_DE_TO_CPG_COUPLING** keyword is available. At each DEM particle of radius R, the gas density ρ_{gas}, temperature T_{gas} and velocity $\boldsymbol{v}_{\text{gas}}$ is evaluated through CPG interpolation. A drag force is then calculated based on the relative velocity $\boldsymbol{v}_{\text{rel}} = (\boldsymbol{v}_{\text{gas}} - \boldsymbol{v}_{\text{dem}})$ as:

$$\boldsymbol{f}_{\text{gas}\rightarrow\text{dem}} = \frac{1}{2} C_d \rho \pi R^2 |\boldsymbol{v}_{\text{rel}}| \boldsymbol{v}_{\text{rel}}$$

where the drag coefficient C_d can be user-defined. If two-way coupling is enabled, the opposite force is then applied to the closest CPG particle. See Fig. 4 for an illustration of this coupling.

If the DEM thermal solver is activated, thermal coupling is also available between the two methods using a user-provided heat-transfer coefficient h. A heat transfer rate $\dot{Q}$ is calculated as:

$$\dot{Q} = h 4 \pi R^2 (T_{\text{gas}} - T_{\text{dem}})$$

Using the thermal solver on structural components as well, this allows two-way thermomechanical coupling between CPG gas, Lagrangian structures, and DEM particles.

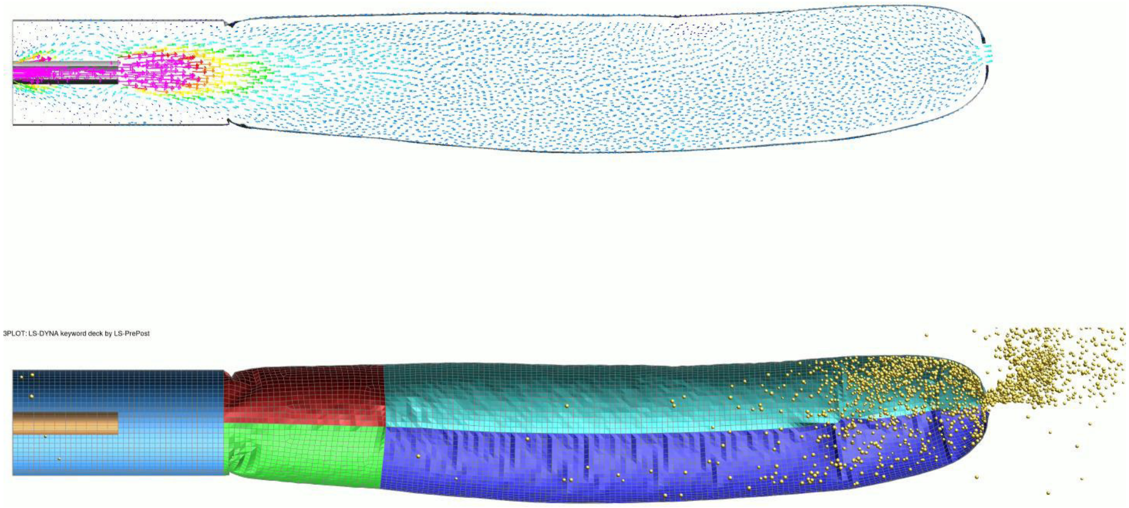

Fig. 4:Illustration of the coupling between the CPG solver and DEM particles. A gas is injected on the far left, along with some DEM particles. The gas then pushes the particles away and through the vent hole on the far right of the domain. The top image shows the gas velocity vectors, while the bottom image shows the DEM particles being pushed through the opening.

3 Towards Predictive Simulations and Virtual Testing

The transition from ***AIRBAG_PARTICLE** to ***AIRBAG_CPG** may appear trivial from a keyword perspective, but in practice the implications are far more complex. Many CPM-based airbag models have been extensively tuned against experiments, often with empirical adjustments layered on top of the physics. Simply switching formulations without reconsidering the physical basis risks losing the fidelity of those simulations. A return to well-defined, physically measurable parameters is therefore essential to ensure predictive capability rather than just curve-fitting.

Achieving predictive airbag deployment simulations requires careful attention to multiple interdependent aspects of the model. Fabric properties must be accurately characterized, not only in terms of tensile behavior but also folding and permeability. Contact definitions play a central role in capturing the interactions between fabric layers and between the airbag and surrounding structures. Equally important are the erosion criteria used to represent sacrificial stitching or breakable fabric components. If these are oversimplified or poorly calibrated, the simulation may diverge significantly from reality. These considerations highlight the need for industry-wide collaboration to move towards fully virtual prototyping.

On the physics side, additional challenges emerge. Inflator gases are not always well characterized, and the mass-flowrate and temperature curves used as input conditions are often of questionable accuracy. Moreover, the input curves used to describe inflator performance are often modified when transitioning from tank test data to in-bag deployment, and the underlying reasons for these adjustments remain only partially understood.

4 Conclusion

The CPG solver is rapidly maturing and showing promising results in terms of accuracy and robustness for airbag deployment simulations. However, transitioning to more physically grounded airbag models demands more than a simple keyword change. It requires a shift in mindset toward rigorous material characterization, careful treatment of contact and erosion behavior, and deeper understanding of inflator gas dynamics. Minor construction details and small timing variations can significantly alter outcomes, making close alignment between experimental data and simulation indispensable. Ultimately, predictive virtual airbag prototyping will depend on a combination of robust physical modeling, comprehensive testing, and collaboration across the industry.

5 Bibliography

[1] P. Lancaster and K. Salkauskas, "Surfaces generated by moving least squares methods.," *Mathematics of computation,* vol. 37, no. 155, pp. 141-158, 1981.

[2] E. Yreux, J. Wang, I. Caldichoury and M. M. Atif, "Continuum-based Particle Gas (CPG): A New Approach for Airbag Deployment Simulations," in *International LS-DYNA Conference*, Metro Detroit, Michigan, USA, 2024.

[3] B. E. Launder and B. S. Dudley, "The numerical computation of turbulent flows," *Numerical prediction of flow, heat transfer, turbulence and combustion,* pp. 96-116, 1983.