Peculiarity of she shaped-charge liner collapse concerning the unevenness in its cross-section

K A Karnaukhov, V D Baskakov, V V Korenkov and O V Zarubina
Department of Physics, Bauman Moscow State Technical University, Moscow, Russia

e-mail: karnaukhov93@mail.ru

Abstract. For harmonical components of the unevenness, simulating the misalignment of the inner and the outer surfaces of the shaped-charge liner the functional connections to estimate the angular deviation of the shaped-charge jets from symmetry axis were developed. Numerical calculations in CAE system ANSYS AUTODYN for the process of collapse of the ring with the consideration of alteration of its thickness in accordance with harmonical components of the unevenness were ran to estimate the distortion of cross-sectional shape of the shaped-charge liner throughout the process of collapse. Obtained results can be used in quantitative estimations of the influence of the inaccuracies of the shaped-charge liner on geometrical and kinematical characteristics of the shaped-charge jets.

Inaccuracies in the configuration of the shaped-charge (SC) have a great influence on the shaped-charge jet (SCJ) behavior: it deviates, the cross-sectional shape distorts (in case of axial symmetry) and the penetration depth decreases.

The majority of well-known mathematical models describing the influence of inaccuracies in the configuration of the SC on the behavior of SCJ, focuses on estimation of deviation in plane case (i.e., [3-6]), but pays little attention to the distortion of the cross-sectional shape.

Works [1,7] show that the inaccuracies in configuration of SC have complex structure, which can be described by the trigonometrical Fourier’s series. For example thickness of the shaped-charge liner (SCL) in the plane of the cross-section can be represented by the following functional connection

\[ \delta(\varphi) \approx \delta_0 + \sum_{i=1}^{l} \Delta \delta_i \cos (i\varphi + \psi_i) \]  

in which \( \delta_0 \) – the nominal thickness of SCL, \( \Delta \delta_i \) – the value of an amplitude of the \( i \) – th harmonic of the inaccuracy of the SCL’s thickness, \( i = 1,2 \ldots,l \) – the number of the harmonic, \( l \) – the number of the last valuable harmonic, \( 0 \leq \varphi \leq 2\pi \) – angular coordinate in the plane of a cross-section of the SCL, \( 0 \leq \psi_i \leq 2\pi \) – phase of the \( i \) – th harmonic.

In addition, it has been discovered that the faceting of the SCJ caused by the harmonics with \( i = 2,3 \) may have a valid influence on the ultimate elongation [1].

The purpose of this work is the development of the simulative representation of the means of an influence of the specific harmonical component (1) of the inaccuracy of SCL’s thickness on the behavior of the SCJ in axially symmetrical case.

The collapse of the SCL in case of the only one harmonical component \( i = 1 \) in the structure of the inaccuracy of the SCL’s thickness may be represented by the convergent movement of conical “sheet”, that has misalignment \( \Delta \delta_i \) of inner and outer surfaces, moreover, \( \Delta \delta_i = \frac{\Delta \delta_1}{\delta_0} = \text{const} \) for every cross-section of the conical “sheet” (Figure 1).
Figure 1. The scheme of the convergent movement of the SCL’s conical “sheet”

The legend of the Figure 1 is as follows: $U$ – the velocity of convergent movement of the “sheet”; $\overline{\delta_1} = \frac{\delta_1}{\delta_0} = 1 + \Delta \overline{\delta_1}$, $\overline{\delta_2} = \frac{\delta_2}{\delta_0} = 1 - \Delta \overline{\delta_1}$ – crest and narrow thickness of the SCL in the cross-section; $\overline{\delta_3} = \frac{\delta_3}{\delta_0}$ – slug’s diameter (the outer jet); $\overline{\delta_4} = \frac{\delta_4}{\delta_0}$ – jet’s diameter (the inner jet); $\overline{\delta} = \Delta \overline{\delta_1}$ – eccentricity of the outer and the inner surfaces; $\overline{\delta}(\varphi) = \frac{\delta(\varphi)}{\delta_0}$; $2\alpha$ – an angle of the conical “sheet”; $\beta, \gamma$ – the angular deviation of the jet and the slug; $r$ – the radius of a random cross-section of the conical sheet.

The solution to a problem of the determination of the angular deviation $\beta, \gamma$ of the jet and the slug is similar to the solution of the problem of impingement of two asymmetric plane jets of an ideal fluid [3].

Write down the law of conservation of momentum along the OX and OY axes:

$$2 \vec{r} \cos \alpha = \left(\frac{\delta_3}{2}\right)^2 \cos \gamma - \left(\frac{\delta_4}{2}\right)^2 \cos \beta,$$

$$\vec{r} \Delta \overline{\delta_1} \sin \alpha = \left(\frac{\delta_3}{2}\right)^2 \sin \gamma + \left(\frac{\delta_4}{2}\right)^2 \sin \beta.$$
The system of equations (2) consists of 4 unknown variables $\delta_3, \bar{\delta}_4, \beta, \gamma$. To find its solution we define the independence of the diameters $\delta_3$ of the jet and $\delta_4$ the slug from eccentricity $\bar{e}$ are determined by well-know law in case when $\Delta \delta_1 = 0$ [2, 3].

$$\delta_3 = 2\sqrt{2\pi} cos\left(\frac{\nu}{2}\right),$$
$$\bar{\delta}_4 = 2\sqrt{2\pi} sin\left(\frac{\nu}{2}\right).$$

Using (3) in (2) and taking into consideration the smallness of the angles $\beta$ and $\gamma$ (that leads to $\sin \beta \approx \beta, \sin \gamma \approx \gamma, \cos \beta \approx 1 - \beta^2 / 2, \cos \gamma \approx 1 - \gamma^2 / 2$) we obtain

$$\beta = \Delta \overline{\delta}_1 f_1(\alpha), \quad \gamma = \Delta \overline{\delta}_1 f_2(\alpha)$$

in which $f_1(\alpha) = \frac{1}{1 + t g^2 \overline{\delta}_1}, f_2(\alpha) = \frac{t g \overline{\delta}_1}{1 + t g^2 \overline{\delta}_1}$.

Comparison of the results for axially symmetrical and plane cases [3] shows the fact that if the inaccuracies $\Delta \overline{\delta}_1$ in plane and axially symmetrical cases are equal the angular deviation in the plane case is twice as big as in the axially symmetrical case, which means that axially symmetrical jets are less sensitive to the inaccuracies of the thickness of the SCL, than plane.

Considering the identity of the approach of the mathematical modeling to the estimation of angular deviation of the jet and the slug in plane and axially symmetrical cases we can use the functional connection that approximates the results of numerical simulations, that was obtained in the work [3], to increase the accuracy of the estimation.

$$\beta = \Delta \overline{\delta}_1 f(\alpha)$$

where $f(\alpha) = 3(2\alpha)^{10} e^{-4.33(2\alpha)}$

For the estimation of the influence of harmonical components $i = 1, 2, 3$ etc on the deformation in the cross-section of the SCJ the numerical simulation of the collapse of the plane ring of a compressible fluid (water) in Lagrangian coordinates was analyzed by the means of CAE system ANSYS AUTODYN. The inner diameter of plane ring was $31 \text{ mm}$, the thickness of the ring’s wall – $1.8 \text{ mm}$. The amount of cells on the thickness and the length of circular element was 4x32. The outer surface of the ring was under pressure of $P = 30 \text{ GPa}$. Values of the inaccuracies of the thickness were 0.15, 0.25, 0.33, 0.5.

Figure 2, 3 represent the form of ring elements of numerical simulations, circular elements are shown on the field of pressure. Analysis of these results shows that the distortion of the shape of the inner surface of the ring, that is responsible for the SCJ’s cross-sectional shape occurs at any number of harmonic $i$. It was learned that at the great values of harmonical amplitudes the inner contour distorts tremendously, ensuring the contribution into the establishment of the number of centers of the SCJ formation.

**Figure 2.** Shape of the circular elements at the moment of collapse $t = 10 \mu s$, inaccuracy of the thickness $\Delta \overline{\delta}_1 = 0.15$: a) $i = 1$, b) $i = 2$, c) $i = 3$
Figure 3. Shape of the circular elements at the moment of collapse $t \approx 10$ $\mu$s, inaccuracy of the thickness $\Delta \delta_i = 0.5$: a) $i = 1$, b) $i = 2$, c) $i = 3$

The $\bar{a}$ as the ratio of the diameter $a$ of the circle, inscribed into the inner contour of the ring to diameter $b$ of the circle, described in the inner contour of the ring. Figure 4 shows the dependency graphs of $\bar{a} = \bar{a}(\alpha)$ for harmonics $i = 1, 2, 3$ in the course of a ring collapse.

Figure 4. Dependency graphs of $\bar{a} = \bar{a}(\alpha)$ for harmonics $i = 1, 2, 3$ when the intolerance of thickness is: a) $\Delta \delta_i = 0.5$, b) $\Delta \delta_i = 0.15$
Analysis of Figure 4 shows that in case of equal values of the amplitudes of intolerances $\Delta \delta_i$ the most distortion comes from the harmonic with $i = 2$.

Numerical simulations not for the compressible fluid but for copper also took place. In that case the plots of $\bar{a} = \bar{a}(a)$ for fluid and copper were completely aligned. It indicates that the density of the material has no influence on the formation of the SCJ.

**Conclusion**

1. Mathematical model for the estimation of the influence of the axially symmetrical SCL’s intolerances on the angular deviation of SCJ was developed.
2. The fact that the harmonic $i = 1$ defining the misalignment of the inner and the outer surfaces of SCL leads not to the angular deviation of SCJ only, but to the distortion of its cross-sectional shape was established.
3. The fact that the great values of the amplitude of the inaccuracy $\Delta \delta_i$ of the SCL may cause the establishment of a number of SCJ’s formation centers was shown.
4. It shows that the greatest input in the distortion of SCJ’s cross-sectional shape was made by the harmonic $i = 2$ of trigonometrical partition law of thickness of the lining in circumferential direction.

**References**

[1] Tarasov V A, Baskakov V D and Dubovskoy M A 1995 *Defensive equipment* 4 54–59
[2] Orlenko L P 2002 Physics of explosion – Ed. 3 p 656
[3] Baskakov V D, Zarubin O V, Karnaukhov K A and Tarasov V A 2016 *Bauman Moscow State Technical University bulletin of Natural sciences series* 2 79–90
[4] Baskakov V D and Karnaukhov K A 2016 *J. Phys.: Conf. Series* 731 012002
[5] Curtis J P 1998 *Proceedings of the 17th International Symposium on Ballistics, Midrand, South Africa* 2 405–412
[6] Dr. Simcha Miller and Mr. Roy Ceder 2001 *Proceedings of the 19th International Symposium on Ballistics, Interlaken, Switzerland* 843–850