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STUDY OF SPIN-COMPENSATED SHAPED CHARGES

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If a standard shaped charge spins during the collapse of its liner, the jet formation process is disturbed; as a consequence, its penetration capability decreases. This loss of performance can be compensated by liner design. We present experimental and numerical data for a 50 mm / 60° charge with fluted liner: on the inner cone surface, asymmetric flutes are running from the base to the apex of the liner.

Experimental results obtained for two liner geometries are shown, e.g., the penetration depth in a steel target as a function of the spin velocity. Two-dimensional numerical simulations of fluted liners are also discussed. They provide a tool to roughly estimate the optimal charge spin rate and its variation trend when one or several design parameters of the charge are changed.

INTRODUCTION

Most of the shaped charge warheads are spinning during their flight to the target. On the one hand, spinning enhances their aerodynamic stability; on the other one, however, the rotation disturbs the jetting process of the charge. In the 1950's, intensive investigations of the spin disturbances and of ways to minimise them were undertaken. Among the various methods then devised to compensate spin rates in the range 20–200 r.p.s., an efficient one was found in the form of fluted liners. Eichelberger conducted extensive experimental research with such liners by systematically varying the different design parameters (number of flutes, flute depth, flutes on the inner or outer side of the liner, etc.). The nomenclature adopted hereafter for liner types and design parameters (Fig. 1) is directly derived from his fundamental work [1].

The present paper is organised as follows: In the next section we shall compare experimental data from [1] with numerical simulations for charges equipped with fluted liners of type III. Having shown the relevance of our simplified numerical model, we shall compute the collapse of type V fluted liners. The last section then presents experimental results for two different geometries of type V fluted liners.

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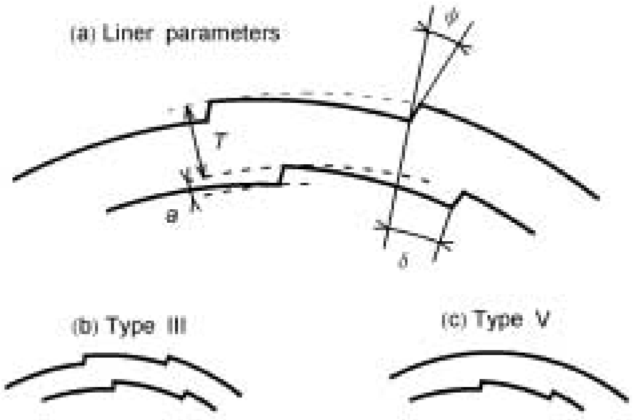

Figure 1: Design parameters for fluted cones and liner types. (a) *T* is the wall thickness before fluting, *a* the flute depth, δ the index angle and *ψ* the angle between step offset and radius. (b) and (c) show the profiles of type III and type V fluted liners respectively.

Throughout the paper, positive spin rates correspond to counterclockwise rotation velocities when looked at from the rear end of the charge.

NUMERICAL SIMULATIONS OF FLUTED LINERS

Due to the enormous amount of calculations and of memory required by three-dimensional simulations, we only computed the collapse of two-dimensional systems which are thought to correspond to cross-sections through a charge with fluted liner. Such an approach was already used by other authors to investigate the behaviour of spinning charges [2,3]. The 20% of the inner mass of the liner are supposed to form the shaped charge jet, while the remaining 80% outer mass produce the slug. In view of these crude approximations we only expect to get some qualitative insight in the phenomenon of spin compensation. The calculations have been done with the HULL program of Orlando Technology [4] in a square Eulerian grid with mesh size 0.1 mm x 0.1 mm. For all materials, strength was neglected.

To check the effect and validity of the previously mentioned approximations, we tried to numerically reproduce some of Eichelberger's experimental observations by computing the collapse of a two-dimensional cut through a type III copper liner with 16 flutes. The index angle δ was varied between 0° and 22.5° (=360°/16). Having numerically determined the mean rotation frequency ν_{jet} reached by the jet during the collapse of a statically fired fluted liner, one evaluates the optimal charge spin velocity ν_o which would compensate the jet spinning as follows. Let us assimilate the jet to a cylinder with radius r_{jet}, mass M_{jet} and spin frequency ν_{jet} ; its angular momentum L_{jet} is given by

$$L_{jet} = \pi M_{jet} \nu_{jet} r_{jet}^2 . \tag{1}$$

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The jet originates from material which, before collapse, is located on a ring with internal radius r_o and external radius $r_o + h_o$ ($h_o << r_o$). Parameter h_o is related to the liner thickness T by the assumption that the jet is formed by the inner 20% of the cone material: $h_o = 0.2\ T$. The momentum L_o of a ring with mass M_{jet} rotating at frequency ν_o is approximately equal to

$$L_o = 2\,\pi M_{jet}\,\nu_o\,r_o\,(\,r_o + h_o\,)\,. \tag{2}$$

By applying the conservation of angular momentum, i.e., $L_o = L_{jet}$, one evaluates the initial rotation rate ν_o which, after collapse, leads to the jet spin velocity ν_{jet}:

$$\nu_o = \nu_{jet}\,r_{jet}{}^2 / [\,2\,r_o\,(\,r_o + h_o\,)\,]\,. \tag{3}$$

The radius r_{jet} is related to r_o by mass conservation:

$$r_{jet}{}^2 = (\,r_o + h_o\,)^2 - r_o{}^2 \cong r_o\,h_o\,. \tag{4}$$

This expression is derived under the assumption that the liner element doesn't stretch during the collapse. The spin frequency ν_o is thus determined by the simple relation

$$\nu_o = \nu_{jet}\,h_o / (\,r_o + h_o\,)\,. \tag{5}$$

The parameters used in our numerical simulation correspond to a cut through Eichelberger's 57 mm charge [1] at a height where $r_o = 18$ mm, $h_o = 0.2\ T$ and $T = 1.539$ mm. With these values (5) becomes

$$\nu_o \cong \nu_{jet} / 60 \tag{6}$$

(it should be noted that ν_{jet} as well as the proportionality factor depend on the position of the cut). As a consequence, to compensate the jet rotation ν_{jet} induced by the flutes, the charge should spin in reverse direction with frequency $-\nu_{jet}/60$. Figure 2 compares experimental and numerical data ; the numerical jet spin rate ν_{jet} had to be scaled by a factor $-1/90$ (instead of $-1/60$) to agree with Eichelberger's experimental determination of the

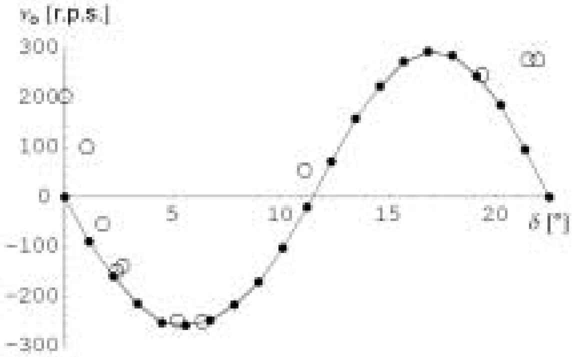

Figure 2: Comparison between experimental (○) and numerical (●) results for the optimal charge spin velocity ν_o as function of the index angle δ for a type III liner. The simulated charge was filled with Comp-B and enclosed in a 1.5 mm thick steel mantle. Observe the reversal of the spin direction at $\delta \cong 12°$. As explained in the text, we have calculated the jet spin frequency ν_{jet} and used the scaling $\nu_o = -\nu_{jet}/90$ to fit the calculated charge rotation velocity on the experimental data, whereas the crude estimation (5) gives $\nu_o = -\nu_{jet}/60$.

optimal charge rotation velocity. There is thus a factor of 1.5 between experimental and numerical results, which is surprisingly good in view of the approximations used to model the rotating charge. The simulation reproduces the change of spin compensation direction when the index angle δ increases. However, the two-dimensional calculation severely underestimates the effect of flutes at index angles close to the boundaries $\delta = 0°$ and $\delta = 22.5°$ of the index periodicity interval.

Having obtained some confidence in this simplified way of simulating a fluted cone, we modelled a type V liner (Fig. 1). The simulation concerns a fluted copper liner fired statically ; the spin rate ν_{jet} of the jet is again computed by assuming that the 20% of the inner liner material produces the jet. The optimal charge spin rate ν_o is then evaluated by use of relation (5). For the calculation, we used the following values : liner radius at position of cut $r_o = 20$ mm, liner thickness $T = 2$ mm, flute depth a in the interval [0.5 mm, 1.2 mm]. The charge is enclosed in a 1.5 mm thick aluminum case with external radius 26.5 mm, filled with LX-14.

Figure 3 presents numerical results concerning the charge spin velocity ν_o as a function of the flute depth a. Interestingly enough, the optimal compensation rate ν_o changes its sign as the flute depth a increases, being positive for $a < 1$ mm and negative when $a > 1$ mm.

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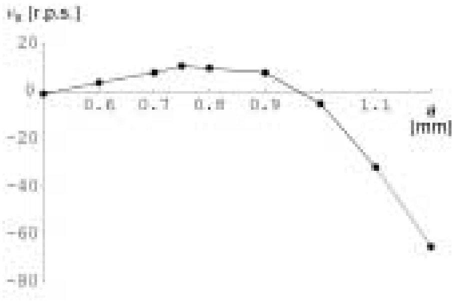

Figure 3: Charge with type V liner. Numerical results (•) for the optimal spin velocity ν_o as a function of the flute depth *a*, 15 μs after initiation of the explosive (t = 15 μs corresponds approximately to the end of the liner collapse). The reversal of the spin direction at *a* ≅ 1.0 mm should be noted.

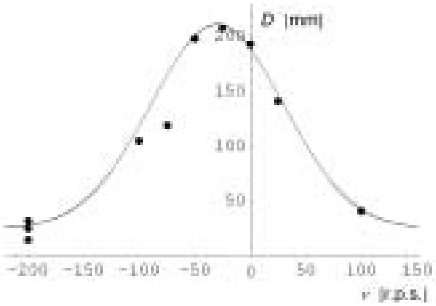

Figure 4: Experimental results for the penetration depth *D* of the jet produced by a type V fluted liner (geometry 1, *a* = 0.6 mm) as a function of the charge spin frequency ν, at 1000 mm stand-off. The maximum penetration is reached at ν = (–30 ± 5) r.p.s.

EXPERIMENTAL RESULTS

Based on these simulations we decided to perform experiments with two kinds of type V copper liners whose characteristics are listed in the following table. In both geometries the depth of flutes decreases linearly as the steps approach the liner apex.

		Geometry 1	Geometry 2
Cone aperture angle	α	60.0°	60.0°
Number of flutes	n	16	16
Outer liner radius at base	r_o [mm]	25.0	25.0
Liner thickness	T [mm]	2.0	2.0
Flute depth at liner base	a [mm]	0.6	1.2
Step angle	ψ	1.5°	1.5°

According to figure 3, charges with a liner having geometry 1 are expected to require a spin compensation of about 5 to 10 r.p.s., while those with a liner characterized by geometry 2 should need a compensation of –70 r.p.s. As a qualitative measure of spin compensation we used the penetration depth D of the jets in steel targets placed at 1000 mm stand-off. The spin velocity ν of the charges was varied between –200 and +200 r.p.s.

Experimental results for geometry 1 (0.6 mm flutes)

Figure 4 presents, for geometry 1, the jet penetration *D* as a function of the charge spin rate ν. The optimal spin compensation is obtained for $\nu = \nu_0 = (30 \pm 5)$ r.p.s. The maximum penetration *D* = 208 mm corresponds approximately to the one of a smooth equivalent liner fired statically.

While the penetration depth only allows a global statement about the mean spin compensation, comparing X-ray pictures of charges with different rotation rates enables to draw conclusions about the local jet spinning. It comes out that, at $\nu = 0$, the front part of the jet (looking like undisturbed) rotates counterclockwise at a high rate (see Fig. 5 and discussion of geometry 2). The second half of the jet spins much more slowly; this makes it difficult to determine its sense of rotation. These conclusions agree with the direction of spin compensation in figure 4.

With the liner of geometry 1, the radial fragmentation of adjacent drops of the jet due to the centrifugal forces is correlated. The jet seems to break up in two (sometimes three) strands along its original axis.

Experimental results for geometry 2 (1.2 mm flutes)

Jets produced by liners with geometry 2 are never clean from tip to slug ; at every spin rate ν some parts are either under- or overcompensated. The maximum penetration *D* = 195 mm is reached at $\nu = 0$. Despite the lack of spin compensation, the Röntgen pictures of these jets exhibit several interesting characteristics (Fig. 6). The jet of a statically initiated charge presents two “bellies ” on its rear part, while the front of the jet remains flawless. If, on the one hand, the charge rotation velocity is increased to –25 or –50 r.p.s., the radial amplitude of these bellies decreases, the first one vanishing even completely; this indicates local spin compensation by the fluted liner. On the other hand, if the charge rotates in the opposite direction at rates equal to +25 or +50 r.p.s., the size of the first belly increases notably. This indicates that particles in the rear of the jet have positive (counterclockwise) spinning rates.

The front part of the statically fired jet doesn’t present any deformation. However, at +50 r.p.s., some drops start to show deficiencies. At –50 r.p.s., in the middle of the same region, a small belly begins to grow. This is a clue that, for a charge fired at 0 r.p.s., the front of the jet has a small negative spin rate, that is, it rotates in opposite direction to the rear part.

Comparing geometries 1 and 2, it appears that the whole jet spinning dynamics is subjected to non-linear changes when varying the flute depth. The change of spinning direction suggested by simulations is observable in the experiments presented here.

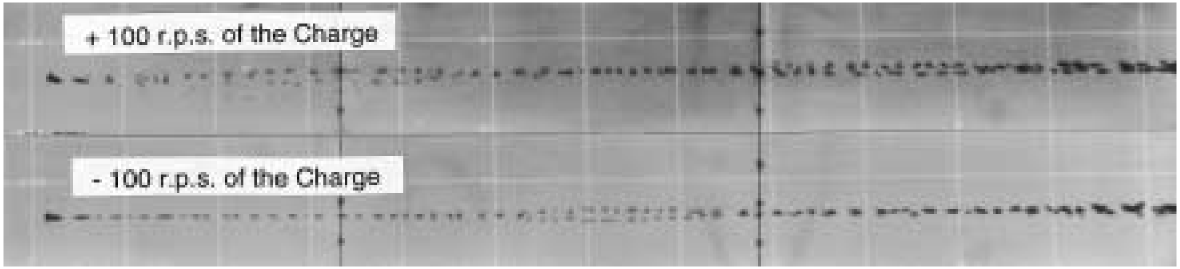

Figure 5: Röntgen pictures of jets produced by liners of type V with 0.6 mm flutes. The charges are spinning at velocity +100 r.p.s. (top) and –100 r.p.s. (bottom) respectively. X-Rays shoots are taken 120 µs after initiation of the charge.

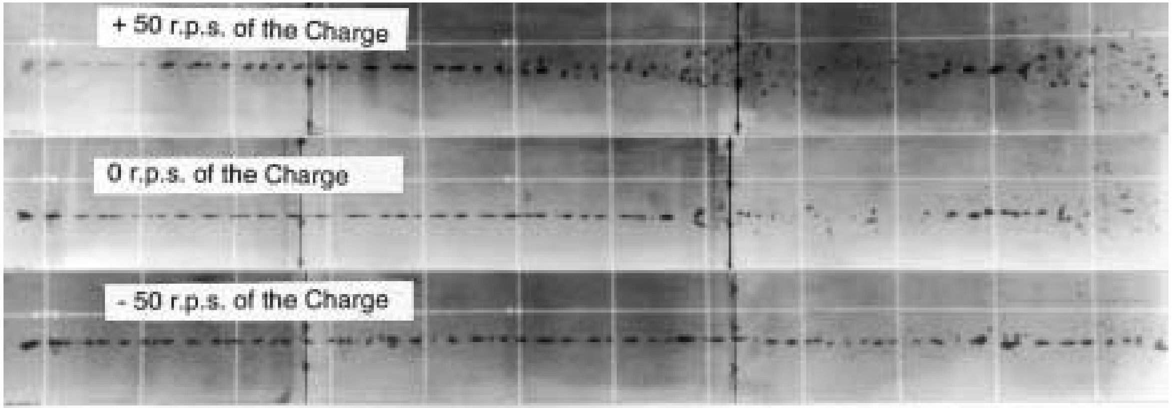

Figure 6: Röntgen pictures of jets produced by liners of type V with 1.2 mm flutes. All X-ray shoots are taken 120 µs after initiation. The charges are spinning at velocity +50 r.p.s. (top), 0 r.p.s. (middle) and –50 r.p.s. (bottom) respectively. Positive signs correspond to counterclockwise rotation when looked at from the rear end of the charge. By comparison of the pictures, one can infer that, for the statically fired charge, the first part of the jet slowly rotates clockwise; the rear part spun counter-clockwise at high rate until disruption.

CONCLUSION

For frequencies ranging from –200 to +200 r.p.s., spin compensation of shaped charges can be achieved efficiently by fluted liners. In the present work we have investigated the possibility of using two-dimensional simulations of fluted liners to get an insight in the mechanisms of spin compensation. We have shown that this simplified approach can be used consistently to get the jet spin rate variation trends when one or several parameters are changed. The optimal charge spin frequency ν_o can be roughly inferred from numerical calculations.

Our experimental results point out that the design with a flute depth linearly decreasing from base to apex of the liner doesn't provide a uniform compensation of the spin over the full length of the jet. The analysis of X-ray pictures of jets produced by charges spinning at various rates led us to the conclusion that, with the designs used here, the front and rear parts of a single jet can rotate in opposite directions, even for statically fired charges. This is in agreement with the numerical results of Kipp et al. [5] showing that the angular velocity can reverse its sign along a jet.

Eichelberger explains spin compensation by two (usually) antagonistic physical causes [1]: the *"thick-thin"* and the *"transport"* phenomena. The thick-thin effect is linked to the differential impulse received by the liner as a function of its local thickness when accelerated by the detonation products (Gurney); the transport effect is related to the impact angle of the detonation front on the liner. In type V liners, the transport effect should not contribute to the tangential motion of the collapsing cone (axisymmetric impact of the detonation front on the liner). However, our results with type V liners seem to indicate that this explanation is not complete, since even in the absence of the transport effect, the spin direction can be reversed just by variation of the flute depth. A consistent theoretical model for spinning charges is still lacking.

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