Particle Blast Method (PBM) for the Simulation of Blast Loading

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Abstract

This paper presents a particle blast method (PBM) to describe blast loading. The PBM is an extension of corpuscular method (CPM), which is coarse-grained multi-scale method developed for ideal gas dynamics simulation. It is based on the kinetic molecular theory, where molecules are viewed as rigid particles obeying Newton's laws of mechanics, while each particle in the particle method represents a group of gas molecules. Pressure loading on structures is represented by particle-structure elastic collisions. The corpuscular method has been applied to airbag deployment simulation where the gas flow is slow. For blast simulation where gas flow is extremely high, the particle method has been improved to account for the thermally non-equilibrium behavior. Furthermore, to better represent gas behavior at high temperature, co-volume effects have been considered. The particle blast method could be coupled with discrete element method, make it possible to model the interaction among high explosive detonation products, the surrounding air, sand and structure.

Introduction

Until recently, continuum-based Eulerian approachs were regarded as most accurate technology for the simulation of blast loading. However, a Eulerian approach to the modeling of blast loading is subjected to several difficulties. One major disadvantage is greater advection error relative to Lagrangian simulations, when advection is used, both momentum and kinetic energy is not conserved at the same time. Also, greater computational effort is needed over Lagrangian simulations due to the advection. Another disadvantage is that there are geometrical complexities are hard to handle with continuum-based Eulerian approachs. For example the simulation of a structure subjected to a landmine explosion, where the land mine may either be buried in sand or placed in a steel pot. Complex geometries need to be considered in the type of simulation and it is known to be very expensive with the continuum-based Eulerian approachs.

To circumvent those difficulties, a particle blast method (PBM) has been proposed to model the interaction between detonation products, air, and structure. The method is based on the corpuscular particle method (CPM), which is implemented in LS-DYNA® for the simulation of airbag deployments. CPM assumes that the system is always thermal equilibrium. This is a reasonable assumption for airbag simulation with moderate temperature and low pressure, however, for blast simulation where gas flow is extremely high, the assumption of thermal equilibrium is invalid and the particle blast method has been proposed to account for the thermally non-equilibrium behavior. Furthermore, to better represent gas behavior at high temperature, co-volume effects have been considered. The particle blast method (PBM) could be

coupled with discrete element method, make it possible to model the interaction among high explosive detonation products, the surrounding air, the sand and the structure.

Overview of the Particle Blast Method

The particle blast method is an extension of corpuscular particle method, which is coarse-grained multi-scale method developed for gas dynamics simulation. It is based on the kinetic molecular theory (KMT). The kinetic molecular theory is the study of gas molecules and their interaction (at a microscopic level) which leads to the ideal gas law (macroscopic relationships). The kinetic molecular theory dates back to 1738 when Daniel Bernoulli proposed a theory that the air pressure against a piston is built up by discrete molecular collisions. Having the kinetic theory as a starting point, in 1860 James Clerk Maxwell derived a very elegant expression for the molecular velocity distribution at thermal equilibrium. He managed to bring more understanding to details about the molecular interaction in an ideal gas. One can, from his statistical descriptions, derive quantities such as the mean free path and frequency of collision. The theory is based on the following assumptions:

1) Gases are composed of a large number of particles that behave like hard, spherical objects in a state of constant, random motion.
2) These molecules are much smaller than the average distance between molecules.
3) The molecules obey Newton's laws of motion.
4) Collisions between molecules or collisions with the structure are perfectly elastic.
5) There are no attractive or repulsive forces between the molecules.

The macroscopic physical properties of gases, such as pressure and temperature, can be related to their composition at a molecular level. KMT can accurately describe the properties of ideal gases; however, the application of the KMT to realistic simulation is not straightforward due to their high computational cost. For example, in a typical the kinetic molecular simulation, the characteristic time scale can be pico-seconds and the length scale can be nano-meters, making a realistic airbag simulation impossible.

To bridge the huge gap between the length scales and time scales that can be studied in atomistic simulation and those that are relevant for industrial process, Dr. Olovsson has proposed the corpuscular method to allow the study of airbag deployment simulation[1]. Corpuscular method is a coarse-grained method that based on KMT, i.e., many molecules are grouped together as a particle. The benchmark study of the CPM method has been performed by Lian et al[2] for airbag deployment with an out-of-position (OOP) occupant, however, directly application of CPM to blast loading simulation is not straightforward :

1) The ideal gas law is unable to capture the sharp pressure drop during adiabatic expansion that a real high explosive will undergo.
2) The assumption that system is in thermal equilibrium is not acceptable for high pressure, high temperature gas dynamics.

The particle blast method (PBM) improves corpuscular method such that it is capable of simulating real gas law with high pressure and high temperature. A co-volume effect has been

introduced in this method to better represent gas behavior at extreme pressure. For an efficient contact treatment, the particles are given a spherical shape. The particle-structure interactions are purely elastic collision. Each particle contains translational energy, as well as spin energy. The balance between translational energy and spin energy is determined directly from the heat capacities.

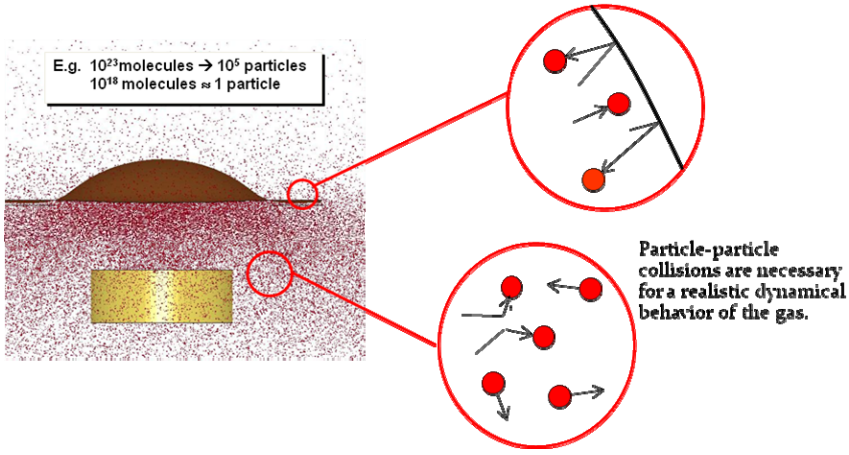

Fig.1 Particle blast method

By grouping many molecules as one particle, particle blast method reduces the degree of freedom of the system by several orders of magnitude. Combined with the increased critical time step, this method makes it possible for simulation of macroscopic systems and longer events.

Numerical Test

The experimental example is taken from [3], where a clamped circular RHA steel plate is exposed to the blast loading from a 15 kg TNT charge. The stand-off distance ranges from 400~1000 mm (Fig. 2). For the case with stand-off of 700mm, the peak deflection in the experiments has been estimated as 47mm.This value is used as the validation of the numerical method.

The plate material (RHA steel) was modeled as a rate-sensitive elastic-plastic bilinear material obeying Von Mises yield criterion. Strain rate effects are accounted for using the Cowper-Symonds model which scales the yield stress with the factor

$$\frac{\sigma_d}{\sigma_y} = 1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{1/p} \qquad (1)$$

where σ_d is the dynamic yield stress, σ_y is the static yield stress, $\dot{\varepsilon}$ is the equivalent strain rate, C and p are material constants. The material parameters used in the simulation are given in Table 1.

ρ (kg/m^3)	E(Gpa)	ν	σ_0 (MPa)	E_p (MPa)	C(s-1)	p
7838	212	0.28	1200	6500	300	5

Table 1 Material properties of the RHA steel plate

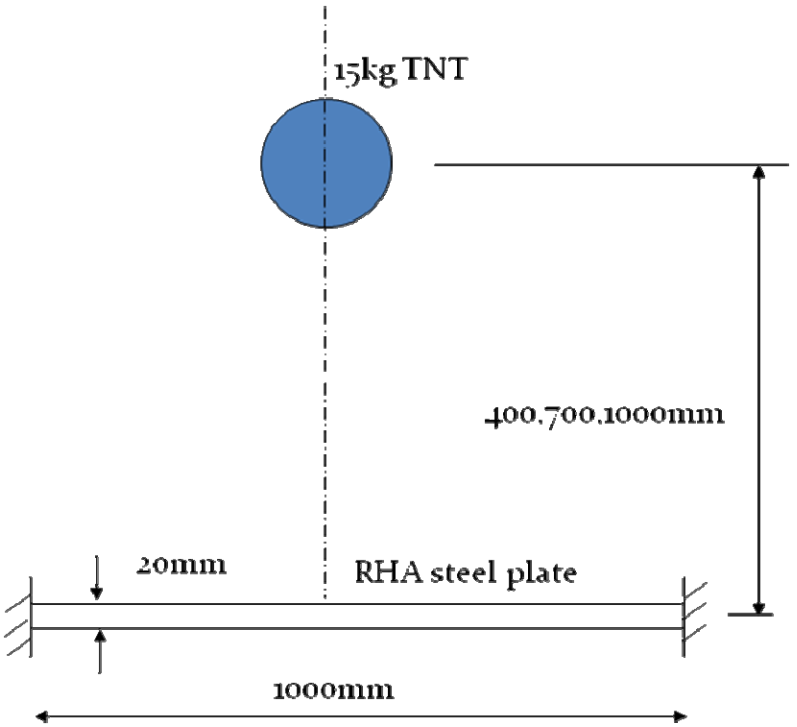

Fig.2 Test set-up

As comparison, an Arbitrary Lagrangian Eulerian (ALE) and a particle model (Fig.3.) of the test set-up were built. The ALE model was run with two different element size (NE=1.2E5, 1,1E6) and the particle model with four different number of particles (NP=1.6E4, 8.0E4, 2.0E5, 8.0e5). In the ALE model, the air and high explosive domain were modeled with 8-node reduced Elurian hexahedrons. The JWL equation of state was used to model high explosive. The JWL equation of state defines the pressure as

$$p = A\left(1-\frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1-\frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega E}{V} \qquad (2)$$

Where A, B, R_1, R_2, and ω are JWL parameters. See Table 2. The air was modeled as ideal gas with initial energy density 0.253 MJ/m^3 and $\gamma = 1.4$.

D(m/s)	A	B	R_1	R_1	ω	ρ(kg/m^3)	E(J/m^3)
6930	371.2	3.231	4.15	0.95	0.3	1630	7E9

Table 2 JWL parameters of high explosive

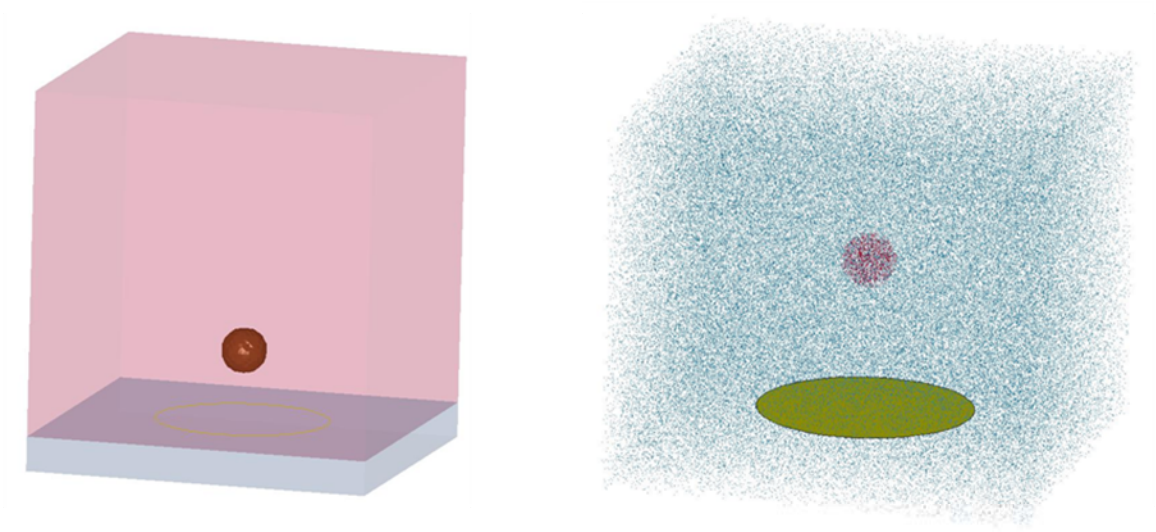

Fig.3 ALE model and Particle Model

The parameters used in the particle blast method of high explosive are shown Table 3. The detonation velocity, internal energy, and density were taken from the JWL equation of state parameters. The heat capacity ratio γ was also derived from JWL equation of state parameter ω as $\gamma = 1 + \omega$. Only co-volume coefficient *b* is used as adjustable parameter

D(m/s)	γ	ρ(kg/m^3)	E(J/m^3)	b
6930	1.3	1630	7E9	0.3

Table 3 Particle parameters of high explosive

Numerical Results

Fig.4 shows the comparison of center deflection versus time with 700mm stand-off distance. It is to be noted that both numerical method predict a smaller peak deflection than observed in the experiments. It is noticeable that with coarse mesh, ALE significantly under predicts the center deflection. ALE model with fine mesh agree with particle blast method very well. It is also interesting that particle blast method seems less sensitive to the total number of particle number; the results of the coarse model (NP=80,000) are very close to the results of fine model (NP=800,000).

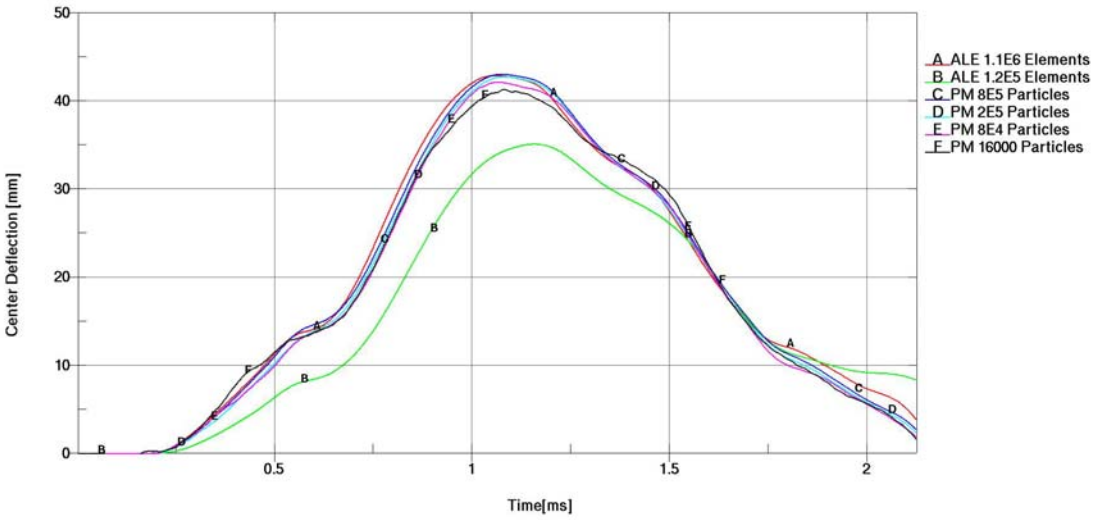

Fig.4 Simulation Results for 700mm Model

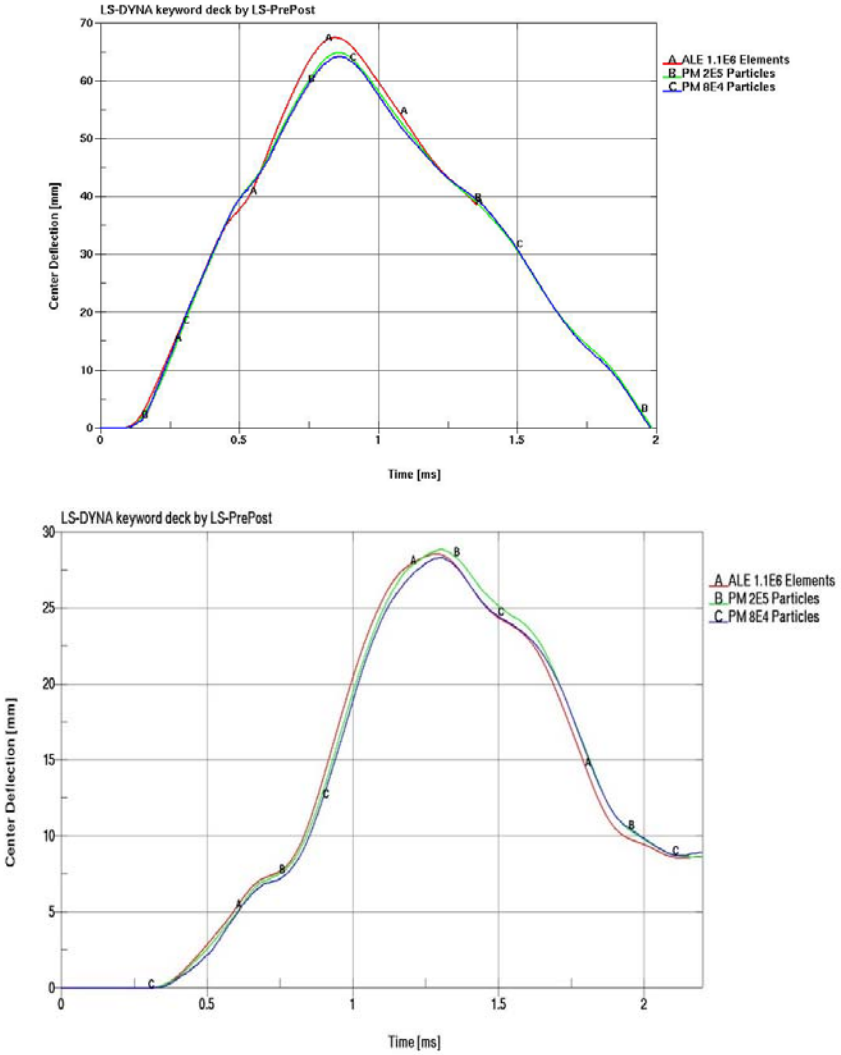

Fig.5 Simulation Results for 400mm and 1000mm Model

Table 4 lists the CPU comparison. The particle blast method is Lagrangian and does not suffer from the advection error that one experiences with ALE method. One can use much less number of particles to get reasonable well results.

Number of Elements (Particles)	CPU time (s)
Arbitrary Lagrange Eulerian (ALE)	
1.1E6	53800
1.2E5	619
Particle Blast Method	
8E5	21807
2E5	2816
8E4	1299
1.6E4	143

Table 4 CPU time comparison

Summary

A particle blast method for the simulation of blast loading has been developed. This method is based on Lagrangian description of motion, thus avoid the advection errors and severe contact problems in coupled Lagrangian-Eulerian approach. Furthermore, the absence of field equations makes the method numerically simple, robust and very efficient. The results from the particle blast method are in good agreement with corresponding ALE simulation results and available experimental data. Compared to ALE method, the particle blast method is more straightforward to use and less CPU demanding. When coupled with DEM, this method is suitable for mine blast simulation.

References

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2. W. Lian, D. Bhalsod, and L. Olovsson, 'Bemchmark Study of the AIRBAG_PARTICLE Method for Out-Of-Position Applications', 10th International LS-DYNA Users Conference, 2008
3. A. Neuberger, S. Peles, D. Rittel, 'Springback of circular clamped armor steel plates subjected to spherical air-blast loading' International Journal of Impact Engineering vol. 36 issue 1 January, 2009. p. 53-60