An ALE Approach to the Simulation of Perforating Process

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Abstract: Perforation is of great importance to improve the oil and gas wells productivity. This research is to simulate the process of perforating based on the structural characteristics of shaped charge jet and the penetration mechanism. The perforating process is analysed with the Arbitrary Lagrange Euler (ALE) method, including the shaped charge initiation, jet formation, and the nonlinear large deformation. In this paper, the jet shape, pressure and velocity are given, the mechanical behaviour of jet penetrating the casing, cement and rock are described in detail. The simulation model and method used in this research are proved to be reasonable and feasible. The result provides a guidance for the real-time research of perforating process.

1. Introduction
Perforation is the most important completion method, and of great significance to improve the productivity of oil and gas wells. There are many aspects involved in the process of perforating bullet, such as explosive initiation, jet formation to a certain depth of intrusive rock stratum, the formation and propagation of detonation waves, and the strong interaction between detonation waves and metal cartridges. The liner is compressed, deformed under high temperature and high pressure to form a jet. The jet movement is accompanied with an extension. The entire perforating process is a multiphase, multi-material, large deformation, large scale and strong coupling problem. It is complex and the influence factors are numerous, which increases the difficulty of numerical simulation. For example, high-speed jets penetrate the perforating gun wall, wellbore fluid, casing, cement ring and rock mass and the dynamic response of various materials, etc.

Lot of researches have been carried on the numerical simulations of jet formation and jet penetration into the target plate. Lee[1] used 2D Euler numerical method to simulate and analyze the jet formed by different shapes of liner, and carried out optimization design research on perforating bullets. Elshenaway[2] simulated underground rock strata with concrete target plates, and considered the influence of concrete strength and confining pressure. Meanwhile, they used experimental and numerical methods to analyze the penetrating ability of the perforating bullet to the strata. These results have provided the beneficial reference for the related question research[3-5]. This paper introduces the method of simulating the perforating process using the Arbitrary Lagrangian-Eulerian (ALE) method. The shape of jet flow was described, the response and pressure fluctuation of wellbore material were given. For numerical simulation of fluid dynamics and nonlinear solid mechanics, the most important problem is which kind of numerical method should be chose. When the continuous body is deformed, the deformed finite element mesh can still provide accurate material interface and motion boundary to describe the dynamic behavior of the continuous body. The Lagrangian, Eulerian and ALE are the common numerical methods. As shown in Figure 1, ALE method has the advantages of both the Lagrangian and Eulerian methods. It does not have the computational difficulties caused by the Lagrangian's mesh distortion. Meanwhile, it can effectively control and track the movement of the material boundaries. Compared with the Eulerian method, ALE has better computational accuracy.
The ALE method performs one or several Lagrangian steps. At this time, the mesh is deformed according to the flow of the material, and then the ALE time step calculation is performed, which can be divided into two steps: a smooth step and an advance step. The smooth step is used to keep the boundary of the deformed object, re-mesh the interior, and keep the topological relationship of the mesh unchanged. The advection step transports the element variables (mass, energy, stress, etc.) and node velocities in the deformed mesh into the re-mesh.

![Figure 1. Comparison of Lagrangian, Eulerian and ALE methods](image)

**2. Numerical simulation of shaped charge jet formation**

**2.1 Geometric model and grid**

A two-dimensional numerical model of the perforating charge is established, as shown in figure 2, and the main dimensional parameters are listed. In view of the fact that the two-dimensional model in LS-DYNA is not suitable for the multi-material ALE method, we a single-layer solid164 unit planar model (thickness 0.05mm) was adapted. In the whole model, explosives, liner and air are described as ALE multi-substances, and common nodes are used between ALE units. The shell is described by the Lagrangian method, and the element calculation method uses constant stress solid element algorithm. The fluid-structure coupling between ALE element and Lagrangian element was defined with the key word ‘constrained Lagrange in solid’. The model adopts the cm-g-μs system of units. The mesh of the perforating bullet is shown in figure 2. Besides a very small number of triangular prism elements, all elements are hexahedral elements.

![Figure 2. Geometric model and mesh of perforating charge](image)

**2.2 Material model**

Air, explosive and liner adopts single-point multi-material ALE unit algorithm. The explosive is selected from TNT, and the Mat High Explosive high energy explosive material model in LS-DYNA is used. The pressure-volume relationship of explosives is described by JWL equation of state, and the specific parameters are shown in Table 1. The liner material is copper, and this material use the Johnson-Cook material model and match the Gruneisen equation state. The perforating shell is made of 20# low carbon steel and is described by the plastic follower strengthening material model.

| \( \rho \) (g/cm³) | \( D \) (cm/μs) | \( P \) (GPa) | \( A \) (GPa) | \( B \) (GPa) | \( R_1 \) | \( R_2 \) | \( \omega \) |
|-------------------|----------------|--------------|--------------|--------------|---------|---------|-------|
| 1.63              | 0.693          | 27.0         | 374.0        | 3.23         | 4.15    | 0.95    | 0.3   |

![Table 1. Material parameters of explosives](image)
3. Numerical simulation of perforating process

3.1 Jet formation

After the charge is detonated, the explosive detonates within a few microseconds to produce detonation products. Under the action of high pressure from detonation shock and detonation product, the liner is crushed and converges along the axis to form a jet flow. In this process, the liner has typical fluid properties. Figure 3 shows the pressure of the liner at several typical moments.

The detonation wave propagates to the center of the cartridge at \( t=5.9821 \mu s \) during the explosive crushing the liner. The pressure peak of the liner reaches throughout the process, \( P_{\text{max}}=18.54 \) GPa. At this point, a smaller jet head forms. When \( t=13.998 \mu s \), the velocity of the jet head reaches the peak value \( V_{\text{max}}=4400 \) m/s, and the difference in velocity between the jet head and the carrot can be clearly observed. At \( t=13.998 \mu s \), the velocity gradient causes necking due to the existence of the jet. At \( t=22.996 \mu s \), the fracture of jet from the necking is observed. At the moment of \( t=38.999 \mu s \), the crushed liner is all gathered on axis.

3.2 Perforating simulation results

Figure 4 shows that the corresponding pressure contours and velocity contours of several typical penetration stages. At \( t=59.975 \mu s \), the jet penetrates the wall of the perforating gun (the blind hole), and the velocity drops to 1893 m/s. At time \( t=335.98 \mu s \), the jet penetrates the cement and then the speed slows down to 809 m/s. At time \( t=600 \mu s \), the calculation finishes. The jet has completely penetrated into the rock, and the velocity drops to 243 m/s. Penetration capacity is further decreased. The speed of the jet is significantly reduced throughout the penetration process. Especially in the process of penetrating the perforating gun wall, the speed reduces from 4000 m/s to 1893 m/s, and further to 809m/s after the penetration of the cement. This results show that the jet has lost a lot of energy before entering the rock. In order to obtain a perforation tunnel with a large aperture and hole depth, it is necessary to increase the velocity of the jet after passing through the cement.
4. Conclusions

With ALE approach, this paper establishes a numerical model of the entire perforating process and analyzes it, and focuses on the penetration of the jet into the perforating gun wall, casing, cement and rock. Numerical simulation of jet, jet extension and jet fracture in the initiation of perforating projectile is carried out, and several typical moments of jet are described and analyzed in detail.

It is found that the jet is formed at a faster speed, and a jet with a distinct jet head and a carrot can be formed at 20 μs. The speed of jet head can achieve 4400 m/s, and the jet basically loses the penetration ability at 600 μs. This paper verifies the rationality and feasibility of the ALE method for solving the perforating process, and provide a guidance for the real-time analysis of the perforating process.

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