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爆轰冲击波动力学方法在爆轰驱动加速飞片计算中的应用

AN APPROACH TO INCORPORATE THE DETONATION SHOCK DYNAMICS INTO THE CALCULATION OF EXPLOSIVE ACCELERATION OF METALS

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李庆忠：中国工程物理研究院助理研究员，1994 年毕业于四川师范学院物理系，1997 年获爆炸理论及应用专业硕士学位。

LI Qingzhong: Assistant professor of China Academy of Engineering Physics. Graduated from the Department of Physics, Sichuan Teacher's Collage in 1994 and received the Master Degree of detonation theory and its application in 1997.

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爆轰冲击波动力学方法在爆轰驱动加速飞片计算中的应用

李庆忠　孙承纬　赵　峰　高　文　文尚刚　刘文翰
（中国工程物理研究院，成都，610003）

摘　　要

将爆轰冲击动力学方法（DSD）的广义几何光学模型（GGO）引入二维流体力学计算编码 WSU 中去，得到耦合计算编码 ADW，对炸药爆轰驱动飞片进行数值模拟。对两类不同尺寸和种类的爆轰装置进行了实验和数值计算，计算结果与实验结果吻合相当好。

An Approach to Incorporate the Detonation Shock Dynamics into the Calculation of Explosive Acceleration of Metals

LI Qingzhong SUN Chengwei ZHAO Feng
GAO Wen WEN Shanggang LIU Wenhan
(China Academy of Engineering Physics, Chengdu, 610003)

ABSTRACT

The generalized geometrical optics model for the detonation shock dynamics (DSD) has been incorporated into the two dimensional hydrocode WSU to form a combination code ADW for numerical simulation of explosive acceleration of metals. An analytical treatment of the coupling conditions at the nodes just behind the detonation front is proposed. The experiments on two kinds of explosive-flyer assemblies with different length/diameter ratio were carried out to verify the ADW calculations, where the tested explosive was HMX or TATB based. It is found that the combination of DSD and hydrocode can improve the calculation precision, and has advantages in larger meshes and less CPU time.

INTRODUCTION

The reactive flow calculation can be applied to simulate detonation propagation process in principle even for the insensitive high explosive (IHE) with a longer reaction zone. However, extra fine meshes are required here in order to describe a well resolved reaction zone. These leads to inevitable problems such as mesh distortion, tedious CPU times, accumulative errors and so on. Recently, the efforts to improve the numerical simulations for propagation of detonation waves in explosives have been made, one of which referred to as Detonation Shock Dynamics (DSD) is more promising. On the basis of Whitham's shock dynamics Lambourn [1] proposed a set of first order hyperbolic partial differential equations to calculate the quasi-steady 2D detonation front, where the empirical dependence of the normal detonation velocity D_n on the front mean curvature κ was employed and the fixed angle between the front and the cylindrical charge side was assumed. Stewart and Bdzil [2] carried out an asymptotic analysis for the detonation propagation in cylindrical charges and deduced a parabolic evolution equation of detonation front. Bdzil and Stewart [3] discussed the dynamics of diverging detonation systems with a slow time scale and concluded that the effect of detonation front on reaction zone can be summed up as the front's mean curvature κ. This is an extension to Jone's work on the cylindrical and spherical diverging detonation waves [4,5]. With reference to the Whitham's shock dynamics, Bdzil [6] worked out an equation for detonation front including its transverse movement due to the boundary effects. Bdzil calls the theories of detonation front propagation as the detonation shock dynamics (DSD). Meanwhile, Stewart [7] put forward a simplified equation for detonation propagation in cylindrical coordinates according to the geometric relation and the assumption of $D_n(\kappa)$. There are other contributions to the DSD field [8, 9]. According to the level set method[10] (LS), the evolution of a geometrical surface controlled by its curvature can be generally described with an equation something like the hydrodynamic equation whose "particle velocity" is the normal detonation velocity. By means of this approach some simple examples of 3D detonation propagation have been worked out [11].

It is suggested in DSD that the propagation of mild curved detonation fronts is controlled by an empirical dependence of the normal detonation velocity D_n on the front's local mean curvature, κ, and basically independent of the details of flow in the reaction zone. There are some variations of DSD model among which the generalized geometrical optics (GGO) model proposed by us improved the Huygens principle calculation with the $D_n(\kappa)$ relation and the sonic condition at explosive edges[8, 12]. In order to improve the numerical simulation of acceleration of metals by explosives the GGO model has been incorporated into the two-dimensional elastic-plastic-hydrodynamic code WSU to form a combination code ADW. The key point for the incorporation is the coupling conditions at the nodes just behind the detonation front calculated by DSD, according to which the hydrodynamics variables are assigned so that the following hydrocode calculation can go on. A simple coupling condition employing the approximate analytical solutions of divergent Taylor waves has been proposed in this work. The experiments on two kind of explosive (HMX or TATB based)/flyer assemblies with different length/diameter ratio were carried out to verify the ADW calculations, and it indicated that the improvement described in this paper resulted in higher precision, and less CPU time even for larger meshes.

1 INCORPORATION THE GGO MODEL INTO THE HYDROCODE WSU

1. 1 The GGO Model

The detonation front propagating in a reactive medium can be described by Huygens principle, but modified with a curvature dependent normal detonation velocity $D_n(\kappa)$ in the GGO model. Let the front at time t be determined with the following eikonal equation

$$F(x,y,z)=t \tag{1}$$

Eq. (1) defines the front surface family and therefore the family of their normal lines (rays) along which the front moves at the normal detonation velocity $D_n(\kappa)$, where κ denotes the local mean curvature of the front. Consequently the GGO model can be generally described as

$$|\nabla F|^2=D_n^{-2}(\kappa) \tag{2}$$

It is a complex non-linear high order equation. However, it becomes simpler in some geometries such as explosive cylinders, where the front curve $Z(r, t)$ observed in the cylindrical coordinates moving along z axis at the asymptotic steady detonation velocity D evolves according to an equation of Burgers type and is similar to that deduced by Stewart and Bdzil[7]. Furthermore, the analytical solution of the asymptotic two dimensional detonation front curve can be obtained for explosive bars, which is basically the same as that obtained by Bdzil[6, 13].

It should be noted that the linear D_n (κ) relation is assumed in above work, i.e.,

$$D_n = D_\infty - \alpha\kappa \tag{3}$$

where D_∞ is the one-dimensional steady planar detonation velocity, usually D_∞ is assumed to be the CJ detonation velocity D_J of the considered explosive, α is a constant depending on explosive properties only and should be calibrated with special experiments.

It is important to the DSD theory how to determine the value and angle of the detonation front at the explosive edges confined by inert materials or adjacent to vacuum. Based on the assumption that the reaction at the edges is completed by two steps, a variation of the sonic condition has been proposed in the GGO model,

$$c^2 - q^2 = D_{ne}^2\left(\frac{\gamma}{\gamma+1}\frac{\sqrt{\delta^2-\sin^2\phi_e}}{\cos\phi_e} - \frac{1}{\gamma+1}\frac{\delta^2-\sin^2\phi_e}{\cos^2\phi_e} - \tan^2\phi_e\right) \tag{4}$$

where D_{ne}, c, γ and q are the normal detonation velocity at the edge, sound speed, isentropic index and particle velocity of detonation products just behind the front respectively, and ϕ_e is the angle from the front's normal to the tangent of the edge curve. It is assumed that the largest portion of the reaction energy Q, $(1-\delta^2)Q$, is released immediately at the front, and the small remainder, $\delta^2 Q$, is progressively released in the reaction zone. It can be deduced that Eq. (4) is equivalent to that given by Bdzil[6]. Especially under the sonic condition, Eq. (4) yields $\tan\phi_e = \delta\sqrt{\gamma^2-\delta^2}/(\gamma+\delta^2)$, which along with the Rankine-Hugoniot relations for oblique detonation fronts and Bernoulli's relation can be employed to adjust the hydrodynamic and geometric variables at the edge. Usually δ can be regarded as an explosive/inert material related constant, it would markedly simplify the code calculations.

1. 2 The Codes GGO2D and WSU

The code GGO2D is based on the GGO model for 2D geometries, in fact it performs the geometrical calculations to determine the detonation front propagation step by step according to the empirical dependence of D_n (κ) and the edge conditions such as Eq. (4). The front curve is described with the spline approximation of the 3rd order. There are only four constants required in the code GGO2D: α, D_∞ or D_J, γ, δ, when the geometry and confinement of the considered problem are given.

This code has been well verified with experimental data for detonation front propagating in explosives of different kind, shape, size and initiation regime, such as straight and arc bars, hemisphere initiated at the center, hemispherical shell initiated at the top point, diffraction blocks with concave boundaries and so on. The tested explosives were JO-9159 (HMX-based), TNT/RDX (40/60), Nitromethane, and IHE-2 (TATB/Fluoroelastomer = 95/5).

The code WSU is a 2-D Lagrangian elastic-plastic-hydrodynamic code for reactive media. Usually the detonation front and the reaction zone are calculated with the artificial viscosity and the reaction rate in the code WSU. In order to numerically simulate the detonation propagation and the full resolved reaction zone fine meshes and tedious CPU time are necessary. Consequently, mesh torsions, cumulative errors and other related problems are inevitable. A better detonation front with preciser shape and run time as well as the products flow in the adjacent zone could be obtained if the code ADW is incorporated into the hydro code. Since the movement of flyers driven by explosives mainly depends on the impulse accepted by the flyer from the detonation products at an early stage, the combination of both codes should result in better calculations on the acceleration of metal flyers driven by explosives.

1. 3 The Combined Code ADW

The shock wave front is separately given first, and then the calculation of the flow behind it can proceed under some match or coupling conditions. This is the basic idea of programming algorithm of which Buckiet and Menikoff [14] proposed the front tracking method for detonation waves. Because of the feature of considered problems mentioned above, the microscopic flow field is important to our requirement. When the combined code ADW is performed the GGO2D and WSU calculations proceed synchronously step by step. In a WSU time step the detonation front is positioned first with the GGO2D calculation for *m* GGO2D time steps, then the WSU calculation follows, where *m* is a fixed integer. Because of coarse meshes the full resolved reaction zone is hardly described here except that more complicated algorithms, such as adaptive meshes, are employed. For the considered problems it is essential for us to learn the precise run time and shape of the front and the products state in the adjacent zone as it just hits the flyer. Therefore, the reaction zone is neglected and replaced by assigning proper values to particle velocity components at mesh nodes just behind the front. The influence of reaction zone on the detonation front can be summed up as the $D_n(\kappa)$ relation.

Bukiet [15] gave an example of random choice method (RCM) calculation for a spherical diverging detonation in Comp. B and compared it with the PHERMEX data. Though the products density at the sonic point is only 93% of the CJ value, its profile is similar to that of a cylindrical Taylor wave except in the zone closely adjacent to the front. The measured density profile is between those of planar and cylindrical Taylor waves.

Every small part of the front can be considered as a portion of a sphere or a cylinder, so that the products flow behind it can be approximately assumed to be the Taylor wave. In order to determine the local front radius and the flow direction for a considered mesh node just behind the front a method of averaging and smoothing has been used. Once the local front radius R corresponding to the considered mesh node is obtained, the corresponding particle velocity components will be calculated according to the Taylor wave model. In the code ADW, an approximate solution for divergent Taylor waves is used for the coupling treatment, whose relative errors compared with the precise solutions are less than 2%[16]. The Riemann invariants α, β at the node are yielded as

$$\beta = \frac{-1}{\gamma - 1} + \frac{N\eta^2}{4(\gamma + 1)} - \left[\frac{N}{4(\gamma + 1)} - \left(1 + \frac{N(\gamma - 1)}{8(\gamma + 1)}\right)\varepsilon\right]\eta^3 \tag{5}$$

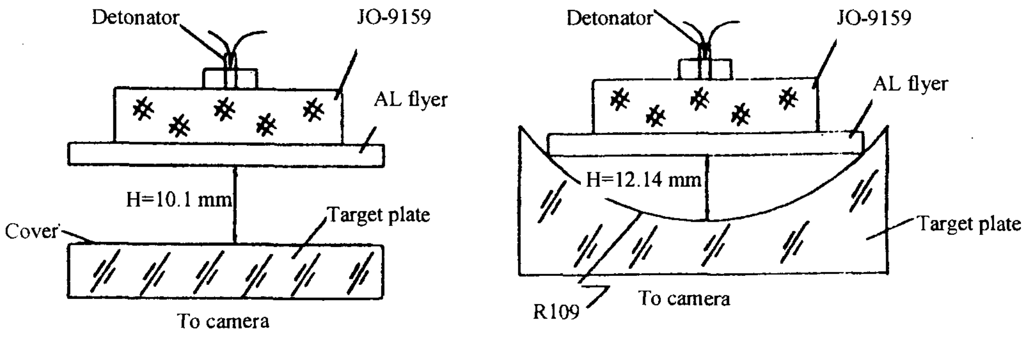
$$\alpha = \frac{3\gamma - 1}{\gamma^2 - 1} - \frac{2}{\gamma + 1}\sqrt{\frac{N\gamma}{\gamma + 1}}\eta + \left[\frac{2}{\gamma + 1}\left(\sqrt{\frac{N\gamma}{\gamma + 1}} - 1\right) - \frac{\gamma - 1}{\gamma + 1}\left(\sqrt{\frac{N\gamma}{\gamma + 1}} + \frac{3 - \gamma}{\gamma - 1}\right)\varepsilon\right]\eta^2 \tag{6}$$

where $\varepsilon = N[12(\gamma + 1) - 2N(2 - N)(\gamma - 1)(6 - \gamma)]^{-1}$, $\eta = [2(1 - S/R)]^{1/2}$. The geometrical index $N = 0, 1, 2$ denotes planar, cylindrical and spherical Taylor waves, respectively. S is the distance between the node and the center of local sphere or cylinder. The assumption of cylindrical Taylor waves is better in practice of this work. The WSU calculation for this step starts after particle velocities at all nodes just behind the front have been assigned.

2 EXPERIMENTS AND ADW CALCULATIONS

2. 1 Assembly of Flat Explosive Charge

The experimental assemblies with flat charge of JO-9159 explosive of density 1.86 g/cm^3 are shown in Figure 1, where the aluminum flyer was of diameter 100 mm and thickness 2.02 mm. The explosive charges had different sizes: diameter 60 mm and thickness 5.10 mm for model A, diameter 80 mm and thickness 10.07 mm for model B. Another difference lay in the shape of the PMMA target plate. For model A it was a strip with transparent surfaces at its top and bottom, and spaced by 10.1 mm from the flyer's bottom surface. For model B it was shaped like a concave-plane plate with transparent top and bottom surfaces too, where the concave arc had a radius of 109 mm and the distance of its lowest point to the flyer was 12.14 mm. When the flyer hit the top surface of target plates, a flash was induced due to compression of the air gap between the cover and the target plate. A smear camera was employed to record the flash signals, which would be treated to obtain the waveform of flyer's hitting time *t* vs the transverse coordinate *r*.



(a) Model A　　(b) Model B

Fig. 1　The experimental set-up of the flat assembly

2. 2　Assembly of Dumpy Explosive Charge

In this kind of assembly IHE-2 cylinders of diameter 50 mm and length 52 mm were used. There were also two types of PMMA target plates respectively denoted by solid or dashed lines as shown in Fig. 2. The copper flyers were all of diameter 50 mm. Five shots have been conducted for this kind of assembly. The details of experimental set up are listed in Table 1.

It should be noted that there were two methods of measurement in experiments, which differed only by using an entire cover foil or a half one. In the latter case, the shock waveform just emerging from the flyer's bottom surface could be recorded as its flash propagated through the uncovered half of the target and got into the camera, meanwhile the hitting time waveform was recorded with the covered half one.

2. 3　Hitting Time Waveforms

The waveforms of hitting time for two kinds of assemblies are shown in Fig. (3～5), where the relative time means the results from shifting the waveforms so that their leading points have the same time zero. The numerical simulations have been conducted with both codes ADW and WSU, where the HOM equation of state (EOS) for explosive and products and Forest Fire reaction rate were employed in WSU calculations. The size of meshes and the time step were 1 mm and 30 ns, respectively.

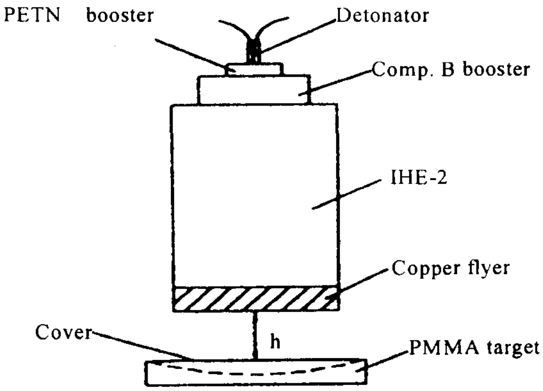
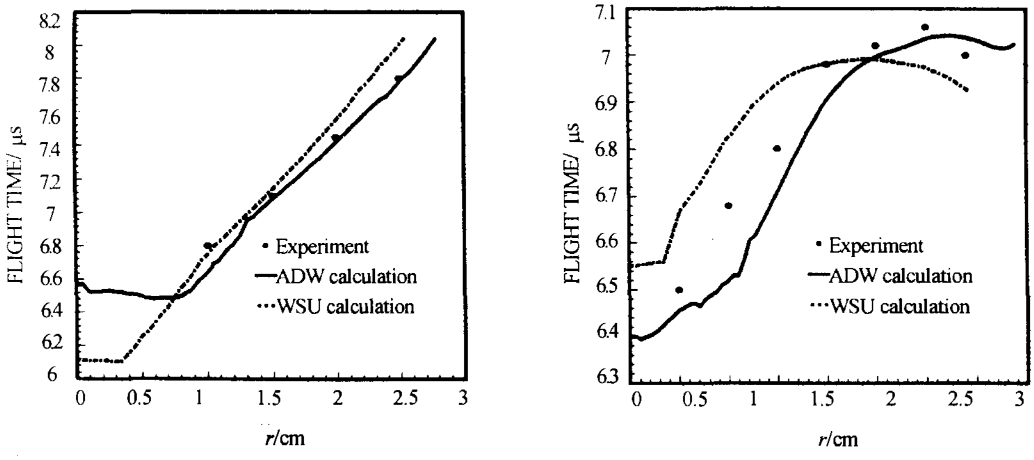


Fig. 2 The experimental set-up of dumpy assembly

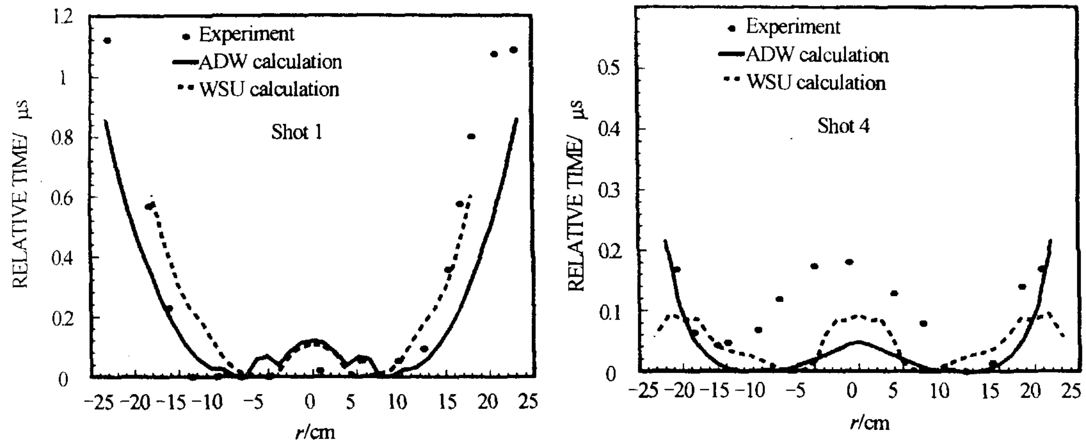
Table 1 Experimental parameters for dumpy assemblies

Shot number	Target shape	IHE-2 density g/cm^3	Flyer thickness mm	Spacing h mm	Cover on target
1	Concave	1.8498	4	15.11	Entire
2	Flat	1.8472	4	10	Entire
3	Flat	1.8999	4	10	Half
4	Concave	1.8682	2	15.28	Entire
5	Flat	1.8437	2	10	Half



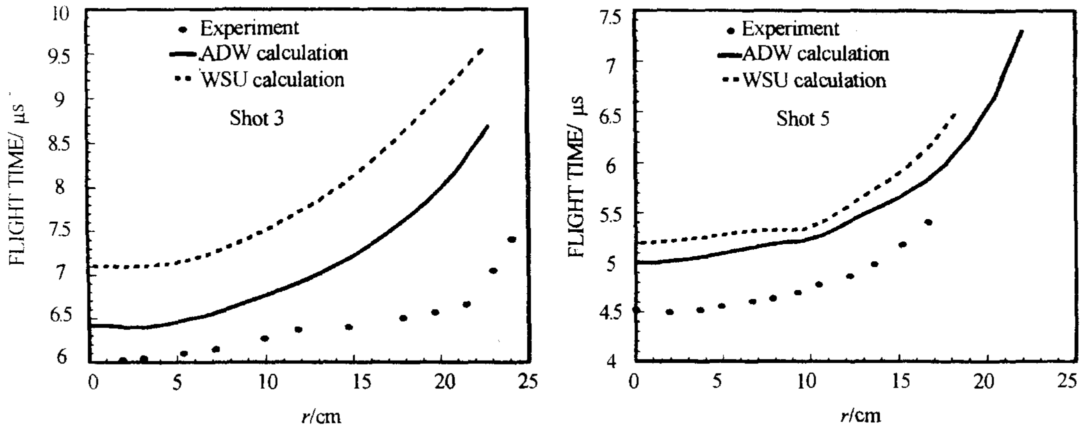
(a) Model A (b) Model B

Fig. 3 Hitting time waveforms of flat assemblies



(a) Shot 1 (b) Shot 4

Fig. 4 Relative hitting time waveforms of dumpy assemblies



(a) Shot 3 (b) Shot 5

Fig. 5 Hitting time waveforms of dumpy assemblies

2.4 Discussion

It has been found that in most shots the ADW calculations are better than the WSU results, and the agreement for flat assemblies is better than that for dumpy ones. This indicates that the code WSU failed in precise calculation of detonation propagation, especially in IHEs. It is also implied that there is a severe side rarefaction in the case of dumpy assemblies. In order to deal with side rarefactions and shearing flows, the hydrocode should be improved further to realize sliding and penetration between meshes.

The comparison of different EOS of products was carried out for Shots 3 and 5. The calculation with HOM equation is better than that with the JWL equation of state. It means that the calibration of EOS of IHE products is important when it is extended to the lower pressure range.

The calculations show a considerable effect of the assignment of particle velocity at the nodes just behind the front on the products flow afterwards. It is required to consider this problem further on a proper theoretical basis. In addition, the constitutive relation of flyer's material, including high strain rate effects, should be involved in the hydrocode, since the pressure of products near the edge is so slow that the material strength can not be neglected there.

3 CONCLUSION

To incorporation of the DSD code into the hydrocode is of benefit to the numerical simulation of flyer's acceleration by explosives. It is caused by a better detonation front described with detonation shock dynamics. The combined code, ADW, consisting of both DSD and hydro codes has advantages in high precision, coarse meshes and less CPU time. It is expected to improve the coupling treatment and the method to deal with severe side rarefactions.

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