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Simulation Study of Shaped Charge Collapse Process and Optimal Standoff Determination

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Abstract—**In this article, the new method for shaped charge warhead optimal standoff determination is developed based on the ANSYS AUTODYN simulation. The warhead standoff is determined on the assumption of the continual jet velocity behavior. The liner material is accelerated and collapsed under the high detonation pressure. The chosen simulation method is used for the process evaluation using the published PG-7V shaped charge for standoff determination. This article, on the other hand, introduces results of simulation of the waveshaper effect on the liner collapse process and on the jet formation and jet velocity. The Eulerian meshing was used to describe the collapse process of the conical liner.**

Keywords-shaped charge; warhead; ANSYS AUTODYN simulation; standoff; waveshaper; jet; PG-7

I. INTRODUCTION

A shaped charge is an explosive charge shaped to focus the effect of the explosive's energy to produce material jet causing penetration of the target to a depth of six or more times the charge diameter. Different parameters have an effect on the shaped charge jet formation, velocity and penetration such as the shaped charge hollow angle α, the liner thickness, the liner density. Due to the relative independence of the jet penetration on impact velocity, the principle of shaped charge is extensively used for variety of antitank systems. The penetration of the shaped charge warhead is strong enough to destroy several types of target even though the initiation of the detonator of shaped charge doesn't occur in the optimal separation distance. The separation distance is called the standoff.

Shape charge effect is influenced also by the manufacturing technology precision, which concerns dimensions tolerance, assembly tolerances ad so on [1]. It is obvious, that charge precision influences the penetration depth dispersion.

One of the most important problems with the shaped charge warhead building is finding of the optimal standoff. If the standoff is shorter to optimal, the penetration effect decreases. If the standoff is greater to optimal, the effect of penetration decreases, too.

The jet formation theory is a very complex. Mathematical models capable of predicting the shaped charge liner collapse process has been published by many authors. Majority of the models usually use some simplifying assumptions. One of the first authors, which focused on an explanation of the shaped charge liner collapse mechanism, was Birkhoff [2]. His work was the starting point for a number of other authors, for example in works [3], [4], [5].

The waveshaper is the body embedded between booster and main shape charge, which changes the path of the detonation wave. The waveshaper modifies the liner collapse process and improves resulting jet formation, thus also improves penetration performance.

In this study, numerical simulation of shaped charge includes some processes: detonator initiation, liner collapse process, jet formation and optimal standoff determination, target penetration at optimal standoff of PG-7V warhead, the waveshaper influence on the collapse process and jet formation. For the FEM simulation results confirmation, experiments on the penetration of specified target with the PG-7V warhead have been performed.

II. SIMULATION MODEL

A. Model

In accordance with the technical documentation of PG-7V warhead accessible on the Department of Weapons and Ammunition, the simple model of shaped charge has been built.

Fig. 1 presents the shaped charge model of the PG-7V warhead which includes following parts: booster, case, waveshaper, liner and main charge. In this model, the front part of the warhead is removed. The remaining parts are also simplified but all their dimensions are retained. The new waveshaper profile has been proposed for the research of its influence on the liner collapse process and the formed jet velocity. This change is shown in Fig. 2.

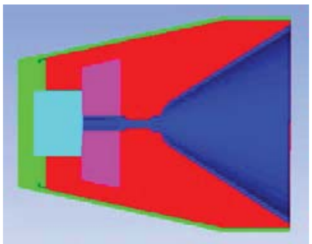

Figure 1. Simple model of PG-7V warhead.

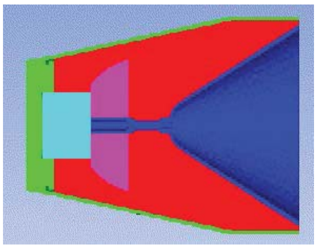

Figure 2. Model of PG-7V with new waveshaper profile.

B. *FEM Model*

The finite element method (FEM) model have been built up using ANSYS AUTODYN software, which is widely used in high explosive detonation simulations, high velocity impacts, and other problems. This software contains its own library of materials but the new materials data can be added requiring density, equations of state, strength models, and other material properties.

All parts of the liner collapse process model have been described by Eulerian grid, which is shown in Fig. 3. The simple model includes 2 parts: PG-7V warhead and an air domain in front of it. Series of Gauss points were set on the liner and the *x* axis for the observation of the jet tip velocity and other parameters. The detonation line was set at the rear edge of the booster. A coordinate system is built to determine positions of jet tip at any moment of jet moving. In this coordinate system, the axis of symmetry of the warhead is chosen as *Ox* axis, the rear edge of booster is chosen as *Oy* axis, and the origin is the intersection point of *Ox* and *Oy* axis. The coordinate system of the model is constructed as shown in Fig. 3.

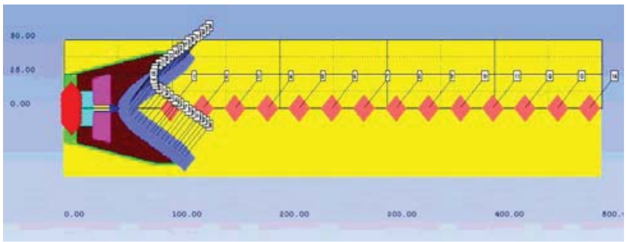

Figure 3. FEM model of the liner collapse process.

Fig. 4 presents the model of the PG-7V warhead with the new profile of the waveshaper. All parameters of model were set up the same as the FEM model for PG-7V warhead.

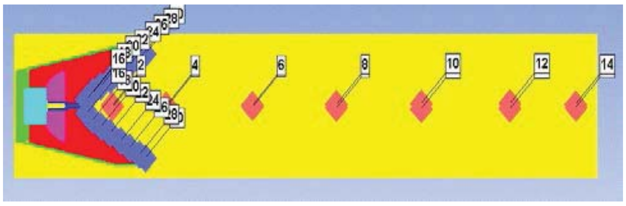

Figure 4. FEM model of the liner collapse process of PG-7V warhead with new waveshaper profile.

III. MATERIAL PROPERTIES OF MODEL

In the model, some parts use the material parameters taken from the ANSYS AUTODYN library and remaining parts use the material parameters obtained from experiments. The warhead case is from Aluminum, booster charge is from PETN 1.77, the explosive A-IX-II is used for main charge, the liner is from CuOF-HC. The new material properties have been added for waveshaper. All parameters of the materials used in the model will be described later.

A. *Material Data Input of Air*

The equation of state for ideal gas was taken for the air. The air parameters are shown in Tab. I.

TABLE I. MATERIAL PARAMETERS OF AIR

Name	**Value**	**Unit**
Density	0.001225	g/cm^3
Equation of state	Ideal Gas	-
Gama	1.4	-
Temperature	288	K
Specific heat	717.5999	J/kgK
Initial energy	2.068e5	kJ/kg

B. *Material Data Input of Waveshaper*

New material is built for the waveshaper, using shock equation as the equation of state. Tab. II introduces the material parameters of the waveshaper.

TABLE II. MATERIAL PARAMETERS OF WAVESHAPER

Name	**Value**	**Unit**
Density	1.385	g/cm^3
Equation of state	Shock	-
Gruneisen coefficient	1.3	-
Parameter C1	2.09e3	m/s
Parameter S1	1.35	-

C. *Material Parameters of Booster and Main Charge*

The main charge material A-IX-II uses the Jones-Wilkins-Lee equation of state (EOS_JWL) to describe its properties. The booster material PENT 1.77 from ANSYS AUTODYN library uses EOS_JWL, too. All parameters of booster and main charge are shown below

TABLE III. MATERIAL PARAMETERS OF BOOSTER AND MAIN CHARGE

Name	**Booster**	**Main charge**	**Unit**
Density	1.77	1.7	g/cm^3
Equation of state	JWL	JWL	-
Parameter A	6.17e8	5.37167e8	kPa
Parameter B	1.69e7	5.37926e6	kPa
Parameter R1	4.4	4.2	-
Parameter R2	1.2	1	-
Parameter W	0.25	0.4	-
C-J detonation velociy	8300	7500	m/s
C-J energy	1e7	8e6	kJ/m^3
C-J pressure	3.35e7	2.9e7	kPa

D. *Material Data Input of Case and Liner*

The material of the case - AL7039 is taken from ANSYS AUTODYNE library. It uses shock equation of state and the strength is described by Johnson Cook model. The liner material based on CuOF-HC uses shock equation of state from ANSYS AUTODYN library and Johnson Cook strength model. Tab. IV presents the material parameters of the case and the liner.

TABLE IV. MATERIAL PARAMETERS OF CASE AND LINER

Name	Case	Liner	Unit
Density	2.77	8.93	g/cm3
Equation of state	shock	shock	-
Gruneisen coefficient	2	1.99	-
Parameter C1	5.3e3	3.94	m/s
Parameter S1	1.33	1.489	-
Strength model	Johnson Cook	Johnson Cook	-
Shear Modulus	2.76e7	4.7e7	kPa
Yield strength	3.37e5	8.97e4	kPa
Hardening constant	3.43e5	2.92e5	kPa
Hardening exponent	0.41	0.31	-
Strain rate constant	0.01	0.025	-
Thermal Softening exponet	1	1.09	-

IV. Computational Results And Analysis

A. *Contact of Detonation Wave and Waveshaper*

The interaction of the detonation wave and the waveshaper as the result of the model simulation is presented below. Fig. 5 – Fig. 7 illustrate consecutive processes of interaction in details.

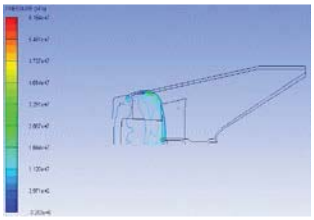

Figure 5. Detonation wave moving aroud the frontal side of the waveshaper.

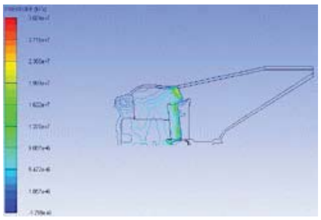

Figure 6. Detonation wave passing in the contact surface.

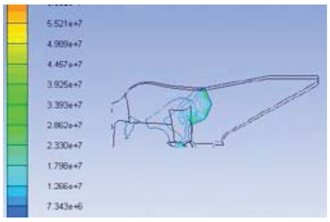

Figure 7. Detonation wave passing over the contact surface

B. *Effect of Waveshaper on Jet Velocity*

The effect of the waveshaper on the jet velocity is shown on Fig. 8 and Fig. 9. The new waveshaper profile of the PG-7V warhead increases the jet tip velocity to the value 8500 m/s. This could be explained by reason that the new profile makes the liner collapse process easier to pass around the waveshaper.

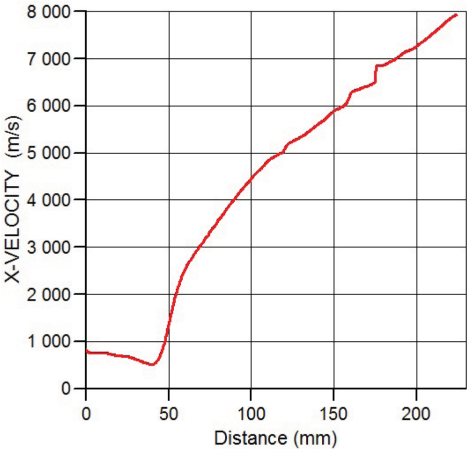

Figure 8. Jet velocity distribution in dependance on the slug + jet length of the PG-7V warhead

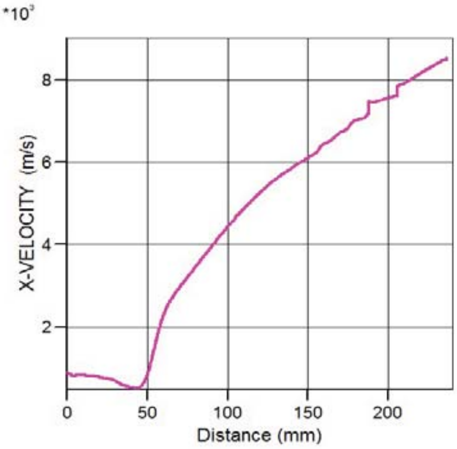

Figure 9. Jet velocity distribution in dependance on the slug + jet length of the PG-7V with the new waveshaper profile

C. *Determination of the Optimal Standoff by Simulation*

One of the most important issues of the shaped charge warhead design is how to determine its optimal standoff. At this value of the standoff, the warhead achieves maximum penetration in the target. Fig. 10 illustrates the time behavior of the jet tip velocity. It is obvious, that the jet tip velocity doesn’t change significantly during the jet formation. However, it is not the decisive factor for the optimal standoff determination.

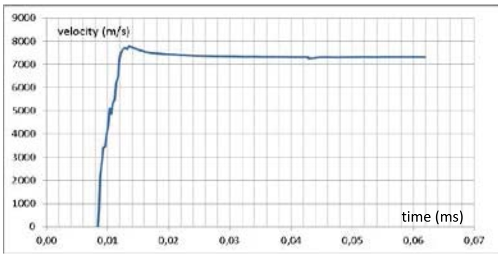

Figure 10. The velocity of jet tip vs. time.

Fig. 11- Fig. 16 consequently show the jet velocity distribution in dependence on the formed jet length, respectively. Fig. 11 illustrates the formed jet velocity at the time moment 14.6 μs. The tip velocity reaches the maximum value around 8000 m/s. The slug is moving at the velocity of about 1000 m/s. The first part of the jet accelerates very quickly under the effect of the detonation pressure. This velocity gradient causes the jet stretch to great length. The jet penetration capability is directly proportional to the jet length.

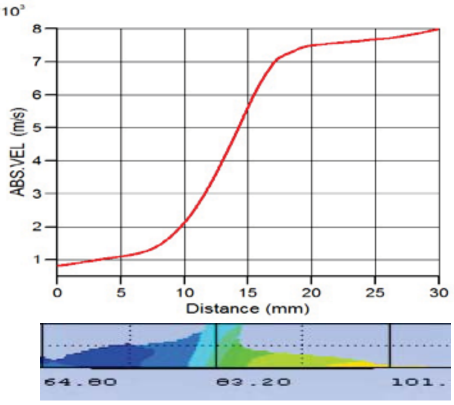

Figure 11. The jet velocity profile
at the slug + jet length equal 30 mm.

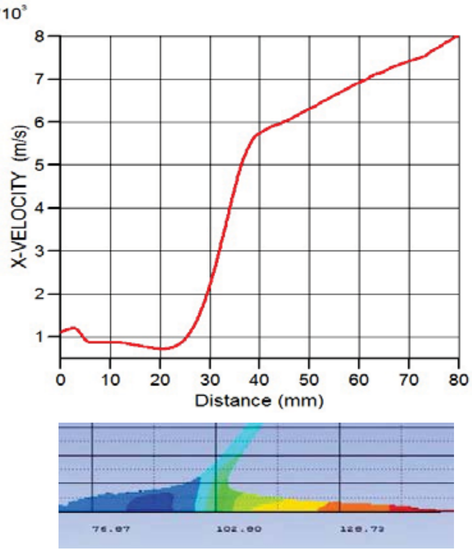

Figure 12. The jet velocity profile
at the slug + jet length equal 80 mm.

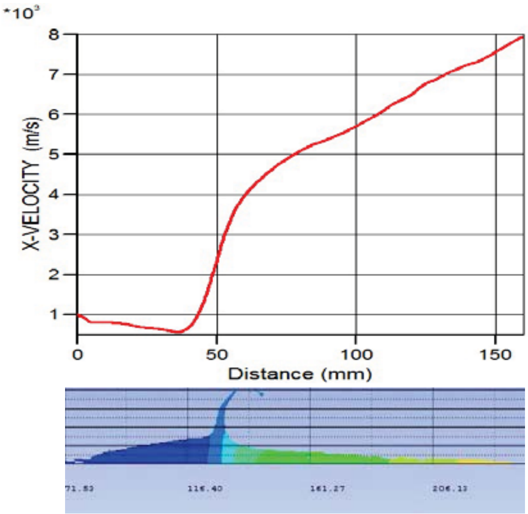

Figure 13. The jet velocity profile
at the slug + jet length equal 160 mm.

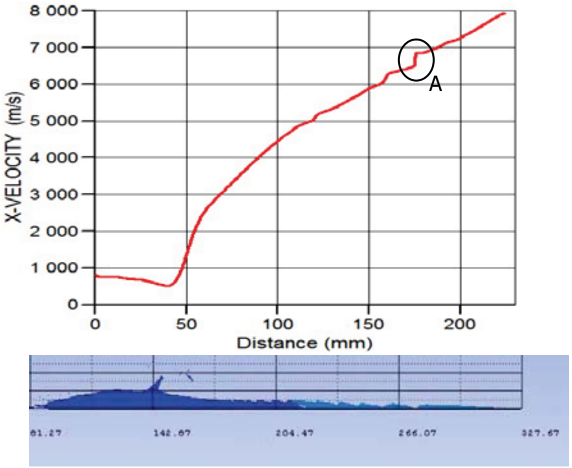

Figure 14. The jet velocity profile
at the slug + jet length equal to 237 mm.

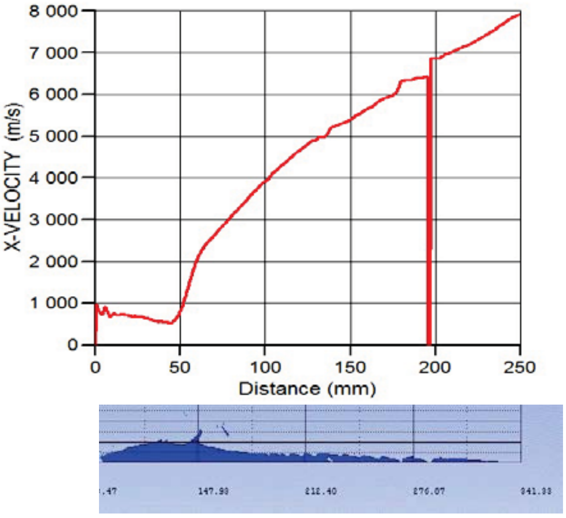

Figure 15. The jet velocity profile
of jet when the slug-jet length is 249 mm.

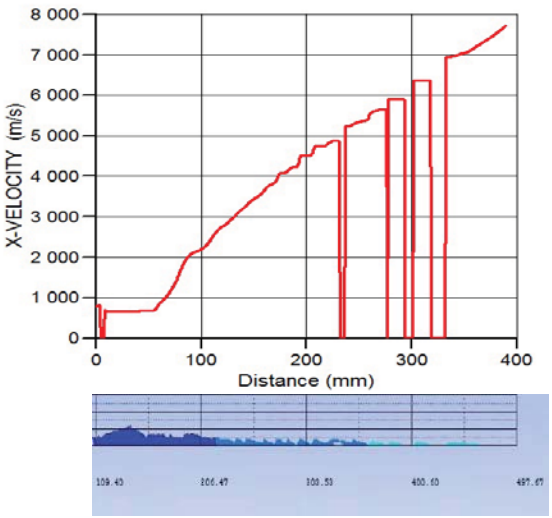

Figure 16. The velocity profile
of jet when the slug-jet length is 380 mm.

Fig. 12 and Fig. 13 show the jet formed and its velocity at the time moments 20.6 µs and 32.14 µs, respectively. All previous graphs show that the jet formed to the time 32.4 µs is continuous. The length of the formed jet is 160 mm and the coordinate of the jet tip is 240 mm.

In Fig. 14, the jump of velocity appears at position A, which is explained by the velocity gradient of the jet formed. At this moment, the coordinates of the jet tip are (327; 0). After this moment, the jet starts to break up along its length (see Fig. 15 and Fig. 16). The optimal standoff of warhead is determined when the jet is longest and simultaneously no jet breakup occurs in this simulation. When the warhead is initiated in the optimal standoff, the distance from the booster rear edge to the target is 327 mm. For the PG-7V warhead according to technical documentation it indicates that when the warhead is placed in the optimal standoff from the target, the distance from the target to the rear edge of booster is between 318mm and 332mm, depending on the precision of the charge.

According to technical documentation of the PG-7V warhead placed in the optimal standoff, the distance from the target to the rear edge of the booster is in range 318 to 332 mm in dependence on the charge precision.

V. CONCLUSION

In this paper, the process of the jet formation and optimal standoff determining are studied. The ANSYS AUTODYN software is selected in this investigation. We can note the main conclusions as shown below:

The model is built in ANSYS AUTODYN 2D code, using the technical documentation of PG-7V warhead. The model is filled with Eulerian grid. The presented method is a powerful technique for studying shaped charge phenomenon.

The whole process of the contact of detonation wave and waveshaper, the liner collapse process, the process of the jet formation, the effect of the waveshaper on the jet velocity, and warhead optimal standoff determination using analysis of the jet formation process were carried out successfully.

The determined optimal standoff is in agreement with the optimal standoff introduced in the technical documentation of the PG-7V warhead. The waveshaper with the rounded shape of frontal side results in a higher velocity than the original waveshaper shape.

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