Air blast pressure characteristics of moving charge

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Abstract. Air blast pressure between moving charge and static charge are obviously different, however, due to the limitation of testing means, most blast or impact experiments were conducted under static state, which bring risks to safety of the target structures. In this paper, based on the finite element software and theoretical analysis, we investigated characteristics of the air blast pressure of moving charge. By introduced the toroidal distribution coefficient and radial distribution coefficient, a calculation model, used to calculate the overpressure with scope of relative distance at range of 0.4–2 m/kg1/3 around blast center was established. The model could quickly calculate overpressure distribution around the blast center. Furthermore, isobars lines of moving charge were obtained by solving the model, some other phenomena were also analyzed.

1. Introduction
Shock wave is an important damage element to the target structure. At present, when conducting blast or impact experiments, even numerical simulation on targets, the charge is usually treated as a static explosion source [1-3]. Some important theoretical derivations and calculation models of air blast load at home and abroad were also obtained on the basis of static explosives [4-6]. But in fact, the charges/warheads all explode in a moving state, velocity of the moving charges have momentous effects on blast load, which cause the shock wave front does not show regular distribution, and ultimately affect the damage power of ammunitions. Patterson [7] experimented with C4 explosive and obtained the air blast pressure data, found that the peak air pressure increases along the direction of charge moving, while in the opposite direction, the pressure decreases. By means of numerical simulation, Zhang [8] obtained the air blast pressure-time histories of 100kg TNT moving at 200m/s, and drawn the conclusion that air blast pressure of moving charge has directionality. With the development of supersonic, hypersonic and other high-speed weapons, ammunition researchers and users are more and more concern about the blast load of charge/warheads under motion condition. However, due to limitation of the test means and expenses, the precise blast center of moving charge is not easy to predict, further lead to limited pressure gauges cannot be properly laid out, and finally, we cannot obtain more air blast data in process of the shock wave propagation, which brings risks to determine the blast load and safety of the target structure.

In this paper, the finite element software Autodyne was used to simulate moving charge blast in air. According to analysis of the distribution characteristics of blast overpressure, a simple model for
calculating the peak air pressure on moving charge was established, which is of great significance in further engineering application.

2. Numerical model

2.1. Numerical model and material model
Shock wave propagation in the air related to many factors. In order to better reveal the characteristics of airblast pressure in motion, spherical charge was used in numerical simulation on TNT charge. Assuming that air blast has the same path along any direction of the sphere, a 2D axisymmetric model was established, as shown in figure 1. OB is the symmetrical axis, and the direction of charge moving. The air domain is 6m long, 3m wide. Using the multi material Euler algorithm, ideal gas state equation and JWL were used for air and TNT respectively [9], the specific parameters are listed in table 1. No reflection boundary was set to simulate infinite air region.

![Simulation simulation model.](image)

**Figure 1.** Simulation simulation model.

| Material | Autodyn material property input data and EOS input data (unit = cm, g,us) |
|----------|--------------------------------------------------------------------------------|
| TNT      | RO D PCJ                                                                 |
|          | 1.63 0.693 0.21                                                                 |
|          | EOS-JWL                                                                 |
|          | A B R1 R2 OMEG E0 V0                                                      |
|          | 3.74 0.0375 4.15 0.9 0.35 0.06 1                                          |
| Air      | RO PC MU                                                                    |
|          | 1.23E-3 0 0                                                                |
|          | EOS-Ideal gas                                                               |
|          | T γ E0 Specific Heat                                                        |
|          | 288 1.4 2.068E-6 7.2E-6                                                    |

The charge moves along OB direction, and O point is the blast core. We define OB is 0° direction, then OB is in 180°. ApA’ and BpB’ are semicircles centered on O, with OA = 1m and OB = 3m. Pressure measurement points are set between two semicircle regions, any point coordinate can be expressed by \((\theta, \bar{z})\), where \(\bar{z} = z/AB\).

2.2. Mesh density studies
Mesh density has great influence on results of numerical simulation [13,14]. In order to select appropriate mesh density, four different mesh sizes, respectively 0.6cm, 1cm, 2cm and 3cm, were used
to divide the grid. The peak pressure data of 11 measuring points in the range of 0.25-1.5 m/kg$^{1/3}$ were compared with those calculated by Henrych [15] empirical formula (see equation 1).

\[
\begin{aligned}
    P &= \frac{1.379}{R} + \frac{0.543}{R^2} + \frac{0.035}{R^3}, \quad 0.05 \leq \bar{R} \leq 0.3 \\
    P &= \frac{0.607}{R} - \frac{0.032}{R^2} + \frac{0.209}{R^3}, \quad 0.3 \leq \bar{R} \leq 1 \\
    P &= \frac{0.065}{R} + \frac{0.397}{R^2} - \frac{0.322}{R^3}, \quad 1 \leq \bar{R} \leq 10
\end{aligned}
\]  

(1)

\[\text{Figure 2. Variation of overpressure with relative distance under different model mesh sizes.}\]

Figure 2 shows the overpressure histories at different relative distances of different mesh densities. As shown, under different mesh densities, the overpressure decreases exponentially with the increase of relative distance. When mesh size is less than 0.5 cm, the overpressure relative distance history is close to that fitted by Henrych formula. Therefore, the air domain is fixed at 0.5cm × 0.5cm.

### 2.3. Verification of numerical model accuracy

Armendt [16] had carried out blast test of moving charge with 0.1701 kg B explosive, at 0.826 m away from the blast core, three measure points with moving direction of 15°, 45° and 105° were arranged, and finally obtained the overpressure and impulse data, Jiang [17] had validated the accuracy of [16]. In this paper, we use method of [17] to verify accuracy of the numerical model, results are shown in table 2. Numerical simulation results are basically in agreement with the experimental data, and maximum deviation is within ±15%. Considering error of the experiment itself, it shows that the numerical model can be used to simulate the blast of moving charge.

\[\text{Table 2. Verification results of numerical model accuracy.}\]

| $R$/m | $\bar{R}$/m.kg$^{1/3}$ | $\theta$/° | $P$ / kPa | Deviation / % | $I$ / Pa.ms | Deviation / % |
|-------|-----------------|---------|---------|--------------|-----------|--------------|
|       |                 |         | Test     | Sim.         | Test      | Sim.         |
| 0.826 | 1.5             | 15      | 627.45  | 609.1        | 3.01      | 70.33        | 78.63        | 10.56        |
|       |                 | 45      | 565.39  | 566.18       | 0.14      | 67.57        | 72.42        | 6.7          |
|       |                 | 105     | 361.99  | 368.33       | 1.72      | 54.47        | 55.37        | 1.63         |

### 3. Numerical simulation results

#### 3.1. Comparison of airblast pressure contours between moving and static charge

Figure 3 shows airblast pressure contours over times with 8 kg charge and velocity of 800 m/s and 0 m/s. We can see, (1) the shock wave front of moving charge still diffuses around in the form of spherical wave, (2) under static condition, shock front in entire circumferential is regular symmetrical, while in moving condition, the pressure at the shock front appears a local high pressure area near $\theta$° direction, and with the increase of $\theta$, the pressure decreases gradually, (3) the center of shock front of static charge coincides with
the detonation core, while that of moving charge shifts in the direction of velocity.

![Figure 3](image)

**Figure 3.** Comparison of airblast pressure contours between moving and static charge.

### 3.2. Effect of TNT mass on moving charge

The intensity of airblast pressure is controlled by relative distance $\bar{R}$ (m/kg$^{1/3}$), by adjusting TNT mass, we can obtain airblast pressure data of moving charge at different relative distances. In this section, with charge moving velocity of 800 m/s, TNT mass of 3.5 kg, 6.8 kg, 8 kg, 10.4 kg and 15 kg, we obtained moving charge air blast overpressure data at different relative distance. In range of 1m to 3m, the relative distance with different explosive mass is among 0.4~2 m/kg$^{1/3}$. 

![Graph 1](image)

![Graph 2](image)
Figure 4. Shock wave pressure time histories at $\bar{z}=0.1$, with different $\theta$.

Figure 5. Shock wave pressure time histories at $\theta=60^\circ$, with different $\bar{z}$. 
Figure 4 shows the shock wave pressure time histories of diverse mass moving charge at $z=0.1$, $\theta = 0^\circ$, $60^\circ$, $90^\circ$, $150^\circ$ and $180^\circ$. We see that, at position with the same $z$ and $\theta$, overpressure decreases with the decrease of TNT mass. At position with the same distance but different toroidal angles, the shock wave pressure time histories of each moving charge are similar, with the increase of toroidal angle, the overpressure of each moving charge decreases and arrival time increases. At the same $z$ but different $\theta$ position, peak air pressure along the direction of charge motion is the largest, which is consistent with the results seen from airblast pressure contours. In addition, with increase of the toroidal angle, the disparity of shock wave arrival time between different moving charges increases.

Figure 5 shows the shock wave pressure time histories of diverse mass moving charge at $\theta=60^\circ$, $z=0.1$, $0.3$, $0.6$, $0.8$, $1$. The figures show at position with the same toroidal angle but various radial distances, the shock wave pressure time histories of each moving charge are similar. With increase of $z$, the shock wave peak pressure of each moving charge decreases and arrival time increases, the changing trend is similar to that of static charge.

In order to display the shock wave overpressure variation tendency of moving charge more intuitively, the curves of shock peak pressure versus toroidal angle at the same relative distance for diverse mass moving charge and at different relative distance for 15kg moving charge are respectively shown in Figure 6(a), (b). Along OB axis, overpressures are symmetrical, and generally decrease in the range of $0\sim180^\circ$, however, the reduction rate varies in different angle region, which shows a trend of slow change into $35^\circ$, then quickly reduce, and finally decreasing slowly. The trend for diverse mass moving charge at the same radial distance and different radial distance for 15kg moving charge is consistent.

![Figure 6](image)

(a) At the same radial distance for diverse mass moving charge. (b) At different radial distance for 15kg moving charge.

**Figure 6.** The curves of shock wave peak pressure versus toroidal angle.

### 4. Results analysis and discussion

#### 4.1. Theoretical formula

The basic relationships between shock front velocity $u$ and overpressure $P$ can be got on the basis of Rankine-Hugoniot equation 2.

$$\frac{P}{P_0} = \frac{2}{\gamma+1}\left(\frac{u^2}{c_0^2} - 1\right)$$

Where $P_0$ is the atmospheric pressure, $\gamma$ is the air specific heat and $c_0$ is acoustic speed. The peak blast pressure of moving charge could be obtained from:

$$\frac{P_m}{P_s} = \frac{u_m^2 - c_0^2}{u_s^2 - c_0^2}$$

$P_m$ and $P_s$ are peak blast pressure of moving charge and static one, separately; $u_m$ and $u_s$ are shock front velocity of moving charge and static one, respectively.
Figure 7. Dynamic blast wave model of moving charge.

Figure 7 shows the dynamic blast wave model of moving charge, \( R \) is the distance from shock front to the detonation core, \( r \) is the radius of the shock front and \( d_r \) is the shock front center displacement. \( \alpha \) and \( \theta \) are angles shown in the figure. Adopted the conclusion drawn by Armendt [16], the shock front velocity of moving charge \( u_m \) could write as:

\[
u_m = u_s + v_r\quad (4)
\]

\( v_r \) is movement speed of shock front center. Consider now, the momentum of moving charge before and after blast is conserved,

\[
m_e v_e = (m_e + m_{air})v_r = \left( m_e + \frac{4}{3} \rho_{air} r^3 \right) v_r\quad (5)
\]

or

\[
v_r = \frac{m_e v_e}{m_e + \frac{4}{3} \rho_{air} r^3}\quad (6)
\]

Where \( m_e \) is the explosive mass, \( m_{air} \) is air mass contained in the shock front and \( \rho_{air} \) is the air density. On basis of the geometric position of figure8(a), the following formula can be added.

\[
r = (R^2 + d_r^2 - 2Rd_r \cos \alpha)^{1/2}\quad (7)
\]

\[
\cos \alpha = \frac{rcos \alpha + d_r}{R}\quad (8)
\]

Under static blast state, \( v_r = 0 \); When moving, along the motion direction or \( \alpha \) is in small angle, \( v_r \) has the enhancement effect on shock front velocity \( u_m \), then \( u_m > u_s \), peak blast pressure increases; With the enlargement of \( \alpha \), the increment of overpressure decreases. When \( \alpha \) is larger than a critical value, the vector component of \( v_r \) in \( \alpha \) direction is opposite to that in \( u_s \) direction, where, \( u_m < u_s \), peak blast pressure diminishes. Moreover, equation(2)–equation(8) show the charge moving velocity \( v_e \), \( \alpha \) and \( R \) are the key parameters affecting peak blast pressure, as \( d_r \) obtained, \( v_e \) would be ascertained, the peak pressure at a point on the shock front can be calculated.

4.2. Displacement of shock front center

Figure 8. The shock front center displacement time histories.
Figure 8 shows shock front center displacement time histories of diverse mass moving charge with velocity 800 m/s. As shown, affected by the velocity of charge motion, the shock wave field will still move along the motion direction after explosive blast and present various stages. In the first stage, the initial period after detonation, the shock wave field moves fastly, approximate to linear growth. Later, in pace with the shock wave front expands along a spherical diameter, the moving velocity of shock wave front center decreases gradually, and leads to the displacement $d_t$ increases gradually, which we called the second stage. Besides, with the increase of charge mass, the curve of shock wave front center versus time moves upward, that is, the displacement $d_t$ increases at the same time for diverse mass moving charge. Furthermore, another worthy noting is that the time for the second stage appear moves backwards, such as, for 3.5kg charge, $d_t$ increases slowly after 900us, but at this time, for 8kg and 15kg charge, $d_t$ still rises sharply.

The shock front center displacement $d_t$ is hard to ascertain, as it is not only affected by charge velocity, but also by the charge mass and time, the values are always changing and it is a hard work to determine the relationship between $d_t$ and $v_c$.

4.3. Simplified calculation model of moving charge overpressure

Since indeterminacy of $d_t$ and the variety of velocity vectors at different angles on the shock front, it is difficult to calculate the peak blast pressure of moving charge in the surrounding space after blast by theoretical arithmetic. However, according to the numerical simulation results and analysis, we give a simplified calculation model, to calculate the overpressure with scope of relative distance at range of 0.4~2 m/kg$^{1/3}$ around blast core as below.

4.3.1 Blast pressure model in circumferential direction

The air blast pressure curves of moving charge under different toroidal angles and relative distances are given in section 3.2. Through analysis, we know that the variation of airblast pressure of moving charge with different mass is homologous. In order to summarize the rule and establish air blast pressure calculation model of moving charge at each position in the space, we normalize the blast overpressure along the circumference and radial direction (peak blast pressure of each position in space are divided by peak blast pressure of corresponding position, for example, in circumferential direction, the overpressure at $\theta=60^\circ$, $z=0.3$ are divided by the overpressure at $\theta=0^\circ$, $z=0.3$, in radial direction, the overpressure at $\theta=60^\circ$, $z=0$ are divided by the overpressure at $\theta=0^\circ$, $z=0$), the results are shown in figure9. As shown, the normalized peak blast pressure decrease with the increase of toroidal angle, but the trend of curves decline in different angles is not consistent. In addition, the normalized overpressure angle histories at different radial distances are homologous, and the influence of relative distance on the toroidal overpressure distribution is not obvious. On the basis, the normalized overpressure between $0-35^\circ$, $35^\circ$ - $90^\circ$, $90^\circ$ - $145^\circ$ and $145^\circ$ - $180^\circ$ are respectively expressed by piecewise linear functions.. As shown in equation2, where, $\bar{\theta} = \theta/180$, $\varphi_{br}$ is toroidal distribution coefficient of peak air pressure.

$$
\varphi_{br} = \frac{P_x(\bar{\theta},z)}{P_x(0,z)} = \begin{cases} 
-0.0368\bar{\theta} + 1 , & 0 \leq \theta \leq 35 \\
-1.784\bar{\theta} + 1.332 , & 35 \leq \theta \leq 90 \\
-0.686\bar{\theta} + 0.783 , & 90 \leq \theta \leq 145 \\
-0.235\bar{\theta} + 0.422 , & 145 \leq \theta \leq 180 
\end{cases}
$$
4.3.2. Blast pressure model in radial direction

Figure 10(a) shows the variation curves of peak air pressure at $\hat{\Theta} = 0$, and various radial distances of moving charge with different mass. The normalized overpressure between $\bar{z} = 0$ to 0.2, 0.2 to 0.5 and 0.5 to 1 can be expressed by piecewise linear functions, as shown in figure 10(b), equation 10 is the corresponding piecewise function expression, where $\varphi_{zr}$ is radial distribution coefficient of peak air pressure.

$$\varphi_{zr} = P_z(0, z)$$

$$P_z(0, z) = \begin{cases} -2.14z + 1 , & 0 \leq z \leq 0.2 \\ -1.01z + 0.773 , & 0.2 \leq z \leq 0.5 \\ -0.346z + 0.443 , & 0.5 \leq z \leq 1 \end{cases}$$

Figure 9. Normalized peak air pressure at different radial distances.
4.3.3. Blast pressure model of moving charge equation 2 and equation 3 have introduced the toroidal distribution coefficient and radial distribution coefficient by studying the distribution rule of peak air pressure of moving charge. We only need to get overpressure $P_{R_0}(\theta,z)$ at $\theta=0$ and $z=0$, the overpressure $P_{R_0}(\theta,z)$ at any location $(\theta,z)$ in the blast space of the moving charge can be calculated.

$$P_{R_0}(\theta,z) = \phi_0 + \phi_m P_{R_0}(0,0)$$

$P_{R_0}(0,0)$ is a function of $\bar{R}_0$, $\bar{R}_0 = OA/\sqrt{M_e}$. Figure 11 shows the history of $P_{R_0}(0,0)$ with $\bar{R}_0$. After fitting, equation 11 was obtained, and the correlation is 99.93%. So far, we have obtained a simplified overpressure calculation model of moving charge, its application scope is the relative distance at range of 0.4~2 m/kg$^{1/3}$ as previously stated.

$$P_{R_0}(0,0) = -0.379/\bar{R}_0 + 2.166/\bar{R}_0^2 - 0.267/\bar{R}_0^3$$

Figure 10. Normalized peak air pressure along radial direction, at $\theta = 0$.

Figure 11. History of $P_{R_0}(0,0)$ with $\bar{R}_0$.

4.3.4. Verification of the calculation model accuracy In this section, we validate accuracy of the calculation model obtained above. When $\bar{R}_0 = 0.44$, $P_{R_0}(0,0) = 7.2$ MPa from calculating by equation 4. After, with equation 12, the overpressure at different toroidal angles and radial distances can be calculated. We compare it with the simulated data, the results are shown in figure 12. As shown, whether in toroidal direction or in radial direction, the overpressure of calculation and simulation are in good agreement with each other, and the deviation is less than ±15%.
Figure 12. Graph of simulated overpressure versus calculated overpressure, where the solid line indicate a 1:1 correlation and the dotted lines indicate 15% variation.

4.4. Solution of isobaric line of moving charge
We obtained a simplified calculation model of peak air pressure of moving charge in section 4.3, based on the model, isobaric line in the blast space can be calculated. Figure 13 shows $P=1.5$ MPa isobaric line at $R_0 = 0.7$ of moving charge, and compared with $P=1.5$ MPa isobaric line of static charge. The isobaric line moves forward obviously along the direction of charge motion, that is, the damage power moves forward, the maximum motion distance is about 0.81 m in direction of $0^\circ$. The area surrounded by isobaric line of moving charge and $y \geq 0$ line is obviously larger than that of static charge, which enhances the damage range along charge moving direction.

Figure 13. Comparison of isobaric lines between moving charge and static charge.

5. Conclusion
Based on the finite element software Autodyn, we established an air blast numerical model of moving charge, the influence of grid size on air blast overpressure was analyzed, and correctness of the model was verified. Later, through air blast pressure cloudy map comparison between moving and static charge, the air blast pressure of moving charge at the shock wave front appears a local high pressure area near $0^\circ$ direction, and with the increase of $\theta$, the pressure decreases gradually, what are consistent with the theoretical analysis. The influence on air blast pressure distribution characteristics of moving charge with various mass was also analyzed, the pressure time histories in different toroidal direction and radial direction are similar. Then, we normalized overpressure data respectively along the circumference direction and radial direction, and finally established a simplified air blast pressure calculation model of moving charge with scope of relative distance at range of 0.4~2 m/kg$^{1/3}$. The correctness of simplified model was verified, when $R_0 = 0.44$, the overpressure of calculation and simulation are in good agreement with each other. At last, we solved the isobaric line of moving charge and compared it with that of static charge, the damage power along motion direction enhances obviously.
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