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The influence of asymmetries in shaped charge performance

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ABSTRACT

Numerical analyses have been performed to investigate the influence of shaped charge asymmetries in the jet characteristics. The shaped charge configuration employed in the numerical analyses has a trumpet copper liner and aluminum casing filled with PBXN-110 explosive charge. Four types of shaped charge defects have been analyzed within the scope of the work as off-center initiation of the explosive charge, detachment of the high explosive fill from the casing, air bubbles inside the high explosive fill and shaped charge liner dimensional inaccuracies. Response of the jet against each of the above defects has been determined in terms of off-axis velocities, named as radial drift velocities, induced throughout the jet.

1. Introduction

Symmetry of a shaped charge device is crucial for the penetration performance since the whole process starting from the liner collapse is theoretically an axisymmetric phenomenon. In order to ascertain the importance of shaped charge symmetry, one can refer to the penetration process of a semi-infinite target by a shaped charge jet. It is a well-known fact that a shaped charge jet elongates and in most cases breaks up into separate particles before it hits the target material. Except the jet tip, all jet particles reach the target material at the bottom of a crater that is previously created by the impact of preceding particles. That is to say, before contributing to penetration depth, a jet particle has to travel inside the target material, i.e. through the crater, without interfering it. By preventing the interference of jet particles with the crater walls, it is assured that all jet kinetic energy is consumed to increase the penetration depth. Even a small deviation from the axis will result in crater wall interactions with jet particles, and consequent decrease in penetration performance. In Ref. [1], the decrease in penetration depth due to crater wall interactions of jet particles is discussed in detail. In practice, it is impossible to have a perfectly symmetric jet because of the limitations of manufacturing processes of shaped charges. Any defect or inhomogeneity inside the explosive fill, dimensional inaccuracies of the liner, casing and their assembly or inaccuracies of the initiation system will disturb the axial symmetry of the shaped charge and the resulting jet will no longer be symmetrical. All these defects or inaccuracies will induce off-axis velocities, i.e. radial drift velocities, throughout the jet and yield misalignments with respect to the axis. Penetration performance will degrade depending on the magnitude of radial drift velocities. The aim of the work presented in this paper is to use hydrocode simulations to determine the effect of shaped charge asymmetries in the resulting jet characteristics. Three-dimensional AUTODYN® analyses have been performed for a shaped charge configuration with some artificial asymmetries introduced and radial drift velocities of the resulting jets have been determined.

2. Shaped charge baseline configuration and hydrocode model

The shaped charge configuration used for the hydrocode analyses has a trumpet copper liner; it is filled with PBXN-110 explosive charge and confined in an aluminum casing. This shaped charge design is illustrated in Fig. 1.

Analyses were performed through the nonlinear dynamics software AUTODYN® utilizing the 3D multi-material Euler solver. Cubic cells (0.5 mm) were used throughout the whole Euler grid for all analyses. It is known that there is an optimum cell size for shaped charge analyses, which asymptotically converges to a small value beyond which no improvement of the results is obtained [2]. However, cell size was taken as 0.5 mm for this study, because the number of cells increases very rapidly for a three-dimensional analysis as the cell size gets smaller and computational time grows considerably. Material models for copper liner and aluminum casing were taken from the standard library of AUTODYN®. The explosive fill, PBXN-110, was modeled using JWL equation of state. JWL parameters of PBXN-110 are given in Table 1.

Shaped charge configuration in Fig. 1 was modeled inside a 3D multi-material Euler grid with the material properties mentioned. Euler grid was formed a little larger than the shaped charge outer

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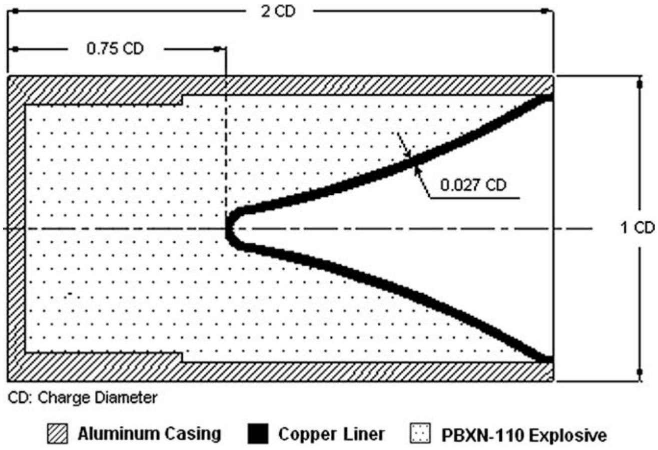

Fig. 1. Shaped charge design – baseline configuration.

Table 1
JWL parameters for PBXN-110 explosive [3]

Reference density (g/cm^3)	1.672
Parameter A (GPa)	950.4
Parameter B (GPa)	10.98
Parameter R_1	5
Parameter R_2	1.4
Parameter W	0.4
C–J detonation velocity (m/s)	8330
C–J detonation energy/unit volume (GPa m^3/m^3)	8.7
C–J pressure (GPa)	27.5

diameter so that the detonation products and deformed casing have some space to expand. This additional space was limited to approximately 0.2 charge diameter distance by a flow out boundary condition applied to the outer surfaces of the grid.

3. Asymmetries/defects applied to the baseline configuration

Shaped charge asymmetries were applied to the hydrocode model described in Section 2. Asymmetries modeled in AUTODYN® simulations are briefly described in the oncoming paragraphs.

3.1. *Off-center initiation of the explosive charge (Fig. 2a)*

Off-center initiation is likely to occur especially if no precision initiation coupler is used in shaped charge devices. In order to represent the off-center initiation encountered in real applications, the initiation point of the detonation reaction was shifted from the axis of the charge by a distance d in the numerical model; 0.0016, 0.0032, 0.0161 and 0.0484 CD shift distances have been analyzed to determine the effect of eccentric initiation on the jet symmetry.

3.2. *Detachment of the high explosive fill from the casing (Fig. 2b)*

In some cases, it is possible to encounter a detachment of the explosive fill from the casing. This is due to stimuli such as aging, thermal loads, etc. To account for this effect in the numerical simulations, a thin half-ring of explosive material with 0.0161 CD thickness and length x was removed from the outer surface of the explosive charge as illustrated in Fig. 2b. Analyses have been performed for three different x values: 0.35 CD, 0.43 CD and 0.57 CD.

3.3. *Air bubbles inside the high explosive fill (Fig. 2c and d)*

Especially in cast explosive charges, air bubbles may be formed inside the explosive fill due to poor quality in vacuuming, casting system and apparatus. To assess the condition of shaped charge jet in the existence of air bubbles inside the explosive fill, spherical air bubbles were placed inside the explosive material in the numerical model as seen in Fig. 2c and d. Although it is not frequent to have big air bubbles inside the explosive charge in real applications, air bubbles in the analyses were taken relatively big with 1.5 mm

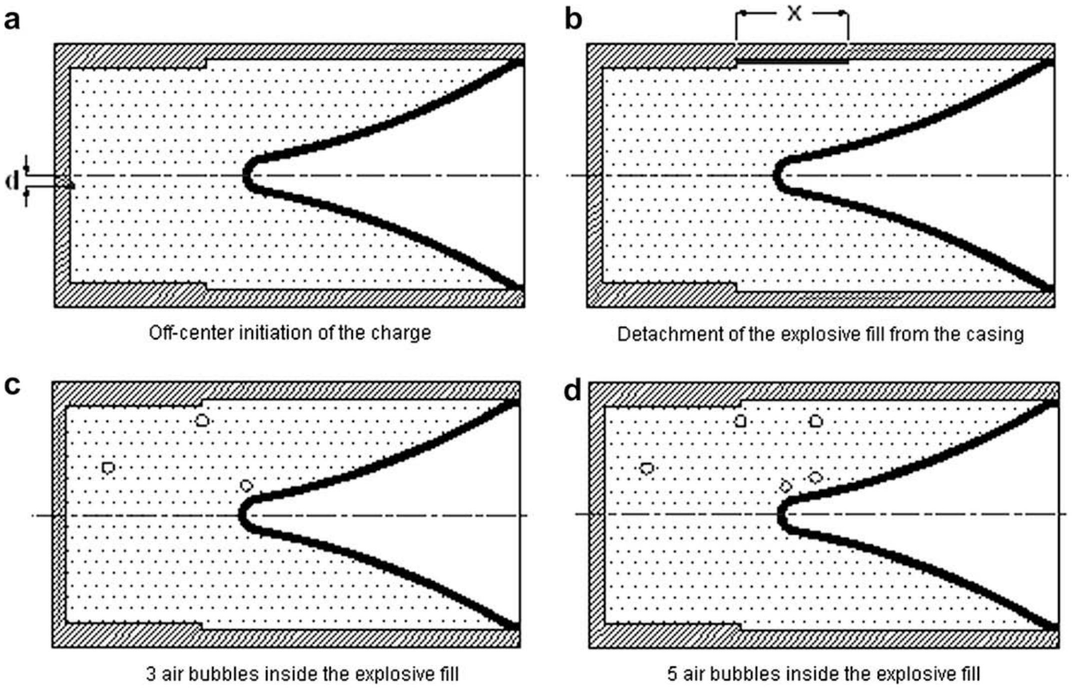

Fig. 2. Asymmetries/defect modeled in the simulations.

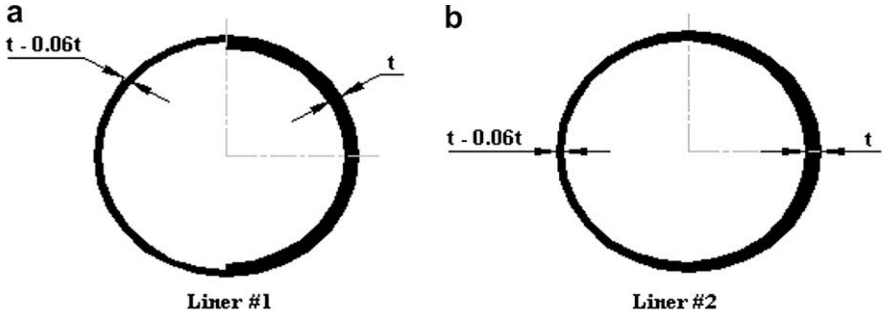

Fig. 3. Liner configurations with 6% thickness variation from the original liner thickness (schematic view, not to scale).

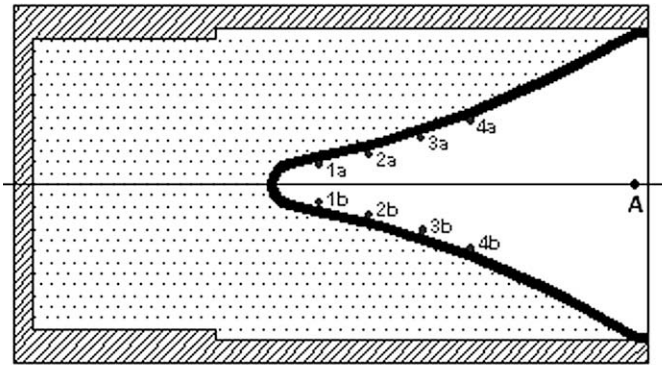

Fig. 4. Location of virtual gauge points.

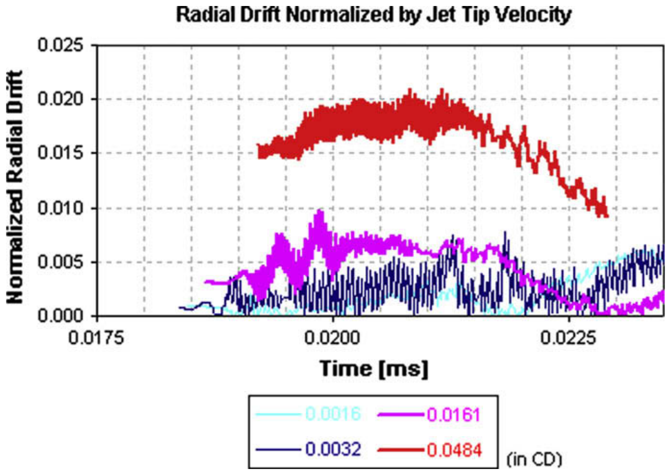

Fig. 5. Normalized radial drift velocities for eccentrically initiated shaped charges.

radius just to represent the effect more clearly. In two distinct analyses, three and five bubbles were placed inside the explosive fill. Bubbles are located such that there is one bubble nearby the initiation point, one at the apex of the liner and one close to casing interface (Fig. 2c).

3.4. *Shaped charge liner dimensional inaccuracies*

Dimensional accuracy of the metal liner includes circumferential and longitudinal thickness variations, runout and form tolerances. Among all of these dimensional and geometric tolerances, circumferential thickness variation has the tightest limits as suggested in Ref. [4]. Therefore, in the numerical simulations only the circumferential thickness variation has been analyzed. Firstly, circumferential thickness variation was given by reducing the thickness of one-half of the liner by 6% of the liner original thickness and applied discontinuously as shown in Fig. 3a. In the second analysis, maximum change in thickness from one-half to the other was still 6% of the liner original thickness yet the change was smoothly applied as seen in Fig. 3b.

4. Results of numerical analyses

The effects of the asymmetries described in previous section have been determined by comparing the radial drift velocities (i.e. off-axis velocities) along the shaped charge jet. Although the actual performance criterion for a shaped charge device is its armor penetration capability, penetration analyses have not been performed within the scope of this work due to the extremely large three-dimensional solution grid required for such an analysis. Still, some useful information about the final performance of a shaped charge device can be drawn from the radial drift velocities; an example may be found in Ref. [5].

In the oncoming paragraphs, results of numerical analyses are given with explanatory discussions in the light of radial drift

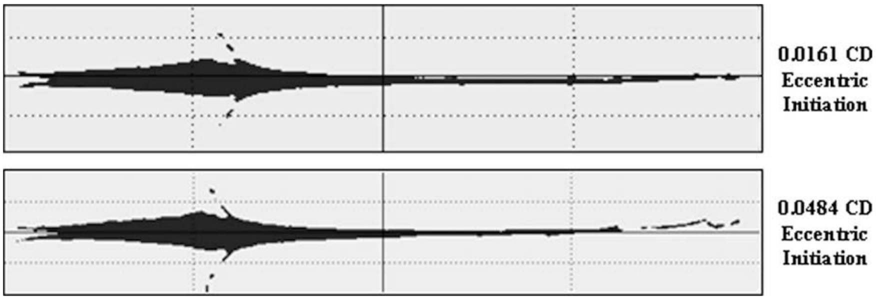

Fig. 6. Jets from eccentrically initiated shaped charges (50 μs from initiation).

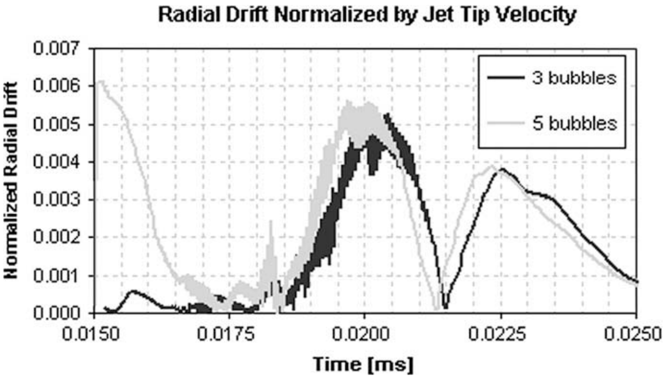

Fig. 7. Normalized radial drift velocities in the presence of air bubbles inside the explosive fill.

velocities recorded on the axis at 1 CD distance from the liner apex. Moreover, for detailed interpretation of the effects of shaped charge asymmetries on final jet quality, the difference between *y* component of the velocities of collapsing liner has been compared at different positions along the axis. In order to record these velocity components, virtual gauge points were placed on the numerical grid, whose location is shown in Fig. 4.

Effect of eccentric initiation was analyzed by offsetting the initiation point from the axis by 0.0016 CD, 0.0032 CD, 0.0161 CD and 0.0484 CD distances. Radial drift velocities for these analyses recorded at Gauge-A (Fig. 4) over the time are given in Fig. 5. The data in Fig. 5 are the radial drift velocities normalized by the tip velocity of baseline shaped charge configuration having no asymmetries.

As clearly seen in Fig. 5, effects of off-axis initiation on drift velocities do not change drastically from 0.0016 CD initiation point shift to 0.0032 CD and 0.0161 CD; yet, a sudden jump in drift velocities is observed for 0.0484 CD off-center initiation. In Ref. [6], which discusses the effect of eccentric initiation of shaped charges experimentally by utilizing flash X-ray radiographs, such behavior in the drift velocities may be observed between 0.0315 CD and 0.0630 CD off-axis initiations. To visualize the information given in Fig. 5 and better understand the radial drift effect on shaped charge jet behavior, two views of jets from shaped charges having 0.0161 CD and 0.0484 CD initiation eccentricity are given in Fig. 6.

Two analyses were performed to determine influence of air bubbles inside the explosive fill as illustrated in Fig. 2c and d; and radial drift velocities recorded at Gauge-A are presented in Fig. 7. The data given in Fig. 7 are also normalized by the tip velocity of baseline shaped charge.

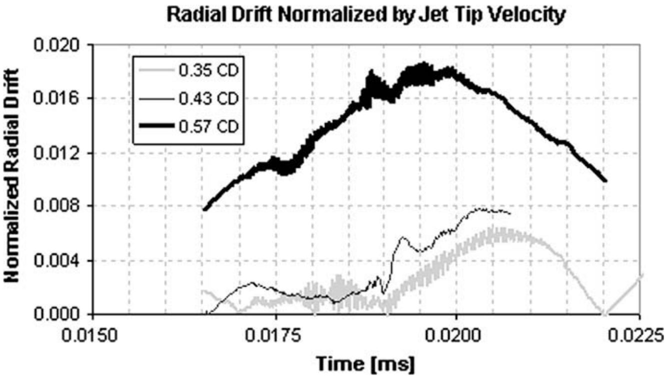

Fig. 9. Normalized radial drift velocities in the presence of explosive detachments from casing.

Radial drift behaviors of the jets from two shaped charges are quite similar as seen from Fig. 7; except for the sudden increase in drift velocity for the shaped charge with five air bubbles at early times. Because the jet tip portion arrives the gauge point earlier than the rear portion, this sudden increase shows the radial drift of the jet tip which can be associated with the additional two air bubbles near the liner apex (see Fig. 2d). To illustrate the jet deviations as it is being formed and to better interpret the source of big drift velocities at the jet tip for five-bubble configuration, difference in *y* components of the velocities of collapsing liner material is compared for virtual gauge pairs (see Fig. 4) 1a and 1b; then for 3a–3b in Fig. 8, where the velocities are normalized by the tip velocity of baseline shaped charge.

For a perfectly symmetric shaped charge, *y*-velocity components recorded at gauge-1a and gauge-1b should be exactly the same, which is theoretically a requirement for all stations along the axis like 2a–2b, 3a–3b, etc. to have an aligned jet. It is evident that differences in *y*-velocity components during the liner collapse process will cause a momentum difference and consequent radial drift velocities. If Figs. 7 and 8 are taken into account simultaneously together with the gauge locations given in Fig. 4, it can be concluded that the big drift velocities observed in five-bubble configuration at the beginning are induced by the difference in *y*-velocity components of collapsing liner near the apex. In addition, one can further deduce that these differences are caused by additional air bubbles near apex portion.

The effect of explosive detachments from the casing was investigated by the three analyses mentioned earlier and the normalized radial drift data recorded at Gauge-A (Fig. 4) are given in Fig. 9. It is clear from the figure that as the length of detachment increases, i.e. as the explosive detachment from casing extends

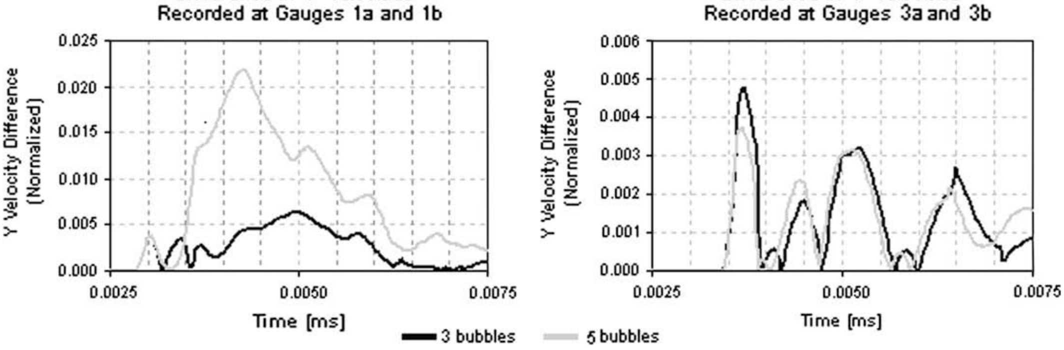

Fig. 8. Differences in *y*-velocities recorded at gauge pairs 1a–1b and 3a–3b (normalized values).

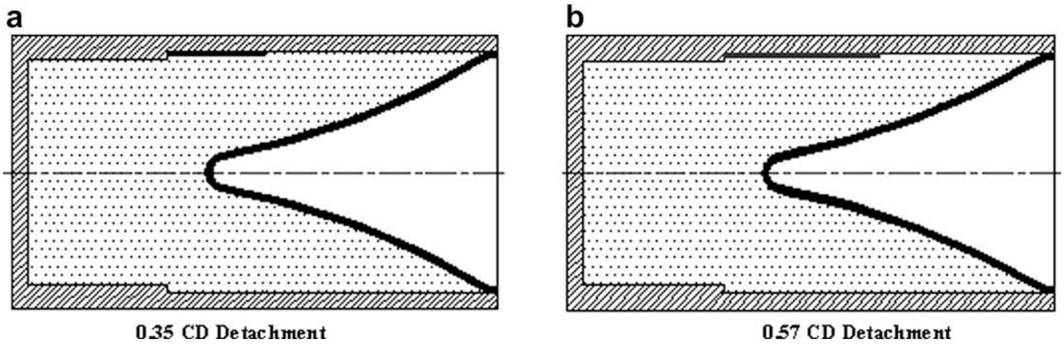

Fig. 10. Increase in detachment length.

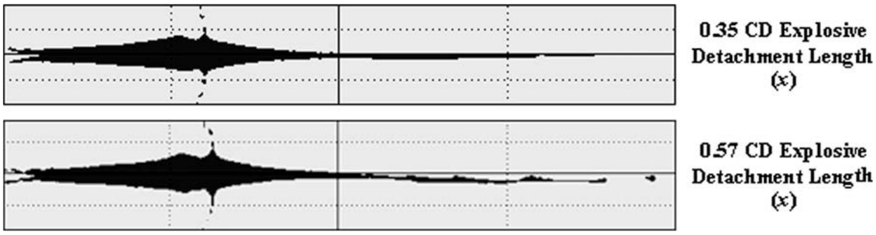

Fig. 11. Jets from shaped charges with explosive detachment from casing (40 µs from initiation).

towards the liner base, radial drift velocity grows; as the detached explosive length extends, a consequent increase will occur in the portion of liner which is inside the zone directly affected by the asymmetry (Fig. 10).

The 0.35 CD and 0.57 CD detachments look the same up to 0.35 CD distance and it may be expected that the tip portion of the jet produces similar drift velocities; however, this is not the case as seen in Fig. 9. This could be explained by the liner collapse and jet formation processes; it is a well-known fact that the tip of a shaped charge jet is not formed only by the liner apex, instead a portion of liner is responsible for jet tip formation due to the phenomena named inverse velocity gradient (reader may refer to Chapter 8 of Ref. [3]). Therefore, as the influence area of asymmetry is enlarged by increasing the detachment length, deviations of jet tip will also increase, because more liner elements affected by the asymmetry will contribute to tip formation as well as formation of the rest. This same interpretation may be applied to the situation for shaped charges with three and five air bubbles.

Lastly, the effect of liner circumferential thickness variation on jet departure from the axis will be discussed. As stated in the previous section, thickness variation in the circumferential direction was taken as 6% of the liner original thickness and two different liners shown in Fig. 3a and b were analyzed in numerical simulations. Normalized radial drift velocities for shaped charge configurations with these two liners are given in Fig. 12.

As seen from the radial drift velocity information, Liner#1, the liner which has a discontinuous thickness variation in the circumferential direction (see Fig. 3a), creates more jet deviations from the axis. The difference between two liners is more evident at the middle portion of velocity–time plot in Fig. 12, meaning that the jet tip from two shaped charges has approximate drift velocities while the middle and rear portions of the two jets differ much larger. Actually, both of the liners form jets with very high drift velocities at the tip portion. Reader may recall the previous discussion about the jet tip deviations in the presence of explosive detachments, which is also applicable to the current situation. However, an additional comment should be made for asymmetric liners such that the liner thickness asymmetry is a continuous defect from apex to base; thus, the deviations are constantly produced while liner is collapsing and larger asymmetries are observed in slug as illustrated in Fig. 13.

Similarly, explosive detachments are also not pointwise defects and act over a portion of the shaped charge; therefore, shaped charges with explosive detachment from casing show quite similar drift velocity patterns over time (compare Figs. 12 and 9) except for the slug portions. Because explosive detachments are not extended to the base of the liner, their effects decay after some time and slugs do not present large departures from the axis (compare Figs. 11 and 13).

5. Conclusions

Shaped charge jet deviations in the presence of four different types of asymmetric defects have been studied through numerical analyses performed through the nonlinear dynamics software AUTODYN®. Results of all numerical calculations show that any asymmetry in the shaped charge configuration will produce radial drift and deviation of jet from the axis. It is the location, magnitude

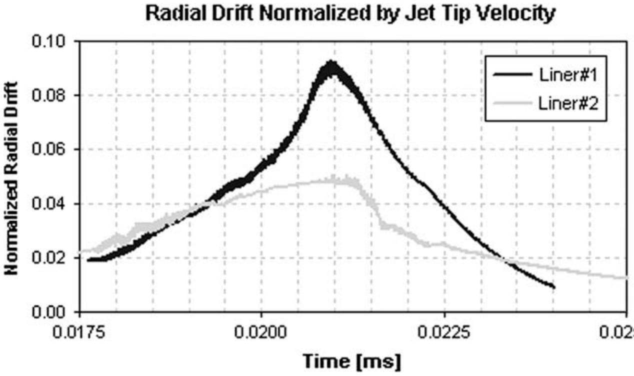

Fig. 12. Normalized radial drift velocities for liners with circumferential thickness variation.

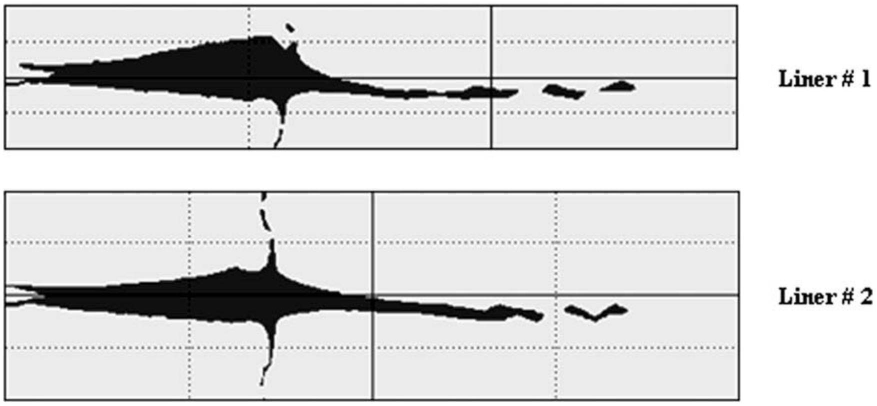

Fig. 13. Jets from shaped charges with asymmetric liners (40 μs from initiation).

and extent of the defect that determine the severity of final jet deviations. That is to say, two asymmetries of same type may produce radial drift velocities from a few meters per second to very large values just by changing the magnitude of the asymmetry. In eccentric initiation of shaped charges, this situation may clearly be observed by comparing the results of 0.0016 CD eccentric initiated shaped charge with 0.0484 CD eccentric initiated one. As an example to the importance of location of asymmetries, one may study the analyses of shaped charges with air bubbles inside the explosive fill, where the jet tip formation process was affected considerably by the additional two air bubbles. It is obvious from the radial drift velocity plots that the largest deviations were produced by asymmetric liners, and the least by introducing air bubbles inside the explosive fill. This may show that the symmetry of the jet is more sensitive to the defects in liner geometry compared to other defects. Still, these results should not be interpreted as criteria to decide which type of asymmetry will be allowed in a shaped charge configuration; because, as stated previously, determining factor of the severity of jet deviations is not the type of the asymmetry; it is the location, magnitude and extent of the asymmetry.

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