Shaped charge and numerical modeling of their detonation

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The phenomenon of directional enlargement of the detonation effects was already known in XVIII century. It depends on the concentration of the energy, which causes local intensification of the explosion influence on the surroundings. As an example can be presented the axial cumulative effect, shown in Fig. 1.

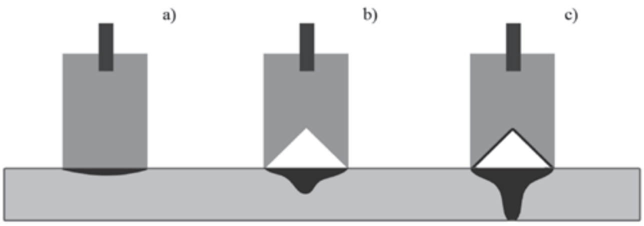

Fig. 1. Effect of the influence of flat charge (a), with hollow (b) and with hollow and liner (c)

Detonation of the cylindrical charge of the explosive, which was directly applied to the plate made of e.g. steel, causes formation of the small crater in the plate. Production of a cavity in this charge, in the shape of a cone (called hollow cavity), causes, due to detonation of explosive, the energy concentration of the detonation products on the small surface, what results in the creation of the crater with the depth similar to the diameter of the charge. Such charges were called hollow charges. This effect was noticed at the end of XVIII century by mining engineer Franz von Bader [1]. He noticed, that patterns, which were pressed on the charge during detonation were impressed on plates made of metal. This was special engraving. At the end of XIX century von Förster studied explosive engraving. He was considered to be the discoverer of the directional action hollow charges. This effect was again disclosed by Charles E. Munroe. He detonated on steel plates blocks of explosive with various initials, e.g.: U.S.N. the (United States Navy), which after the detonation impressed on the plates. In 1888, in the work of C. E. Munroe 'Modern Explosives', were described studies on the use of the shaped charges of the explosive, especially the historical experience, depending on the detonation of the explosive gelatin charge, which in the consequence of the appropriate hollowing of the charge leads to obtaining on the rock the inscription MUNROE [2]. Similar researches were led in the Germany by E. Neumann and M. Neumann (1911), and they discovered, that the effect of the directional action of the hollow charge can be significantly increased [1], if the hollow cavity is lined with the layer of solid e.g. metal, glass, ceramics, with the shape of the cavity. This layer is called the liner, whereas the hollow cavity with the liner is called the shaped charge. The directional penetration effect is called the Munroes effect (in United States) or the Neumanns effect (in the Germany). In the studies of the phenomenon of the directional penetration effect Jerzy Bałaczyński Eng. participated also. He published the work 'Matematyczna analiza działania naboi wydrążonych' in 'Przeglądzie artyleryjskim' No 1/1924. During the World War II the cumulative effect was used in many types of armour-piercing weapons, where as an example can be mentioned hand grenade launchers: in the Germany with the name 'Panzerfaust' and in the USA 'Bazooka'. Many construction were developed in the Germany, used among others to destroy ships or shelters. The largest representative from this group was the construction from the SHL (Schwere Hohlladung) series called Beethoven [1]. Its composition included hemisphere liner with the diameter 1800 millimeters and the charge of the explosive having mass of 5 metric tons. Birkhoff [3] in the USA and Ławrientiew [4] in the USSR developed bases of so-called hydrokinetic theory of detonation. This theory assumes, that the liner material during formation of the jet behaves as the liquid, and be more specific incompressible liquid, because the compressibility of the liner is being skipped. This assumption is not fulfilled, because in the collision area occurs high pressures reaching up to 100 GPa. The directional penetration effect can be strengthened by the appropriate formation of the detonation wave front [5]. Thanks to theoretical considerations and experimental researches the structure of the jet, mechanism of its formation [6, 7, 8] and the penetration of the obstacle (uniform [9], several-layer [10]) were established. The pressure of the detonation products gradually deforms and drives the jet. In the result of the pressure growth proceeds the propagation of material accumulated near the axis into two parts, which masses and speeds depend on the parameters of the shaped charge. The first of them is called the slug and the second is the jet.

- the slug - contains the larger part of the mass of the liner, it is created from the external part of the liner, moves relatively slowly (its speed usually does not exceeds 1 km/s),
- the jet - it is elongated, strongly warmed stream of the liner material, it is created from its internal part, the front of the jet achieves the largest speed 7-10 the km/s. The speed distribution along the jet can be treated as the linear in the approximation; by masses it is 10- 20 % of liner.

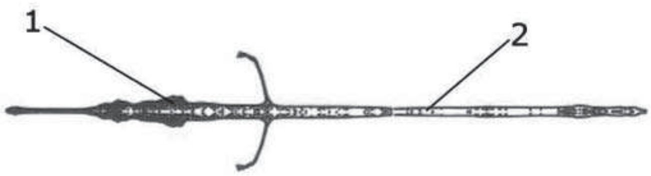

Fig. 2. Picture of slug (1) and jet (2)

In the result of shearing effects occurrence, stream and liner turn in opposite directions. It was discovered in the result of shaped charges properties studies, that the speed of the jet front diminished with the growth of the cone opening angle. For the large opening angles (over 140° - however lack of the exact boundary) instead of the jet several high-energy fragments are created. With the proper parameters selection almost whole liner material creates the uniform body with the large speed 2-3 km/s – it is so-called Explosively Formed Projectile - EFP. Many studies were led under the influence of different parameters on the cumulative effect, both from the side of the shaped charge, and also obstacle [1], which showed the shortages in the hydrokinetic theory of the directional penetration effect. It is possible to obtain the shaped charges generating streams with the speed of 100 km/s, and the possibility of reaching speed of approximately 700 km/s [11] is foreseen. Calculation equations were built up using next parts describing influence of particular factors. Description of these analytical methods can be found in [1]. Technical development, introduction of the computers, development of numerical methods, and especially pioneer work of Richard Courant and Herbret Robbins 'What is Mathematic" An elementary approach this ideas and method' published in 1941, which describes the finite element method, that caused complicated calculations become easier. Development of this method, which was not only mathematicians contribution, caused that the large quantity of the scientific works is published, where smaller or larger degree computer modeling is used. At present except the finite element method are also applied different numerical modeling methods. Even though the phenomenon of the cumulation is already well-known from long time ago, the first work, which related to this modeling appeared in 1976 [12]. With the technical progress computers made possible to solve more and more complicated models. The problem of jet generation from the shaped charge can be also modeled by the use of adequate computer codes. The phenomenon of the directional penetration effect belongs to quickly changing dynamic interactions. Behavior of materials during the simulation describe suitable models, and the basic model for metals in the conditions of strong dynamic loads is the model of elastic/viscoplasticity body. The mathematical-physical model of this phenomenon is based on the equations of the continuous centers (the behavior laws, Johnson-Cook constitution model or also Steinberg-Guinan equations of the state for solids and hydrokinetic model of the solid explosive detonation products). Among the methods, which can be helpful in modeling of the given phenomena can be mentioned:

- the Lagrange method,
- the Euler method,
- the Lagrange-Euler method,
- the Smooth Particle Hydrodynamic method,
- the Finite Element Method,
- the Free Points Method.

The Lagrange method

In this method, time and the name tags of the medium elements, are the independent variables. The spatial mesh which covers studied body (creating cells), moves and deforms together with it [13-16]. There is no transportation of the mass by the spatial boundaries of cells. The easy approximation of boundary conditions is the advantage of this method. However the basic disadvantage is the fact, that the numeric mesh while phenomena modeling with a large deformations undergoes the considerable deformation, for even so-called pathological deformation, for which further calculations do not have the physical sense. One of the ways of dealing with the problem is reconstruction of the mesh (form time to time) during the analysis (so-called adaptive meshing) [17-18], leading to the improvement of its regularity. Such a reconstruction is complicated and can lead to the loss of calculations precision.

The Euler method

The method bases on creating the immobile, not necessarily regular spatial mesh covering the area subjected to the analysis [19-21]. In this method studied body moves on the background of the immobile mesh. Except the mesh approximation lines of considered area boundaries are introduced. The boundaries of the studied body during movement create the irregular cells, which shape changes in the time. The advantage of this method is obtaining better results in the case of the phenomena, which are accompanied by the strong deformation. However, the disadvantages are the difficulty during energy streams, mass and momentum calculations, and also the need for applying complicated algorithms. Usually the computational process divides on several steps, consisting in, that the given stream is first calculated in the approximated way, and then is corrected depending on the number of approximation steps. The degree of calculations complexity grows up.

The Lagrange-Euler method

It is the building of algorithms, which aim is the possibility of both kinds of elements usage [13-15]. Connecting these methods very large number of algorithms can be obtained. In this group of methods are distinguished, among others, following groups of algorithms:

a) the algorithms, in which the area subjected to the analysis is being covered by the motionless Euler mesh, whereas the medium is treated as the group of movable particles, that is the Lagrange mesh moving through the mesh eyes of the Euler mesh. The Euler mesh serves for the field parameters qualification, whereas the Lagrange mesh serves for medium parameters qualification. Calculations are first led for the movable mesh, and then parameters of the motionless mesh are calculated. As an examples of such methods can be listed:

- Particle In Cell method - the method allows to model any large deformations of the medium and the complex moves of the multiple mediums.
- The large particles method - instead of discreet particles set (as it has places in the method of PIC), mass in Euler cell is considered as the whole.

b) algorithms, in which medium interior is described as in the Euler method, however bodies boundaries of the free bodies surfaces are described as in the Lagrange method. The use of this method leads to significant complexity of computational algorithms, but better description of the medium boundaries is possible, behavior in cells, even with a significant deformation of the medium. By the use of this method were modeled constructed and subjected to ground testing cumulative shaped charges with the mass 420 kg (272 kg of explosive, while the copper liner had the mass of 85 kg) [18].

Smooth Particle Hydrodynamic method - SPH

The method was worked out initially to simulate liquids dynamics in astrophysics. Swegle made her useful for simulating the phenomena of explosion [19]. In this method body is divided into sub-regions, and then every one of them is replaced by material particle, described among others by the position vector and mass. Particles interact between themselves, and its range defines the parameter of smoothing out, which decides about their number. The bigger smoothing parameter the more particles between themselves, what improves the pattern stability, but the time of calculations extends. Changes of the physical sizes of the given particle are obtained in the result of summing up the effects of surrounding particles influence on it with weights determined by the use of function (so-called core, the function is dependent among others from the parameter of smoothing out) in the point of given particle position. To the advantages of this method can be listed the easiness of simulation of bodies with complicated shapes and good stability of the method. To the disadvantages belong, among others, difficulty of function (core) and parameter of smoothing out selection. Using this method were tested charges with various dimensions [15, 20-21]. Also known is the method MSPH - Multi-Phase SPH - which improves computational stability and allows better seizing of jet creation process [22].

Authors of the work [13] introduced exemplary results of the jet forming process by the use of shaped charge with hemispheric liner, and then compared it with experimental results taken from works [23-24], what allowed them to evaluate applied by them free points method. Following geometrical and material parameters were assumed [23]:

- explosive (octol 75/25), density $\rho_0 = 1{,}81\ g / cm^3$, diameter S_L = 6,985 cm and height H_L = 9,0 cm,
- the copper liner: diameter S_w = 6,35 cm and thickness G_w = 0,206 cm.

Results of numerical analysis are presented in Fig. 3.

The time t = 0 is the moment of the charge initiation. On the below figure are compared results received by the free point method (a) with the results from the Lagrange method - PIC (b). The numerical analysis in the work [22] was divided into two stages.

Until t = 15 μs calculation were made with the assistance of the

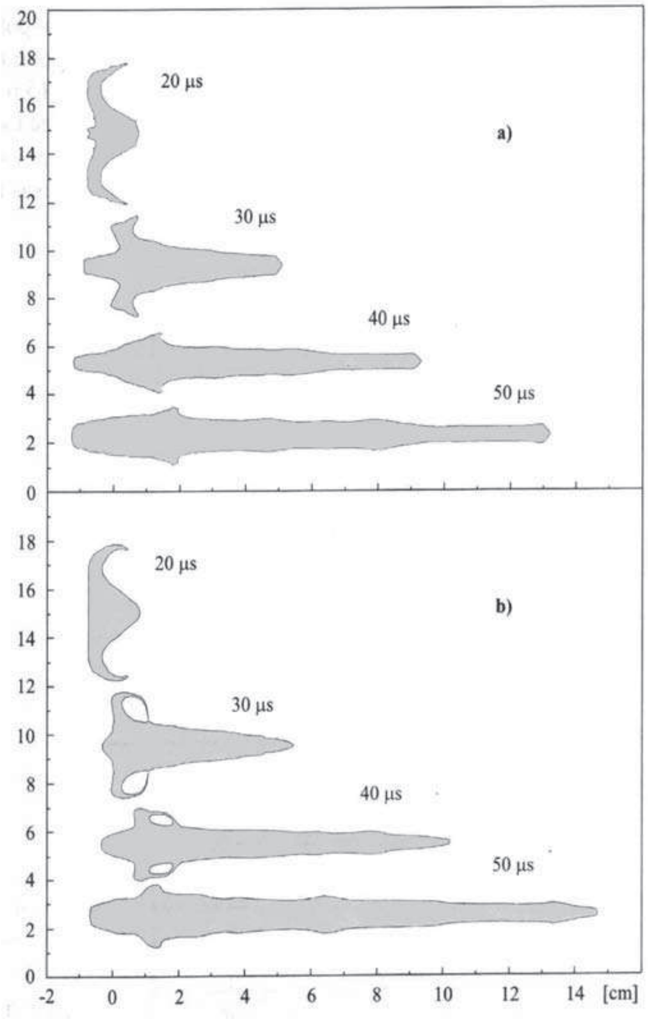

Fig. 3. Process of jet generation a) outline of jet calculated by free points method, b) results by Lagrange method - PIC [15]

numerical code based on the Lagrange method, while the next phases were modeled in Euler coordinates with the assistance of the PIC method. It was also compared, among others the jet front speed and the dependence of mass contained in the jet with respect to its mass speed. Results obtained for the distribution of jet particles mass speed as the function of their position with respect to the assumed axis are burdened with smaller fluctuations.

It was proved, that proposed physical model and built computer code assure the suitable exactness of modeling results. Moreover, the problem of modeling shaped charges was widely discussed in the work [15].

The Finite Element Method

Built model is treated as the material continuum, which divides into the finite quantity of elements with finite dimensions [13, 25]. The model is covered with the elements mesh, to which belong certain quantity of nodes, that is points with specific coordinates in space with the defined degrees of freedom and physical influences on surrounding. Every element, from the mathematical point of view, is a matrix of values dependent among the nodes degrees of freedom belonging to the element. The method applied for shaped charges modeling is so-called Arbitrary Lagrangian Eulerian method- coupling of the Lagrange method with the Euler method. This procedure consists of two following one after another steps: the mapping step and advection step. The advantage of using of this method is the assurance of the solid topology of the FEM mesh, however the range of the problems, which can be modeled with the aid of the ALE procedure depends on the degree of algorithms responsible for smoothing out the FEM mesh complicity [26].

The Free Points Method

In this method, built model is covered with the mesh of material points with appropriate densification. Properly chosen, in the initial moment, material points move together with the medium. The numerical solution consists in determination of the next positions and dependent values in these points. They can freely change theirs position at with respect to each other. Motion and the medium parameters in every point are determined from the problem equations, basing on nearest neighboring points parameters. Thanks to this, one can model freely large deformations of the medium [13, 15].

Applying this the method, by the use of physical-numerical model in the form of computer codes developed by the WAT team under the supervision of the Charles Jach, Prof. [15], was led the tests of shaped charges used for perforation of production wells and optimization of their constructions [27-28]. Modeled elements, related to shaped are as follows [29]:

- the liner - adequate mass, thickness, shape, geometrical dimensions, material type and its structure [30] have been studied and optimized years for years. Liner applied to the production wells perforation should be characterized by discontinuous jet structure, which enables formation of compact slug, making able to plug the hollow formed by shaped charge, at the same time making difficult, and even blocking the free medium outflow from the deposit. From studies [29] can be concluded, that liners made by the powders pressing technique possess these properties and do not plug formed crater,
- the explosive - should possess the high detonation speed, what has the direct transfer to the detonation pressure,
- the casing.

During designing of shaped charges used for these aims should be considered additional factors, such as:

- temperature and pressure in the production well - imposes additional requirements concerning charge resistance to high temperature and pressure,
- geometrical restrictions - they are connected both with the diameter of the production well (the overall dimensions of charge are in the average from 30 to 80 mm), and also required perforation thickness,
- parameters of deposit rock - having direct transfer, both on the depth of the perforation and also to the outlet hole, and created crater shape. Carried out experimental verification of the theoretical model [13, 15] of the jet formation process [31] states, that the model does not represent exactly the final part of slug formation process. This results form not taking into consideration in the theoretical model the convergence effects of detonation wave with the charge axis, occurring in the surroundings of the liner top.

Summary

Computer modeling is usually cheaper, than proper experimental researches, enables detailed tracking of occurring phenomena, what allows understanding of the intricate problem nature. It allows for the experimental studies limitation, which are expensive, time-consuming and dangerous. Theory and simulation are joined by conducted experiments. Is not possible to run computer simulation without adequate theoretical knowledge, which should be confirmed by experimental studies.

Literature

1. Walters W. P., Zukas J. A., Fundamentals of shaped charges. A. Wiley-Interscience Publication, 1989.
2. Nowak H., Smoleński D.: Ładunki kumulacyjne w wojsku górnictwie i przemyśle. MON, 1974, 14.
3. Birkhoff G., MacDougall D., Pugh E., Taylor G.: Explosives with lined cavities, J. Appl. Phys. 1948, 19, 6,563–582.

4. Лаврентьев М.А.: Кумулятивный заряд и принципы его работы. УМН 1957, 12, 4/76,41–56.
5. Cudziło S., Maranda A., Nowaczewski J., Trębiński R., Trzciński W. A.: Wojskowe materiały wybuchowe. Wydawnictwo Wydziału Metalurgii i Inżynierii Materiałowej Politechniki Częstochowskiej 2000, 334.
6. Włodarczyk E.: Analiza parametrów strumienia i zbitki w procesie kumulacji. Biuletyn Wojskowej Akademii Technicznej, 1992, 12(484), 13.
7. Babul W., Ziemba S.: O wpływie wytrzymałości na rozciąganie (R_r) materiału oporowego na całej długości działania strumienia kumulacyjnego na głębokość przebicia. Biuletyn Wojskowej Akademii Technicznej 1960, 9(98), 42.
8. Muszyński J., Ziemba S.: O wpływie wytrzymałości na rozciąganie (R_c) żeliwa na efekt jego przebicia ładunkami kumulacyjnymi. Biuletyn Wojskowej Akademii Technicznej 1960, 10(99), 40.
9. Nowak H.: Wnikanie strumienia kumulacyjnego w jednolitą przeszkodę. Biuletyn Wojskowej Akademii Technicznej, 1970, 1(209), 59.
10. Nowak H.: Wnikanie strumienia kumulacyjnego w masywną przeszkodę składającą się z kilku warstw różnych materiałów. Biuletyn Wojskowej Akademii Technicznej, 1969, 1(197), 110.
11. Nowak H.: Ładunki kumulacyjne służące do wytwarzania strumieni o stosunkowo dużej prędkości. Biuletyn Wojskowej Akademii Technicznej, 1968, 3(187), 79.
12. Chou P. Ch., Corleone J., Krapp R.R.: Criteria for jet formation from impinging shells and platter. J Appl. Phys., 1976, 47, 7, 2975-2981.
13. Praca zbiorowa pod red. Jacha K.: Komputerowe modelowanie oddziaływania ciał metodą punktów swobodnych. PWN, 2001.
14. Lee W.H.: Computer simulation of shaped charge problems. World Scientific 2006.
15. K. Jach, Modelowanie komputerowe zjawisk kumulacyjnych. WAT, 1990, Warszawa.
16. Thiel M., Levatin J.: Jet formation experiments and computations with a Lagrange code. J. Appl. Phys. 1980, 51, 12, 6107-6114.
17. Molinari J.F.: Finite element simulation of shaped charge. Finite Elements in Analysis and Design, 2002, 38, 10, 921-936.
18. Huerta M., Vigil M.G.: Design, analyses, and field test of a 0.7m conical shaped charge. International Journal of Impact Engineering, 2006, 32, 1201–1213.
19. Swegle J. W., Attaway S. W: On the feasibility of using smoothed particle hydrodynamics for underwater explosion calculations. Computational Mechanics, 1995, 17, 3, 151-168.
20. Liu M. B., Liu G. R., Zong Z., Lam K. Y.: Computer simulation of high explosive explosion using smoothed particle hydrodynamics methodology. Computers and Fluids, 2003, 32, 3, 305-322.
21. Liu M. B., Liu G. R., Zong Z., Lam K. Y.: Meshfree particle simulation of the detonation process for high explosives in shaped charge unlined cavity configurations. Shock Waves, 2003, 12, 6, 509-520.
22. Hongfu Q., Kunpeng W., Weiran G.: Numerical simulation of shaped charge jet using multi-phase SPH method. Transactions of Tianjin University, 2008, 14, 1, 471-575.
23. Lee W. H., Kwak D.: Elastic – plastic flow using operator splitting and aprticle-in-cell method in a two-dimensional Eulerian hydrodynamic code. Report LA-10857, 1988, UC-32.
24. Harrison J. T.: A two stage , hydrodynamic, numerical technique , HOIL and an analysis of the results of a hemispherical shaped charge liner collapse. 8th International Symposium on Ballistics- Orleando, 1984.
25. Chandrupatla T.R, Belgundu A. D.: Introduction to finite elements in engineering. Prenticle Hall, 2002, 1.
26. Małachowski J., Łazowski J., Wybrane przykłady modelowania zagadnienia sprzężenia w środowisku ALE. Modelowanie inżynierskie, 2007, 3,33, 107-112.
27. Jach K., Trębiński R., Wilk Z., Zygmunt B.: Badania ładunków kumulacyjnych z wkładkami proszkowymi do perforacji odwiertów naftowych. IV Międzynarodowa konferencja uzbrojeniowa- Waplewo, 2002, 107-112.
28. Wilk Z., Zakrzewski A., Griesgraber K., Frodyma A., Jach K., Świerczyński R.: Optymalizacja konstrukcji ładunków kumulacyjnych do perforacji odwiertów z wykorzystaniem metod symulacji komputerowych. Nafta-gaz, 2006, 62, 12, 673-679.
29. Wilk Z., Zygmunt B.: Zastosowanie ładunków kumulacyjnych do perforacji odwiertów geologicznych. Biuletyn Wojskowej Akademii Technicznej, 2007, 1, 245-258.
30. Schiferl S. K.: Texture and textural evolution In explosively formed jest. J. Appl. Phys. 1989, 66, 6, 2637-2650.
31. Cudziło S., Mroczkowski M., Świerczyński R., Jach K., Sarzyński A., Trębiński R., Doświadczalna weryfikacja modelu procesu formowania się strumienia kumulacyjnego. Biuletyn Wojskowej Akademii Technicznej, 2000, 12, 45-59.

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