Numerical Study on the Process of Fixed-axis Rotation of Object Under Action of Shock Waves

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1 Abstract

When the explosions occur, the force is applied to the peripheral objects by the shock wave and causes the movement of objects. However, the object motion in flow field is a large-displacement transient process, in which the coupling problem between object motion and flow field is also considered. Even when the object being studied interacts with other objects, various constraints need to be considered. In this paper, the numerical study of fixed-axis rotation of object on the ground under action of shock waves is carried out. The weak coupling algorithm is used to solve the coupling problem between flow field and object motion, and the displacement constraint is applied to object to achieve the constraint between object and ground. The force and object motion at different height of gravity center and positive pressure time are analyzed, and the flow field around object is studied. The results show that the variation laws of rotation speed of object at different height of gravity center are consistent, and the laws under different positive pressure time have some similarities. It is also the case with aerodynamic forces of object along the direction of inflow and perpendicular to ground.

2 Introduction

In daily life, explosive products are prone to explosions due to improper management or storage, and lead to various accidents [4]. Huge force is often applied to ambient objects by the blast wave and causes the motion of objects. However, due to the complexity of such problems, related research is scarce.

On the problems of shock waves rounding obstacles, domestic and foreign experts have invested a lot of energy [1]~[3]. At present, most of the researches on the problems involving shock waves in literature are the propagation of shock waves, and some also study the deformation of structures under action of shock waves [5], but there are few studies on the force and motion of objects induced by shock waves. The object motion caused by shock waves is a coupling problem with complicated flow. Moreover, objects in life usually interact with ambient objects, so the constraints on the objects need to be considered in the calculation process.

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In this paper, the numerical simulation of fixed-axis rotation of object on the ground under action of shock waves is carried out. The weak coupling algorithm and displacement constraint are used to solve the coupling problem between flow field and object motion and the constraint problem between object and ground separately. The force and object motion at different height of gravity center and positive pressure time are studied, and the change law of flow field around object is analyzed.

3 Computational Model and Numerical Method

The object motion caused by shock waves is quite complicated. The object may slip on ground, may rotate, or may leave ground. In this paper, the object motion is simplified. The bottom edge of leeward side of object is assumed to be hinged to ground so that the object can only rotate. Fig. 1 shows the section diagram of calculation model. The total mass m of object is 15T, and its length, width and height are respectively 2.2m, 2.5m and 4.5m, that is, $a = 2.2$m and $c = 4.5$m.The h represents height of gravity center. In order to study the influence of h on motion and force of object, h is respectively 1m, 1.25m, 1.5m and 2m.

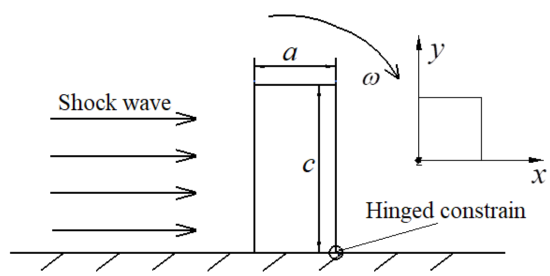


Figure 1. The section diagram of computational model

The shock wave is a spherical wave when it propagates in free fields. In order to reduce calculation amount, it is assumed that the object is far away from explosion source. In this condition, the explosive blast can be approximated as plane wave. The inlet and outlet of calculation domain uses pressure inlet boundary condition and pressure outlet boundary condition respectively, and the object is 15m away from the former. The overpressure of shock wave at inlet of calculation domain is 2Mpa, and the positive pressure time $\Delta\tau$ is respectively 10ms, 20ms, 40ms, and 60ms.

When object is in contact with the ground, some of their boundaries are fused, but when the object is rotated, the boundaries will separate. The problem is usually difficult to solve and may even lead to the termination of calculations. To solve this problem, the minimum distance between object and ground is limited to ΔL. Once the distance between the object and the ground is less than ΔL, the motion of the object is limited to prevent contact with the ground and the problem of boundary fusion or separation. Herein, ΔL is 0.02m. In addition, once the rotational angle of object reaches 90°, the calculation will be terminated.

During the calculation, the force generated by shock wave will cause motion of object, and the object motion will affect flow field. This is a process of intercoupling. In this paper, the weak coupling algorithm is used to solve the coupling problem. The weak coupling algorithm analyzes flow field and object motion separately. After flow field is computed, the object acquires aerodynamic forces and moments from coupled region and motion equation is solved, and then its velocity or displacement is fed back into flow field to change boundary conditions of flow field. Repeated iterations like this. Due to large displacement of object, the mesh in flow field will be greatly affected, so spring smoothing and mesh reconstruction techniques are used to update the mesh, and the mesh adaptive method is used to properly encrypt the mesh.

Based on unsteady three-dimensional Euler equation, the gradient is interpolated by the node-based Green-Gauss method. Space and flow term are discretized with Roe—FDS flux scheme and second-order upwind scheme separately.

In order to verify the grid independence, numerical simulation is carried out for the working conditions with a positive pressure action time of 60ms and a grid number of 800,000, 2.1 million and 3 million, respectively. The calculation results show that 2.1 million grids can meet the required accuracy.

4 Calculation Results and Analysis

Figure 2 shows the variation of object's rotational speed ω over time when h is respectively 1 m and 2 m. As can be seen from Fig. 2, when h is constant, the variation law of rotational speed over time under different positive pressure time has some similarity. After the shock wave encounters object, ω increases continuously in short time, and the longer the positive pressure time, the faster the speed increases. After a period of time, the change law of ω over time is approximately linear law. In addition, when $\Delta\tau$ is constant, the variation law of ω over time under different height of gravity center has consistency, but the higher the height of gravity center, the greater the rotation speed.

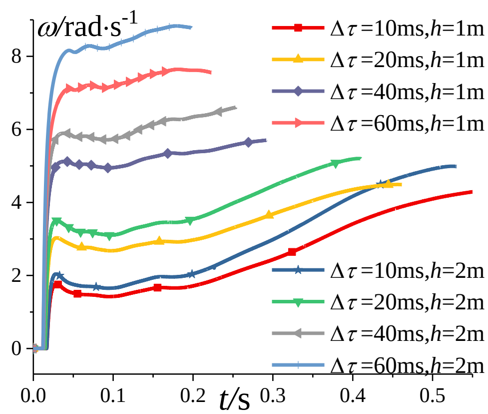


Figure 2. The change curves of rotational speed ω

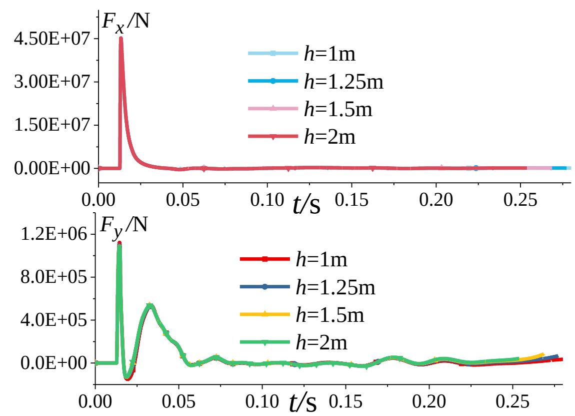


Figure 3. The change curves of F_x and F_y when $\Delta\tau = 40$ms

Fig. 3 shows the change curves of the component F_x in the x direction and the component F_y in the y direction of aerodynamic force applied to object at different height of gravity center when $\Delta\tau = 40$ms. As can be seen from Fig. 3, when $\Delta\tau$ is constant, the variation law of F_x and F_y over time under different height of gravity center has consistency. After the shock wave encounters object, the F_x reached the peak in an instant and then decreases rapidly, but the decreasing speed is getting smaller. On the other hand, the curve of F_y oscillates continuously, but after a time, its value remains fairly constant.

Fig. 4 shows the change curves of F_x and F_y when $h = 1$m. As can be seen from Fig. 5, the change law of F_x and F_y is similar under different positive pressure time. The longer the positive pressure time, the larger the oscillation amplitude of curve of F_y.

As can be seen from Fig. 3~4, within the time t_1 when the shock wave encounters object to a certain time t_2, the values of F_x and F_y are large, and the motion of object is greatly affected, but after t_2, the motion of object is less affected by both. In $t_1 \sim t_2$, the effect of F_x is far greater than that of F_y in terms of the momentum generated by aerodynamic forces on objects. Therefore, F_y can be ignored when analyzing the motion of object.

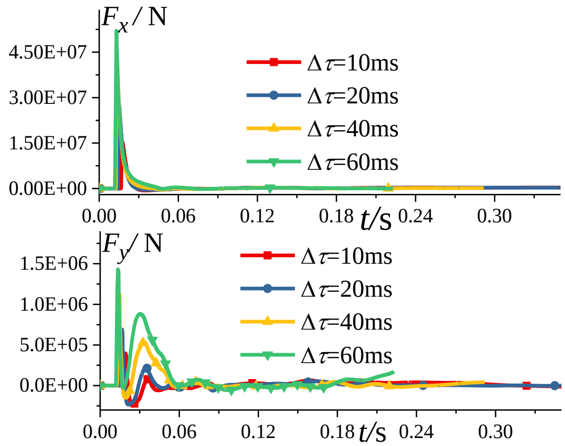


Figure 4. The change curves of F_x and F_y when h=1m

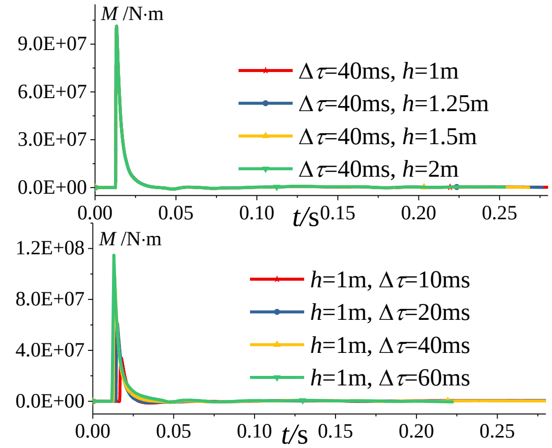


Figure 5. The change curves of M

Fig. 5 shows the change curves of moment M with respect to the fixed axis on the condition of $\Delta\tau = 40\text{ms}$ or $h = 1\text{m}$. As can be seen from Fig. 5, at the same condition, the variation law of M is consistent with the change law of F_x.

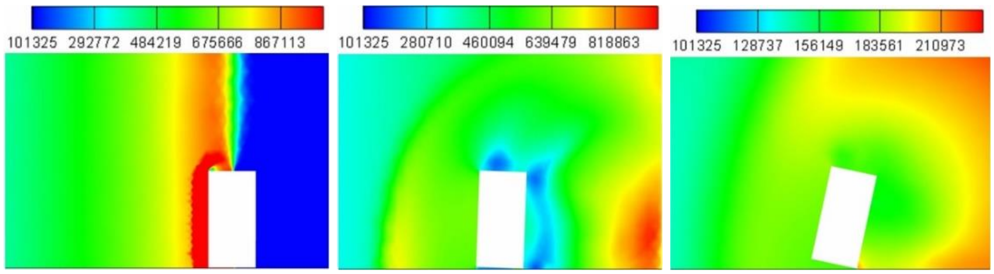
Under different positive pressure time and height of gravity center, the motion and force laws of object have similarities. When the flow field around object is analyzed, we can only take one of the simulations for analysis. In this paper, the simulation with the condition of $\Delta\tau = 40\text{ms}$ and $h = 1\text{m}$ is used to analyze the flow field around object. Moreover, under the same condition, since F_x has a much greater impact on object motion than F_y, this paper only analyzes the variation law of F_x.

Figure 6 shows the pressure distribution around object on the symmetrical plane at different moments.

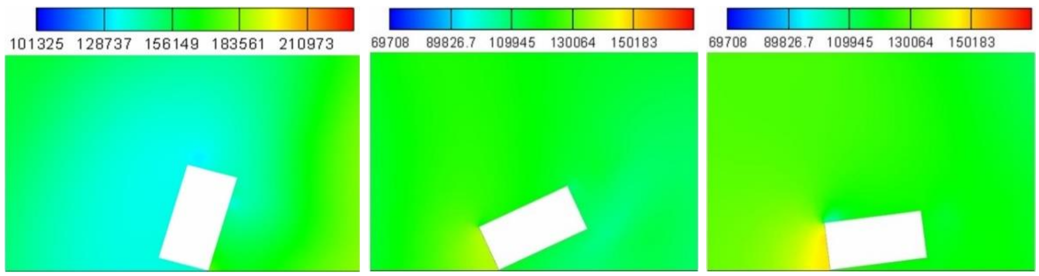
As can be seen from Fig. 6(a), when the shock wave collides with the windward side of object, the phenomenon of normal reflection occurs, and a high pressure region is formed near the windward side, so that the F_x rapidly increases to its peak in a short time. As can be seen from Fig. 6(b), the high pressure region forms pressure difference with surrounding region, resulting in flow of gas and generation of sparse waves. The sparse wave propagates rapidly from the edge of high pressure region to its interior and causes a rapid drop in pressure wherever it goes, resulting in a rapid drop in F_x from the peak. However, as the wave velocity of sparse wave near windward surface decreases, the decrease of pressure in high pressure zone becomes slow, which makes the speed of decrease of F_x smaller. Due to the inertia, when the pressure in high pressure zone near windward side is less than surrounding pressure, the gas continues to diffuse, so that the value of aerodynamic force on windward side is further reduced. As can be seen from Fig. 4, when the positive pressure time is short, the value of F_x will even be less than zero.

As can be seen from Fig. 6(c), the pressure near windward side is relatively high, resulting in an increase in F_x. As can be seen from Fig. 6(d), the pressure near windward side will gradually decrease, while the pressure near leeward side is relatively large, which makes the value of F_x gradually decrease. This change in pressure near windward and leeward side causes the curve of F_x to oscillate.

As can be seen from (e) and (f) in Fig. 6, with the reduction of pressure of inflow and the rotation of object, the change of pressure around the object is small, but the area of windward side will change, making the F_x curve change slowly. At this time, the value of F_x is mainly related to rotation angle of the object.



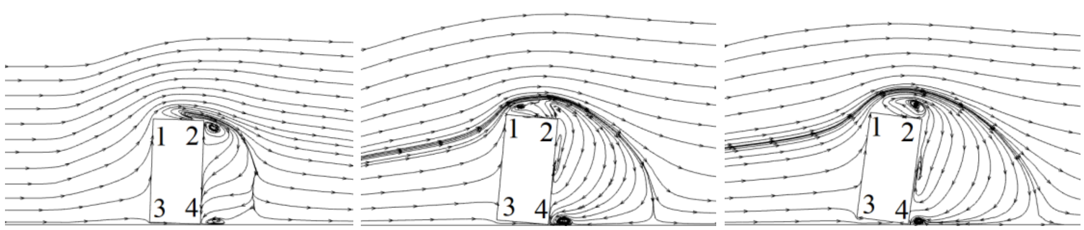
(a) t=0.014s (b) t=0.023s (c) t=0.058s



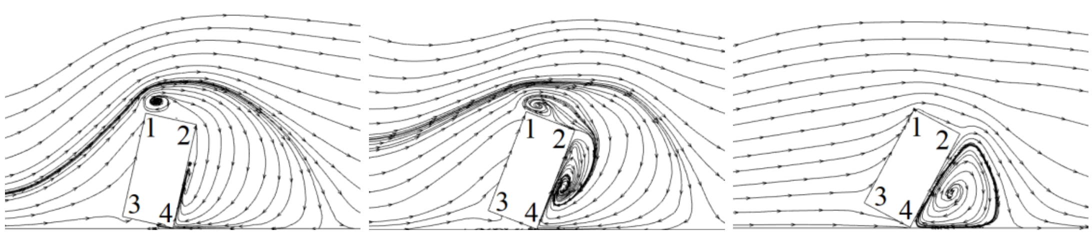
(d) t=0.071s (e) t=0.23s (f) t=0.29s

Figure 6. Cloud picture of pressure distribution around object at different moments

The aerodynamic force changes greatly only when the shock wave passes through the object, so this paper only analyzes the streamline distribution within the first 0.12s. Figure 7 shows the distribution of streamline around the object on the symmetrical plane of the flow field at different moments.



(a) t=0.023s (b) t=0.034s (c) t=0.042s



(d) t=0.06s (e) t=0.089s (f) t=0.114s

Figure 7. Distribution of streamline around object at different moments

According to (a) ~ (d) in Fig.7, when shock wave passes through the object, the detached vortices will be formed alternately near corner 1 and corner 2. As can be seen from (d) ~ (e) in Fig.7, with the decrease of pressure of incoming flow, the detached vortex near corner 4 will gradually disappear, while strong detached vortex will be formed in corner 1 and the leeward surface of object. As can be seen from (f) in Fig.7, the detached vortex near corner 1 gradually disappears, while the detached vortex near the leeward side gradually expands and is away from the object. The existence of detached vortices near the object cause the pressure around object to change greatly, which leads to the oscillation of aerodynamic force.

5 Conclusion

In order to numerically simulate the fixed-axis rotation of object on the ground under the action of shock waves, the weak coupling algorithm is used to solve the coupling problem between flow field and object motion, and the displacement constraint is applied to the object to realize constraint between object and ground. Some useful conclusions can be drawn:

(1) The variation law of rotation speed curves of object with time under different height of gravity center has consistency; the variation law of rotation speed curves of object with time under different positive pressure times has some similarity.

(2) The variation of the component in the direction of inflow and the component in the direction perpendicular to ground of aerodynamic forces applied to the object with time at different height of gravity center is consistent; their variation with time is similar under different positive pressure time.

(3) The greater the positive pressure time, the greater the oscillation amplitude of the curve of the component in the direction perpendicular to ground of aerodynamic forces applied to the object.

(4) For aerodynamic forces applied to the object, the component in the direction of inflow is much larger than the component in the direction perpendicular to ground, so the latter can be ignored when the motion of object is analyzed.

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