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SIMPLIFIED MODEL AND EXPERIMENTAL ANALYSIS OF THE BLAST WAVE OVERPRESSURE

[1,2]LI JIANMIN, [1]XIONG SHIBO, [3]XIAO FENG

1. Institute of Mechano-Electronic Engineering,Taiyuan University of Technology, Shanxi,Taiyuan,030024;

2. School of Information and Communication Engineering ,North University of China, Shanxi, Taiyuan,030051;

3. No.208 Research Institute of China Ordnance Industries,Beijing, 102202

E-mail: [1] l_s_525@163.com

ABSTRACT

The mechanisms of generation, propagation and attenuation processes of blast wave are complex and multiple factors are involved, which makes the existing blast wave model is not suitable for engineering application for its difficulty in parameters determining and problem solving. A simplified model of the blast wave is proposed in this paper. To verify the correctness of the model, 10 explosion experiments were made with three pressure sensors placed in different locations of the explosion tower. The experimental results show that the model curves correctly reflect the characteristics of the experimental curves. The proposed model is workable.

Keywords: *Blast Wave, The Numerical Model, Peak Pressure, The Correlation Coefficient*

1. INTRODUCTION

The blast wave is the most common physical phenomenon in nature. There is a class of discontinuous in which the wave parameters change over time and may produce negative pressure [1]. Blast wave hits objects or spreads along the object surface in the course of the campaign. Along with a variety of phenomena, such as reflection, diffraction, transmission, and a strong impact and thermal effects on the object, the qualitative and quantitative analysis of these phenomena and effects is a classic problem of explosion after effects [8].

In simple environment (there is a single model of the building in open space, see Fig.1), explosive is almost changed into gaseous detonation products with high pressure (10^{10} ~ 3×10^{10} pa) and high temperature (3.5×10^{3} ~ 4×10^{3} ℃) at the moment of explosives. And this gas is rapidly expanded and forced the gas around leaving the original position. So the gas in forefront forms a compressed air layer, namely blast wave, and with spherical form around to rapid expansion. The wavefront at the pressure *P* is continuously decreased and the pressure dropped after the wavefront with the increase of the distance d away from the wave source. At a certain distance, the pressure below atmospheric pressure after the wavefront forms shockwave negative pressure zone at a certain distance, and in the negative pressure zone air is sucked rather than being discharged. The propagation rules that explosion caused the air overpressure with time as shown in Fig.2 [2,3].

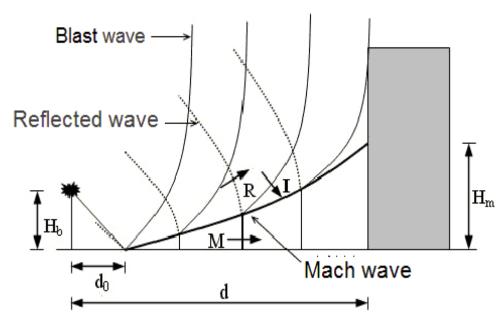

Fig.1 Surface Shock Wave Forms

In section 2, we analyze complex numerical calculation of the blast wave and propose a simplified model of a blast wave within 5% of the standard deviation. In section 3, a simplified model of the blast wave, the explosion tower blast wave experiments. In section 4, we verify the correctness of the simplified model of a blast wave through point-by-point comparison of the measured waveform and the theoretical waveform method. Section 5 gives a conclusion to the whole paper.

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This simplified model later is applied to the target surface, the acoustic vertical target accuracy test system with high rate of fire, which also achieves good results.

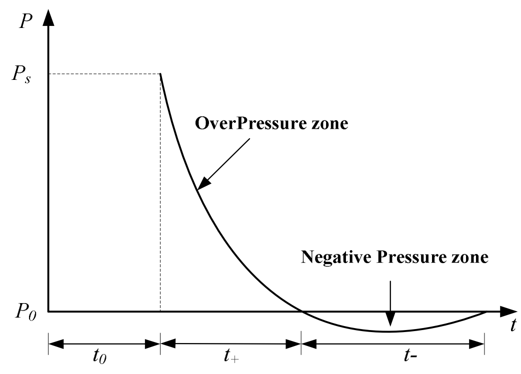

Fig.2 Aschematic Of Explosion Shock Wave Pressure Curve

2. THE EXPLOSION WAVE OVERPRESSURE MODEL

2.1 Blast Wave Overpressure Equation And The General Solution

For completing description of the course of time of ideal blast wave (assuming the explosion occurred in a static uniform atmospheric, explosive source is spherically symmetric), it is usually expressed as a function of time [7] in the actual analysis and research, and the following is a general equation of the blast wave pressure variation.

$$\frac{\partial \Delta p}{\partial t} + bf(\boldsymbol{r}, t)\Delta p = P_s^{+}\varphi(\boldsymbol{r}, t) \qquad (1)$$

Where R represents the studying position vector from the measuring point to the center of the explosion; Function ***f(r,t)*** and ***φ(r,t)*** is a function of distance and the time with the measuring point.

For the ideal air explosion, when the object of studying for a fixed measuring point in the space, the overpressure function is only related to time, without having to consider its relationship with the distance. In the case of one-dimensional type, we have the following for equation (1):

$$\frac{\partial \Delta p}{\partial t} + bf(t)\Delta p = P_s^{+}\varphi(t)/t^{+} \qquad (2)$$

The general solution of the equation [7]:

$$\Delta p = p_s^{+} e^{-bf(t)dt}\left[\frac{1}{t^{+}}\int \varphi(t) e^{bf(t)dt} dt + 1\right] \qquad 0 \le t \le t^{+} \qquad (3)$$

Where ***f(t)*** is the viscous coefficient of the overpressure change process, and ***φ(t)*** *is* the overpressure transfer driving force. Because they are associated with the changes in real time of the explosion wave field, it is difficulty to conduct a further analysis.

2.2 Simplified Expression Principles Of The Peak Pressure Of The Blast Wave

From the above, peak pressure of the blast wave general solution expression is too complex, and the results are not readily available, not suitable for engineering designs applications. We can simplify the processing according to the following principles peak pressure of the blast wave expressions [4-6].

First, follow the basic laws of acoustics

Such as "equal area criterion", that is not too small distance, the rising rapidly pressure of positive pressure integral area should be equal to the pressure drops slowly of negative pressure integral area. This is because, the rapid pressure rise is due to rapid expansion of the gas generated by the blast, the pressure slowly decreased due to the gas slowly contraction, expansion. After contraction the atmospheric, reverts the original undisturbed state. Obviously this process follows the equal area criterion.

Second, mature fire explosive point explosion numerical calculation theory

Based on the need of the analysis and verify the calculation, the expression should be simple and be able to take advantage of some mature software mathematics software and accumulation. According to the numerical research, qualitative available in Fig.2 describes the pressure of the blast wave. In the figure, t_+ is for the action time after the start of explosion positive pressure.

Next to resolve the data in Fig.2. In general, an analytic function is difficult to describe the complex process of the explosion. Certainly, sectional mathematical model is more accurate, but with the difficulty of describing its dynamic characteristics and the transfer function, such as a linear system. We intend to describe it by the composite of two exponential functions.

$$\begin{aligned} y_1 &= e^{-t/t_+} \qquad t \in [0, \infty) \\ y_2 &= \frac{t}{t_+} e^{-t/t_+} \qquad t \in [0, \infty) \\ p(t) &= y_1 - y_2 \end{aligned} \qquad (4)$$

Where ***P(t)*** is the normalized pressure and $\boldsymbol{t_+}$ is the positive overpressure role time.

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The two exponential functions and the composite waveform are shown in Figure 3, the product of the sampling interval of time and sampling points is the time ***t.***

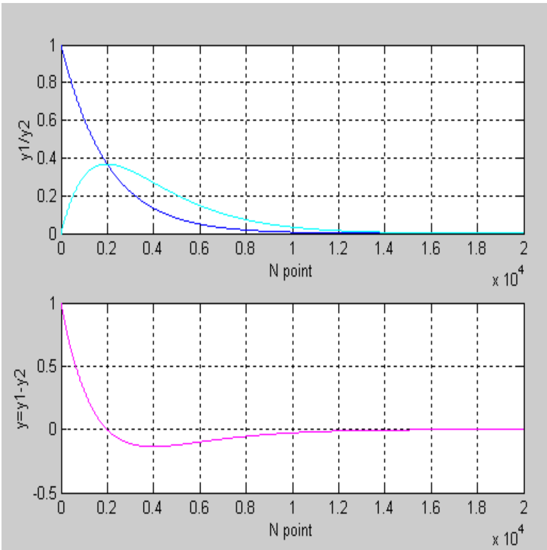

Figure.3 The Composite Model Of Explosives Explosion Pressure Mathematical Functions

Consider the actual situation, finishing the above results, the blast wave pressure parse may wish to use the following expression.

$$p(t) = 0 \qquad t < t_0$$
$$p(t) = A_p \cdot (1 - \frac{t}{t_+}) e^{-t/t_+} \qquad t \ge t_0 \qquad (5)$$

Where A_p is the pressure amplitude, (***t***) is the pressure - time function, t_0 is the explosion delay time and ***t+*** is the after the explosion of positive pressure time.

First, it is a single-pulse signals, the signals described by the formula 5, the rise time is zero; this is impossible, it is just a simplified mathematical. Actual blast pressure signal is very short in rise time, theoretically estimated to be approximately the microsecond range, but the farther away, the pressure rise time is longer; In the tests, mainly due to the sensor, so that the rise time to increase distortion. The shorter the rise time, high frequency components are more abundant; as you see the blast pressure test requirements of the high-frequency response of the test system is highly. The low-frequency component contained in blast wave pressure signal is also very rich, ***t+*** the greater, the stronger low frequency components. It should choose the appropriate test system, the error control to the permitted extent.

Second, estimate the maximum pressure by empirical formula [4], when the explosion of TNT equivalent 1kg, a distance of 1m, explosion peak pressure of the free field is about 1.05 MPa; distance of 0.5m, the peak pressure of the free field is approximately 6.6MPa. The free-field the explosion pressure test, due to a variety of reasons, the closer the more difficult to achieve.

3. EXPERIMENTAL MEASUREMENTS OF THE BLAST WAVE

3.1 Sensor Arrangement In The Explosion Tower

The experiment was conducted in the explosion tower, the arrangement of the explosion tower is set in Figure 4.

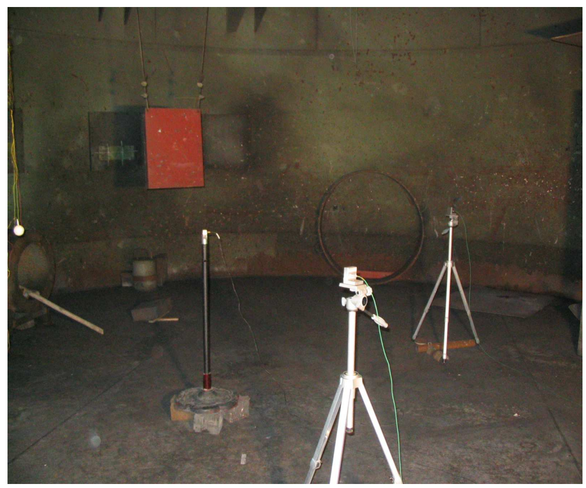
Figure.4 The Hanging Dynamite And Sensor In The Explosion Tower

In Figure 3, the left end of the little white ball is the hanging of TNT, 100g, off the ground 1m. Explosives as the center for three sensors off the ground 1m and the arrangements are as follows.

1m-bit: from the center 1m, Switzerland Kistler 211B1 piezoelectric sensor, the sensitivity is 0.544mV/psi;

2m-bit: from the center 2m, American PCB 113A21 ICP sensor and the sensitivity is 3.95mV/kPa;

3m bit: from the center 3m, American PCB 102A07 ICP sensor and the sensitivity is 14.25mV/kPa.

3.2 Typical Explosion Pressure Of Curve

It was measured 10 rounds, and figure 5 is the first rounds of the measured curve.

In the above figure, the vertical axis is presented

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the voltage value (***V***), and the horizontal axis is presented time (***points***), the diagram of the signal is inverted. (***Sampling frequency***)

Depend on the measurements, apart from individuals, the waveform and the amplitude of the pressure is normal, and it has good reproducibility. 1m bit peak pressure is approximately 6 to 7 bar, and the pressure rise time is about 12 ~ 15μs; 2m bits peak pressure is approximately 1.5 to 1.7 bar, and the pressure rise time is about 17 ~ 20μs; 3 m bit peak pressure is approximately 0.5 ~ 0.6bar, and the pressure rise time is about 23 ~ 26μs.

It should be noted that the zone of negative pressure in the pressure signal, where there are many small-amplitude high frequency fluctuations, these high-frequency fluctuations in the time, amplitude and frequency with the randomness. It can be concluded that this is caused by second combustion of Propellants residue, similar experiments in the muzzle high-speed photography may confirm this point.

3.3 Peak Pressure Of The Blast Wave

Finishing 10 rounds in different position of the pressure peak data are shown in Table 1.

The simplest model of the blast wave is the point of the explosion wave model, facing to the exact solution of this problem, von Neumann (Von Neuman), Taylor (Taylor) [4], pointed out that near the blast wave field pressure decayed at $1/r^3$ (r is the distance away from the fried-point); far away blast wave field, as a weak shock wave, it decayed 1/ r. Seeing from Table 1, the blast wave peak pressure of the measured waveform and the classical theory is consistent with the test data is also trusted.

Table 1 Peak Pressure Of The Blast Wave

number	1m bit			2m bits			3m bits		
	voltage /V	Peak of sampling points	pressure /kPa	voltage /V	Peak of sampling points	pressure /kPa	voltage /V	Peak of sampling points	pressure /kPa
1	-3.91	1023	539	-7.64	1060	152	-2.84	3654	56.8
2	-4.28	1024	588	--	--	--	--	--	--
3	-3.99	1024	550	-5.92	1062	118	-2.76	3722	55.2
4	--	--	--	-7.88	1059	157	-2.74	3802	54.8
5	-4.83	1024	686	-9.00	1039	180	-2.72	3913	54.4
6	-4.01	1024	553	-7.52	1059	150	-2.82	3762	56.4
7	-4.64	1024	640	-8.48	1038	170	-2.76	3879	55.2
8	-4.17	1024	575	-8.60	1038	172	-2.78	3897	55.6
9	-3.71	1024	512	-7.80	1038	156	-2.62	3852	52.4
10	--	--	--	-8.72	1038	174	-2.72	3904	54.4
average			580.38			158.78			55.02

4. BLAST WAVE SIMPLIFIED FORMULA VALIDATION

The purpose of this study was that the point by point comparison between measuring curve and explosion wave pressure simplified formula, and proposed a method for evaluation, to test within 5% of the standard deviation of the simplified formula. To do this:

4.1 Simplified Formula Discrete Numerical Model

Experimental measurement curve is discrete numerical after A / D sampling. Simplified formula 5 should be sampled the same number of data points, and point by point comparison alignment should pay special attention to the starting point. Below to 2048 sampling points, the sampling resolution of 12bit, binary offset code (both positive, and negative, 2048 corresponds to the value 0), for example, shown in Propellants

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explosion pressure signal numerical model of the process in Figure 6.

Numerical model was equal to simplified formula of discretization .

$$p1 = 0 \qquad N \in [0,199] \tag{6}$$
$$p1 = 2047 \cdot \left(1 - \frac{N}{b \cdot 200} \cdot e^{-a \cdot N / b \cdot 200}\right) + 2048 \qquad N \in [200, 2047]$$

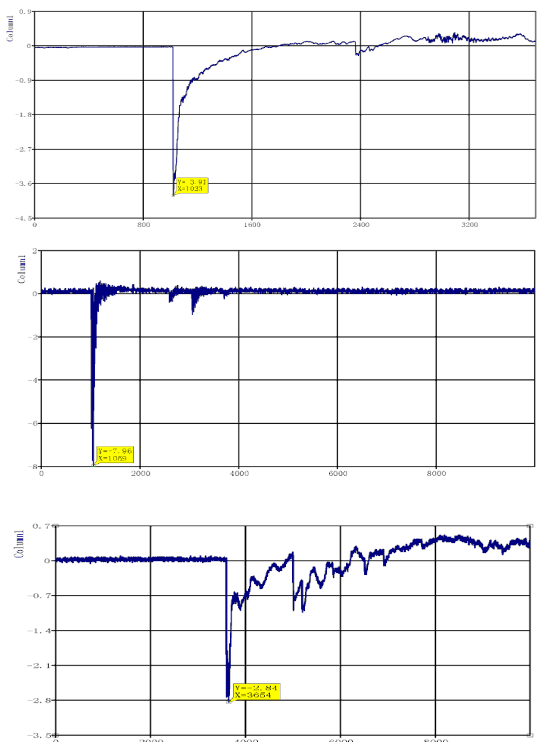

Fig.5 Explosion Pressure Curve

(Top: 1m-Bit; Middle: 2m-Bit; Bottom: 3 M-Bit)

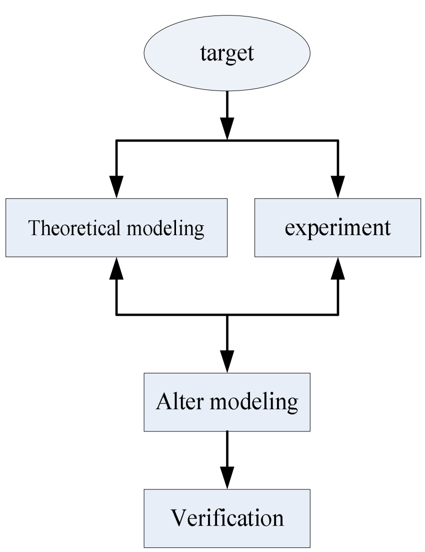

Fig.6 Numerical Modeling Process

And formula 6 completely corresponds to formula 5, width takes 12bit maximum sample point in 4095.It is necessary to say that the rise time of theoretical research simplified formula equal to the value 0, which is impossible in the objective physical world. When the test system using measuring high-frequency response, the rise time is about 10μs magnitude, besides with the measuring point distance increases, the rise time increases. Formula 6 in the number of a, b is established according to the different distance correction of the rise time and waveform.

It is also noted that the measured explosives explosion pressure signal is superimposed a second combustion of gunpowder residue which caused fluctuations, superimposed high-frequency noise, the latter is due to the measurement system noise, long cable interference. In order to reduce the impact of such noise, firstly to standardize the 10 of measured curve amplitude, align the starting spot , superimposing and averaging then compare between formula 6 point-by-point.

4.2 Point By Point Comparison Test

In the study, compare the experiments measuring curve and blast wave pressure simplified formula in equation 5 point-by-point in this study. And evaluate the agreement by using correlation coefficient .See Figure 7 below.

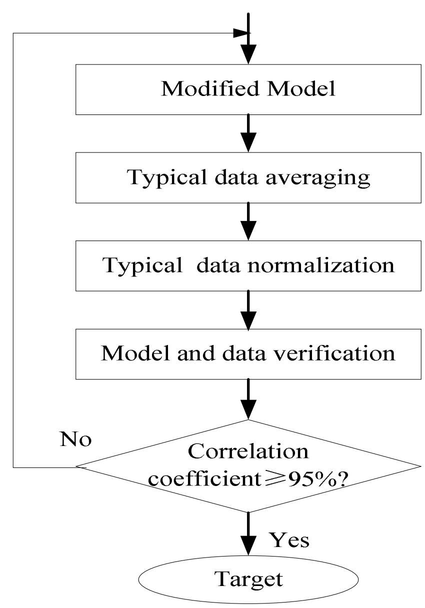

Fig.7 Model Validation Process

In the figure, the sum of the multiple data for averaging, and test data is more typical. The so-called "normalization" is a unification that the

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amplitude of model and the test data ; specifically, the test data values are multiplied by a constant, rounded, into the 0 to 4095 integer and scope consistent with the calculated values of the model .

Model authenticity verification is through the experimental curve and the correlation coefficient of the curve of theoretical calculation model. This is a more stringent comparison method: The correlation coefficient is 1, the two curves are identical; correlation coefficient is 0, and there is a completely different. x_i, y_i, calculates their average, calculated as the correlation coefficient r_{xy}

$$r_{xy} = \frac{\sum_{i=1}^{N} x_i y_i - N\overline{x} \cdot \overline{y}}{\sqrt{\sum_{i=1}^{N}(x_i - \overline{x})^2 \sum_{i=1}^{N}(y_i - \overline{y})^2}} \quad (7)$$

Process of validation process is shown in Figure 7, the model curve and the experimental curves in Figure 8;And in the figure, the lower part of the test curve is already eight times the sum, average processing, and amplitude normalization.

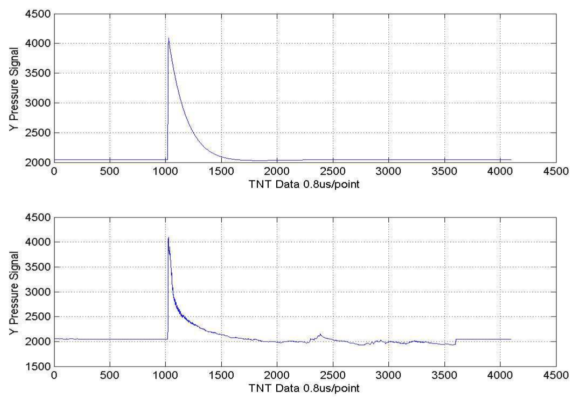

Fig.8 Model And Experimental Curves

Equation 7 calculated the correlation coefficient matrix:

$$CorrYtYa = corrcoef(Yt, Ya) = \begin{bmatrix} 1.0000 & 0.9564 \\ 0.9564 & 1.0000 \end{bmatrix}$$

That cross-correlation coefficient equals to 95.64%.

5. CONCLUSION

By the theoretical analysis and experimental verification, it was found that the model curve reflects the characteristics of the experimental curve correctly, that the standard deviation within 5%. It is reasonable and correct to create a simplified model (Equation 5) of the explosion wave. And this simplified model later is applied to the target surface, the acoustic vertical target accuracy test system with high rate of fire (discussed in detail later), which also achieves good results.

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