Numerical Study of Interactions between Blast Wave and Moving Bodies in Ambient and Indoor Areas

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1 Abstracts

This paper deals with blast effects prediction numerically on the moving bodies and a building in ambient and indoors terrains. Two-dimensional, unsteady, compressible, inviscid equations were solved by the implicit-time formulation. For the spatial discretization, the second order upwind scheme was employed. To simulate the moving bodies which impacted by the blast wave, moving mesh model was applied to shift the mesh sizes and movement. An approach to predict the blast loads (1) on the moving shells of vehicle and an immobile building in an open area and (2) on the movable window and obstacles indoors was described. Besides, serial images of transitory flow phenomena were displayed and compared by the distributions of species concentration and velocity vectors. The crashed effects, pressure sand velocity time histories, and the movement of gravity center of moving bodies were also presented to analyze and compare with different boundary conditions. The interactions among blast waves, reflected shock waves, moving body and other obstacles were described in the results. Finally, the proposed physical model and the numerical simulations developed in the present work are expected to be extended to solve shock wave interactions with other complex geometry and boundaries.

2 Introduction

The physical phenomena associated with blast waves caused by explosions have been studied for more than half a century. The assessment and prediction methodologies of explosion hazard play an important role in the area of research for explosion disasters. Generally speaking, explosions are not happened in the battlefield. From time to time, fatal explosions take place at urban terrains and factories. The serious threats by the blast waves are due to the gas density, pressure, temperature, and velocity suddenly changed around an explosion point. In recent years, some large vehicle bombs to attack city centers cause severe damages and widespread disruptions to the functions of businesses. It is difficult to predict the radius of damage to buildings experiencing in the complex structures the blasts from such bombs [1]. In the past decades, many researchers conducted the empirical and numerical approaches to predict the blast effects, including propagation, collision, consolidation, reflection and dissipation during interacting of the blast waves with ambient environment and obstacles in explosive processes [2-4].

Smith et al. [5] studied both experimentally and analytically in the area of blast wave interactions with buildings and structures in an urban landscape. The channeling effect and the resulting loading enhancement were also studied. Remennikov et al. [6] presented an accurate numerical prediction of the effects of adjacent structures of the blast loads on a building in urban terrain. Chaudhry et al. [7] developed the gas dynamic equations which represent the different aspects of hyperbolic (nonlinear) equations with second order moving mesh technique. Snyder [8] used a computational approach consisting of a flow solver, a six degree-of-freedom (6DOF) trajectory calculator, and an unstructured dynamic mesh algorithm to simulate the store separation from transonic aircraft. This new approach offered the ability to obtain accurate store separation predictions with quick turnaround times. In this paper, we will be dealing with numerical predictions of the blast effects on the moving bodies and immobile building in open and enclosed areas, respectively. So the above new approach will be employed in this study to evaluate the behaviors of blast interactions with moving bodies.

3 Mathematical Formulation

The transient flow studied here is characterized by shock propagation, interaction, and reflection. In this paper, the purpose is to study the blast effect when the shock waves are interacting with the obstacles. The present numerical method that utilizes the cell-averaged control volume scheme is described in the following section. The governing equations of mass and momentum can be expressed in Cartesian coordinates as:

$$\frac{\partial \rho}{\partial t} + \nabla(\rho\vec{v}) = 0 \tag{1}$$

The conservation of momentum is described as:

$$\frac{\partial}{\partial t}(\rho\vec{v}) + \nabla(\rho\vec{v}\vec{v}) = -\nabla p + \rho\vec{g} + \vec{F} \tag{2}$$

where p is the static pressure, $\rho\vec{g}$ and $\vec{F}$ are the gravitational body force and external body force, respectively. Note that E is the total energy and is defined as:

$$\frac{\partial}{\partial t}(E) + \nabla\,(\vec{v}(E+p)) = -\nabla\,(\sum_j h_j J_j) + S_h \tag{3}$$

where E is the total energy, $\nabla\,(\sum_j h_j J_j)$ is the transport term of enthalpy due to species diffusion, and S_h is the term defined as the blast source term.

In numerical scheme, the spatial discretization of the heat flux term was calculated by method of central differences and the inviscid term was treated with Roe's upwind scheme. Temporal integer was obtained by using the first-order implicit formulation to capture the transient behavior of moving shock waves.

4 Moving mesh conservation equations

The moving mesh model employed in this study was used to study the flows where the shape of the domain changed with time due to the motion on the domain boundary. The integral form of the conservation equation for a general scalar, ϕ, on an arbitrary control volume, V , whose boundary is moving can be written as：

$$\frac{d}{dt}\int_V \rho\phi dV + \int_{\partial V} \rho\phi(\vec{u} - \vec{u}_g)\cdot d\vec{A} = \int_{\partial V} \Gamma\nabla\phi \cdot d\vec{A} + \int_V S_\phi dV \tag{4}$$

where ρ is the fluid density, $\vec{u}$ is the flow velocity vector, $\vec{u}_g$ is the grid velocity of the moving mesh, Γ is the diffusion coefficient, and S_ϕ is the source term of ϕ.

Here, ∂V is used to represent the boundary of the control volume V. The time derivative term in Equation (4) can be written, using a first-order backward difference formula, as:

$$\frac{d}{dt}\int_V \rho\phi dV = \frac{(\rho\phi V)^{n+1} - (\rho\phi V)^n}{\Delta t} \quad (5)$$

where n and n+1 denote the respective quantities at the current and next time steps. The volume V^{n+1} at the (n + 1)th time step is computed from

$$V^{n+1} = V^n + \frac{dV}{dt}\Delta t \quad (6)$$

where dV/dt is the time derivative of the control volume.

A six degree of freedom solver was used to model flows where the shape of the domain changed with respect to the motion on the obstacle boundaries. Translational and angular motions of the center of gravity were calculated from the object's forces and moments balance on a solid body. The governing equation for the translational motion of the center of gravity is:

$$\dot{\vec{v}}_G = \frac{1}{m}\sum \vec{f}_G \quad (7)$$

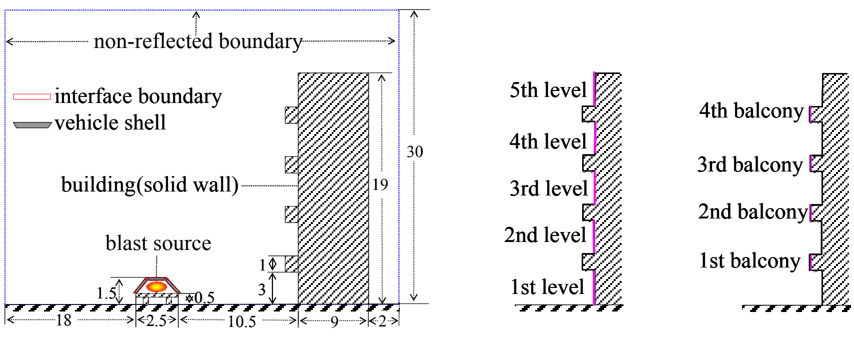
where $\dot{\vec{v}}_G$ is the translational motion of the center of gravity, m is the mass, $\vec{f}_G$ is the force vector due to the gravity, and $\dot{\vec{\omega}}_B$ is the angular motion of the object which is computed using the body coordinates.

5 Results and Discussion

To consider and predict the serious threats by the blast waves in an explosion, the cases including a two-dimensional vehicle bomb in outside area and a factory indoors were simulated.

5.1 Two-dimensional vehicle bomb impact on a building

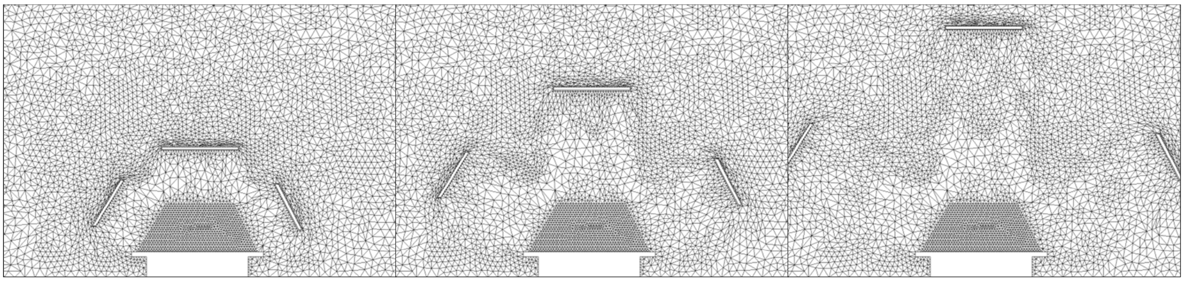
A simple geometric model including a vehicle bomb and a building was designed to simulate blast loads on three shells of the vehicle and the building. The dimensions and boundary conditions are displayed in Fig. 1. Initially, the blast source of vehicle bomb with high pressure and temperature of 500 atm and 1000 K, respectively, and the species air with 10^9 J lasting 10^{-3} seconds was full in this trapezoid space of vehicle where the area was 1.9 m^2. The blast source was enclosed by three movable shells which weighted 20 kg each. The blast wave propagated spherically through the surrounding ambient air of pressure 1 atm and temperature 300 K.



(a) (b) (c)

Figure 1 schematic illustration of vehicle bomb impact a building (a) calculation domain and boundary conditions (b) denomination of levels (c) denomination of balconies

To preserve the precise flow phenomena, the meshes in the interface regions around the movable bodies were maintained at the same relative locations. However, resulting from the body movement, the mesh sizes for the space outside these regions were adjusted. In this case, the minimum and maximum length scales are 0.001m and 0.02 m, respectively. Besides, the maximun cell skewness was set to be 0.7. In Figure.2, serial frames of mesh deformations are presented at 1 ms, 2 ms, and 3 ms, respectively.



(a) 1 ms (b) 2 ms (c) 3 ms

Figure.2 Deformations of the mesh systems while the shells moving

Serial images of species diffusions are presented in Fig. 3. It is obvious that the strong blast pushing three shells moves forward with supersonic speed, as shown in Fig. 3(a). The serious impact by the blast waves are these lower levels. For observing the development of blast wave, the right moving shell was set to be stagnated in the space close to the building. Thus, the volumes between shell and building would be close to zero and simulation could be continuous, as shown in Figs. 3(b)~3(d).

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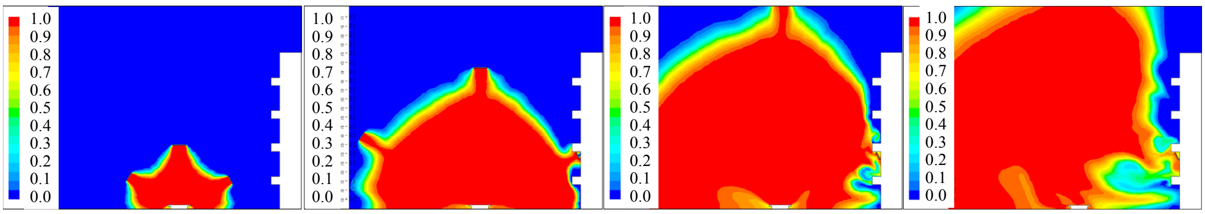
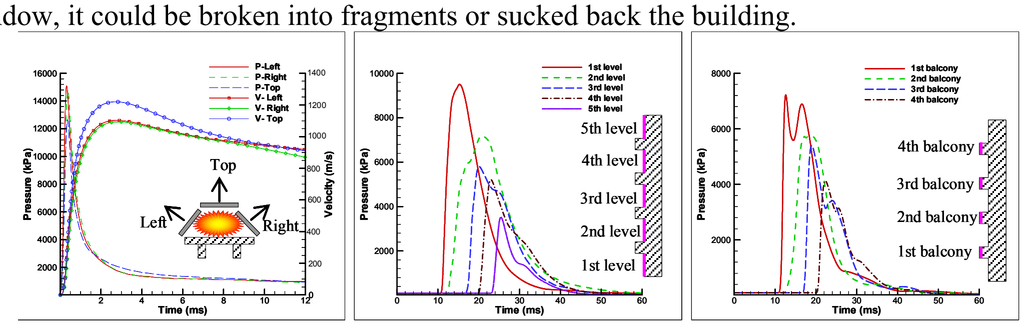


(a) 5 ms (b) 15 ms (c) 25 ms (d) 35 ms

Figure 3 Serial images of species diffusions of vehicle bomb impact a immobile building

It is clearly that the moving velocity of top shell is faster and average pressure is lower than others because of the fact that its normal surface is larger under the impact, as shown in Fig. 4(a). On the surfaces of each level and balcony, the blast loads at the higher altitude are less severe and arrive at a later time, as shown in Fig. 4(b) and 4(c). Otherwise, two pressure peaks on the first balcony are caused by reflected waves from the upper and lower levels. From the results, we can predict that the impulse caused by the right shell is about 16,500kg·m/s. On the other hand, sucking effects were formed by the reflection after the blast wave impacting on the wall of building. If the solid wall were the window, it could be broken into fragments or sucked back the building.



(a) p-t and v-t histories of shells (b) p-t history of each level (c) p-t history of each balcony

Figure 4 species concentration blast loads on shells and building

5.2 Two-dimensional blast wave impact on a window indoors

A schematic illustration and boundary conditions of a two-room factory where the left room is a workshop and another is an office are displayed in Fig. 5. The rectangular window is 10 kg and movable while it was pushed by blast wave. The initial pressure and temperature of the simulated blast source were assumed to be at 100 atm and 500 K, respectively. The pressure and temperature of ambient air are set as 1 atm and 300 K, respectively. Four cases with different boundary conditions are presented in Table 1. Except the window and its interface region, all walls are set as immobile.

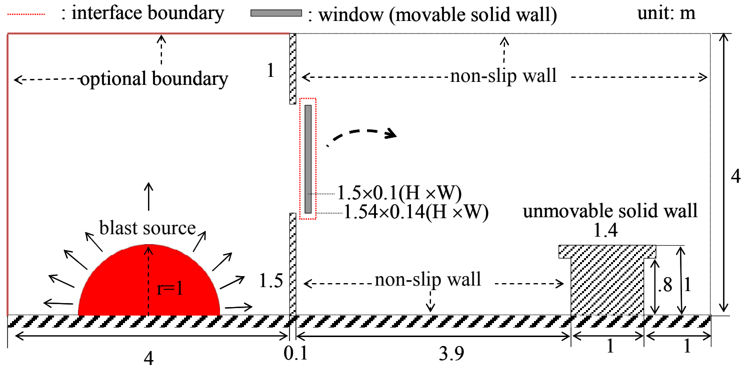


Figure 5 schematic illustration of blast explosion in a two-room factory (left is workshop and right is office)

Table Description of optional boundary conditions in workshop

boundary	Case 1	Case 2	Case 3	Case 4
top	non-slip wall	non-slip wall	ambient	Ambient
side	non-slip wall	Ambient	non-slip wall	Ambient

Serial images of velocity vectors in Case 4, where both optional conditions are ambient, are represented to describe the flow structure, interactions between blast wave and window, and the movement of window, as shown in Fig. 6. Initially, the semicircle blast wave propagated radically from the left workshop. The blast wave passed through the central space of partition and impacted on the table and top wall in the office during the time when the window was pushed and moved to right side, as shown in Fig. 6(a). Meanwhile, part of blast energy had run out through top and left sides. Fig. 6(b) shows the window was impacted by both incident blast and reflected flow from the right wall at 19 ms. Then it was turned reversely by the reflected flow from the lower partition and right wall, as shown in Fig. 6(c). The window still turned counclockwise and blowed upward, as shown in Fig. 6(d)~(f).

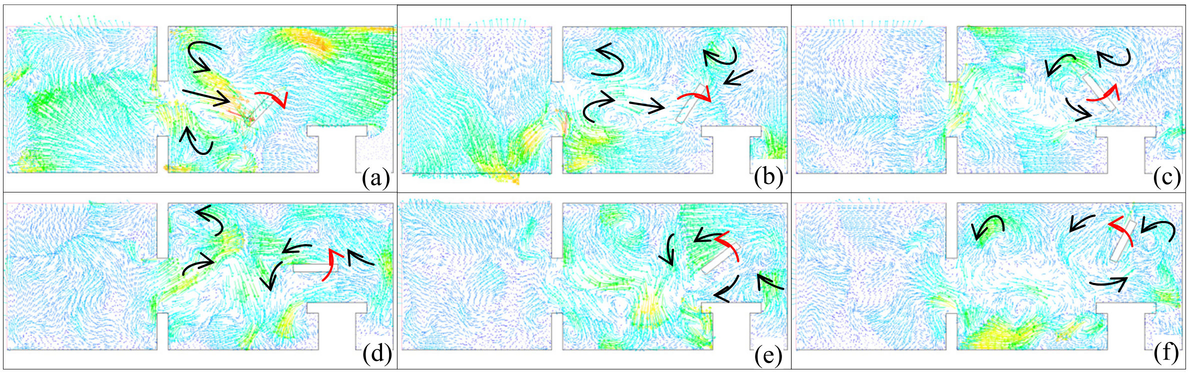
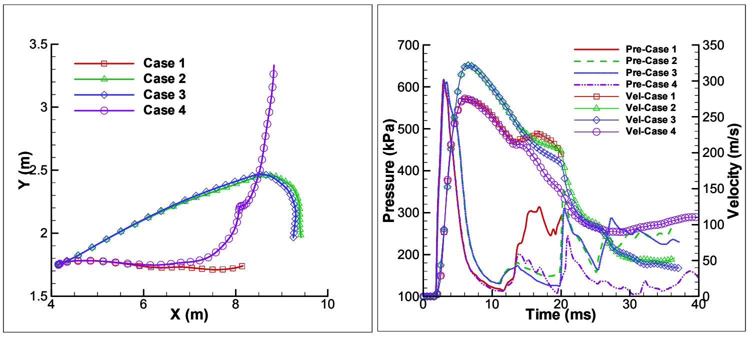


Figure 6 Velocity vectors in Case 4 (a) 14 ms (b) 19 ms (c) 25 ms (d) 29 ms (e) 34 ms (f) 39 ms.

Naturally, the balst effect would be lost while the boundaries are ambitent. Otherwise, the reflected wave would passed through the central space and enlarged the impact in the office. The window crashed on the table directely by the strong blast wave and reflected wave from workshop, as shown in Fig. 7(a). The moving velocities in Case 2 and Case 3 are faster than others because that the reflected wave effect is stronger from workshop while it was counteracted in Case 1 and lost in Case 4, as shown in Fig. 7(b). Actually, the persons would be hurt and the facility would be damaged seriously in this office if they were there.



(a) g.c.- t histories (b) p-t and v-t histories

Figure 7 blast loads on window indoors

6 Conclusions

To conclude, the numerical method with unsteady-state and moving mesh system has been developed and it has demonstrated to provide a promising tool to simulate the more complex flow fields. In these simulations, the results presented the behaviors of the blast loads via the flow structure and phenomena of impacting, interaction and reflection. Meanwhile, the impact scale and body movement were influenced by the boundary conditions in a factory.

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