Numerical Simulation Optimization of Mach Reflection of Near Ground Air Explosion

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Abstract. In order to optimize the numerical simulation method of Mach reflection, three numerical simulation schemes of ALE method, LBE method and coupling method are compared based on the finite element analysis software LS-DYNA. The calculation results are compared with the test data of UFC 3-340-02 manual and related literature, and internal comparison is made to put forward the numerical calculation optimization scheme of Mach reflection. The results show that the calculation results of the three schemes are in good agreement with UFC 3-340-02 and test results. When only Mach reflection is considered on a single surface, LBE method is selected. The coupling method and ALE method are selected when considering the interaction of shock wave between non ground objects. When the object is completely or mostly in the Mach reflection region, the calculation time of the coupling method is only one sixth of that of the ALE method. When the effect of the object on the air flow field is strong and the area in the Mach reflection region is small, ALE method is selected.

1. Introduction

Shock wave is a kind of strong compression wave, which is one of the main factors that ammunition explosion causes damage to personnel, equipment and protective structure. According to whether the incident angle of shock wave reaches the critical incident angle $\alpha_c$, the reflection of shock wave can be divided into three types: normal reflection, regular reflection and Mach reflection\cite{1}. Liao Zhen and Tang De Gao\cite{2} used the multi material algorithm in AUTODYN to build a 2D axisymmetric model to simulate the Mach rod produced by near ground explosion and analyzed the propagation law of Mach wave and the variation law of shock wave parameters of Mach stem. Du HongMian et al.\cite{3} used the interpolation algorithm "V4" in MATLAB to analyze and verify the propagation characteristics of air and ground shock wave. Yao Chengbao and Wang Hongliang\cite{4} established a two-dimensional multi-media fluid numerical method based on Euler coordinate system, which can simulate the strong shock wave with high density ratio and high-pressure ratio, obtaining the distribution of reflected overpressure, impulse and other shock wave loads in a large scale from the projection point of the explosion center on the ground.

Because Mach reflection occurs after regular reflection, which is far away from the explosion point and includes the interaction between shock wave and the ground, the numerical simulation of Mach reflection is difficult. In order to carry out more efficient numerical simulation of Mach reflection, this paper lists three methods to simulate Mach reflection based on LS-DYNA, and compares the simulation results UFC 3-340-02\cite{5} manual, test data\cite{2} and strength theory reference formula\cite{1} to verify the
rationality of the experimental results. At the same time, the calculation efficiency of three numerical simulation methods is compared, and the best scheme of Mach reflection numerical simulation under different conditions is given.

2. Numerical simulation of Mach reflection of near ground air explosion

2.1. Calculation condition and material model
In order to compare the numerical simulation results with the experimental results, the calculation conditions in reference 1 are selected to simulate the near ground air explosion. The TNT equivalent is 1.17kg, and the height from the ground is 1.5m. Air material selection MAT_Null, EOS_LINEAR_POLYNOMIAL is used to define the initial energy state of the air domain. The internal pressure of air can be expressed as

\[ P = C_0 + C_1 \mu + C_2 \mu^2 + C_3 \mu^3 + \left( C_4 + C_5 \mu + C_6 \mu^2 \right) E_0 \]  

where \( C_0, C_1, C_2, C_3, C_4, C_5, C_6 \) is constant, \( \mu \) is the gas density, \( E_0 \) is the internal energy per unit volume. Explosive material selection MAT_HIGH_EXPLOSIVE_BURN. The internal energy parameters of burn are defined by EOS_JWL equation

\[ P = A \left( 1 - \frac{\omega}{R_1 V} \right) e^{R_1 V} + B \left( 1 - \frac{\omega}{R_2 V} \right) e^{R_2 V} + \omega E \]  

The material parameters and equation of state parameters related to air and explosives are shown in the following table:

| Material          | Unit (mm, t, s) | MAT_NULL       | EOS_LINEAR_POLYNOMIAL | MAT_HIGH_EXPLOSIVE_BURN | EOS_JWL          |
|-------------------|----------------|----------------|-----------------------|-------------------------|-----------------|
| Air               |                | RO PC MU       | C₀ C₁ C₂ C₃ C₄ C₅ C₆ E V₀ | RO D PCJ             | A B R₁ R₂ OME G E₀ V₀ |
|                   | 1.23E-12       | 0 0            | 0 0 0 0 0.4 0.4 0.25 1 | 1.63E-9 6.93E6 2.1E4   | 3.75E5 3750 4.15 0.9 0.35 4300 1 |

2.2. Finite element model of ALE method
In order to improve the calculation accuracy and reduce the amount of calculation, 2D modeling method is adopted in the three modeling schemes. To realize the numerical simulation of ALE method, the air domain model with the size of 11000mm × 5000 mm is established. Symmetrical boundary conditions are set at the boundary of charge center, and reflection boundary is set at the bottom. To define multi material combination to fill the explosive to the designated position in the air domain, INITIONAL_VOLUME_FRACTIONAL_GEOMARTY so as to avoid independent modeling of TNT and improve the modeling efficiency. The result shows that the convergence is good when the grid size of air domain is 10 mm.
2.3. Finite element model of LBE method
LOAD_BLAST Enhanced a keyword used to load shock wave in LSDYNA. The biggest advantage of this keyword is that it doesn't need to establish the air domain, and the load acts on the segment directly, which greatly reduces the workload. LBE method has been widely used in the direct interaction between shock wave and target segment in infinite air domain. The calculation of overpressure and duration of shock wave is realized by calling TM5-855 test data programmed into CONWEP program and loaded on the user selected segment. For the numerical simulation of Mach reflection, blast = 4 is selected, and the ground node normal vector are selected. LBE method is used to calculate only the single action of shock wave and each selected target and does not calculate the reflection of shock wave between targets, therefore, the target steel plate is established as the overpressure monitoring objects. The detection position is shown in the following figure 2.

2.4. Finite element model method coupling LBE and ALE
Although the LBE method is very simple and easy to load, it can only calculate the interaction between shock wave and single object surface, and it cannot simulate the reflection of shock wave between multiple objects. Therefore, the LBE loading mode can be coupled with ALE algorithm in order to use the simplest loading mode to load the Mach reflection. At the same time, the mesh of non-Mach reflection region is omitted to save computing time. To compare the calculation time and calculation accuracy with ale modeling method, set the mesh size to be also set as 10 mm, and the model is shown in the following figure. In order to make ale air grid receive the Mach reflection load loaded by LBE, a layer of element should be set up near the blast facing element and should be set as ambient layer. Because the distance between the formation position of the Mach stem and the horizontal distance of the detonation center is about 3 m, the air region after 3 m has been established, which reduces the modeling workload compared with the ALE method.
3. Comparison of numerical simulation results of Mach reflection

3.1. Numerical simulation results of Mach reflection
The calculation shows that the solution time of ALE method is 85 min, that of coupling method is 14 min, and that of LBE method is 5 min. The Mach rod overpressure of ALE method, coupling method and LBE method is shown in the figure below.

Figure 4  Mach reflection overpressure of ALE method (L represents the horizontal distance from the blasting center)
Figure 5 Mach reflection overpressure of coupling method

Figure 6 Schematic diagram of Mach reflection area of LBE method

It can be observed from the trace of three wave points that the waveforms of incident wave, reflected wave and Mach wave obtained by the coupling method are relatively clear, which is easy to get the change of Mach stem height. The ALE method considers the interaction between explosive and air domain at each time, which is greatly affected by the input physical parameters, resulting in the complexity of air domain data. Before 6 meters from the charge center, the shape of Mach stem of ALE method is clear, but the interface between irregular reflection area and regular reflection area is fuzzy at 6-8m. In the coupling method, the LBE keyword is applied to the explosion load by calling the test data of COMWEP program, which ignores the stiffness and inertia effect of air, thus simplifying the interaction between explosive and air domain, and concentrating the load calculation near the Mach stem.
3.2. Comparison of numerical simulation results of Mach reflection
The simulation results are compared with the theoretical curve in UFC 3-340-02 and the experimental curve in the reference, and the results are shown in the figure. It can be seen from the figure that the height of three wave points of three methods are in good agreement with UFC 3-340-02 and reference experimental results. The test curve is on the low side after 5m from charge center. This is because the actual ground material parameters in the experiment is different from those assumed in CONWEP program, resulting the conversion coefficient \( w_e \) of shock wave after interaction with the ground is different. In addition, there are errors in the layout of the measuring points and the measuring instruments, which leads to the slightly lower trace of the three wave points.

![Figure 7](image)

(a) Comparison of numerical simulation results of Mach reflection (figure a represents the comparison of three-point wave trace between simulation results and experiment, figure b represents the comparison of Mach stem overpressure)

On the basis of experiments, J. Henrych obtained the formula of peak overpressure in infinite air explosion \( P_{\text{max}} \) of ground explosion

\[
R = \frac{0.0662}{Z} + \frac{0.405}{Z^2} + \frac{0.3288}{Z^3} \quad (1 \leq Z \leq 10)
\]

where \( Z \) is the ratio of the distance \( R \) from the explosion point to the structure to the mass of TNT \( W \). When the existing ground blocks the shock wave, the shock wave only propagates to half of the infinite space. If the ground is rigid, \( W_e = 2W \) can be brought into the above formula, to get the ground burst overpressure \( P_{\text{MGR}} \). However, in real experiment, the ground is not rigid, so the blocking situation of shock wave can be determined according to different working conditions, that is, the TNT equivalent \( W \) can be changed. The fitting coefficient \( K = \frac{W_e}{W} \) is introduced. The overpressure of Mach stem can be calculated as \( P_{\text{m}} \)

\[
P_{\text{m}} = P_{\text{MGR}} (1 + \cos \phi)
\]

In COMWEP program, the relationship between the TNT equivalent conversion coefficient fitted by J. Henrych formula and the intensity at the highest point of each Mach stem position obtained by numerical simulation of Mach reflection in this paper is shown in the figure. It can be seen from the figure that the fitting coefficient \( K \) is between 1.4 and 1.5, which is in good agreement with the theoretical formula.

4. Conclusion
Based on LS DYNA software, we use ALE method, LBE method and coupling method to simulate Mach reflection of near ground air explosion. The conclusions are as follows:
1. The simulation results of the three methods show that the accuracy of the three methods is high. The three point wave trace of Mach reflection is consistent with the experimental results of UFC 3-340-02 and related literature. The fitting coefficient of Mach reflection intensity needs to be adjusted through the actual working conditions.

2. On the premise of the same element size, the LBE method has the shortest solution time, and the coupling method only takes 1/6 of ALE method, which has higher efficiency.

3. The ALE method takes into account the interaction between explosive and air, the stiffness and inertia effects of air, and the air grid calculation results are more detailed than the coupling method. However, LBE method does not need to establish air domain, so it cannot get the change of flow field. The coupling method can omit the mesh of non-Mach reflection region and reduce the workload of solution.

4. LBE method is selected to check the Mach reflection intensity of a single target.

5. When the reflection of shock wave between non ground targets is considered in the calculation, the range of Mach stem can be estimated by the angle of incidence roughly first. If the range of Mach rod is larger than that of normal reflection and regular reflection, the coupling method is selected to omit the air domain outside the range of Mach stem region and reduce the calculation time. On the contrary, if the most area of the object is in the regular reflection range and needs to consider the negative pressure area and other complex flow conditions, ALE method is selected.

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