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IMPROVED DRIFT VELOCITY COMPUTATIONS FOR SHAPED-CHARGE JETS

STEVEN B. SEGLETES

JUNE 1987

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A new technique has been devised to calculate the inherent interdispersion of shaped-charge jet particles (called drift velocity), which offers substantial improvements over a technique originally proposed in a previous report, "Drift Velocity Computations for Shaped-Charge Jets," ARBRL-MR-3306. The original formulation calculated jet particle drift velocities from jet radiographs in a way which was biased by warhead tilt, and was thus of limited value in assessing the quality of the shaped-charge jet. The new technique is able to predict the magnitude and direction of the reference particle drift velocity and warhead tilt in a rational way. As a consequence of being able to remove tilt induced drift velocities from the calculation, a measure more closely related to the quality of the jet may be determined.

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1. INTRODUCTION

There are several models to predict the penetration of a shaped-charge jet. Most of them, and certainly the majority of early models, are one dimensional in nature using a hydrodynamic approach which is modified to account for material strengths, viscosities, cutoff velocities, etc.[1-4] On the other hand, the inter-particle dispersion of jet particles is probably a more realistic way (albeit a more difficult way) to account for the deleterious effects of target standoff on jet penetration. Such three dimensional inter-particle dispersion effects have been studied by researchers, and have been codified into models by several of them.[5,6]

In Smith's PENSO code[6], a reverse engineering approach is employed whereby jet dispersions are to be estimated knowing the penetration standoff behavior for a type of charge. The dispersion characteristics of the jet are defined ad hoc by the user. One hopes to gauge the "correctness" of the dispersion coefficient estimates by comparing the predicted penetration standoff curve to known experimental values.

The approach taken by Segletes[5] entails measuring jet dispersion (i.e. drift velocities) directly from jet radiographs. The validity of the dispersion measurements is gauged by feeding the data into a code (PENJET) for estimating penetration based on a particular dispersion distribution.

A primary limitation of any model which hopes to predict jet penetration, while accounting for inter-particle dispersion of the jet, is the ability to accurately assess the magnitude of inter-particle dispersion. To make this assessment from jet radiographs ideally requires accurate information on the placement and orientation of the shaped-charge warhead as a coordinate reference for the resulting jet. For the size of shaped charges of interest in the laboratory, the required length of film needed to capture the image of the charge and the resulting particulated jet becomes excessive. Also, flash radiographic film cassettes can only be used to x-ray lightly confined exploding charges (for fear of damaging both x-ray tubes and film cassettes), and even then only with the use of blow away (non-stationary) film cassettes. Thus, it becomes impractical to routinely capture both the warhead and particulated jet on the same piece of film.

As a result of these practical limitations, the experimenter is typically limited to one or more pieces of film containing images of the following: a) a portion of the particulated jet; and b) fiducial lines which are ostensibly parallel with the original charge axis of the warhead. Unfortunately, such an experimental setup makes it impossible to locate where on the radiograph the shaped charge warhead axis actually lies. As a result, Segletes[5] was able to calculate relative drift velocities (i.e. drift velocities of jet particles relative to some reference particle) as measured in a reference frame of the radiograph fiducials (which are at best nearly parallel with the charge axis of symmetry). The exact relationship between the assumed and actual jet axes was however unknown, and the angular disparity between the two axes was termed the warhead tilt, or simply tilt.

In Segletes' model[5], absolute drift velocities (needed for the penetration calculation) were estimated by augmenting the relative drift velocity of each particle by a drift velocity associated with the reference particle. This reference drift velocity was calculated so as to equalize the dispersion angles of all the jet particles with a minimum of scatter (the dispersion angle is the angle between the assumed charge axis of symmetry and the absolute velocity vector of the particle). The rationale for enforcing the condition of equal dispersion angles was that a straight jet under the influence of charge tilt would tend to produce exactly this distribution of drift velocity. However, because the warhead tilt was not removed from the absolute drift velocity calculations, the calculations were able to provide only limited quantitative information on the inter-particle dispersion of jet particles.

2. THE MODEL

The description of the three flash x-ray experimental facility for radiographically recording jet flight is described by others (e.g. Blishe, Simmons[7] and Segletes[5]). The method used presently to obtain relative drift velocity of jet particles (i.e. the drift velocity of jet particles with respect to a reference jet particle) is identical to Segletes' original method, with one small difference: the reference particle for the jet is presently taken as the lead particle of the jet, whereas the previous method used an arbitrary particle near the rear of the jet. Unlike the original method, absolute drift velocity calculated via this new method is insensitive to the choice of reference particle, so the jet tip seems as good a choice as any.

One of Segletes' original results was to show that warhead tilt and/or reference particle drift velocity were very significant and could not be ignored in the calculation of jet particle drift velocities from radiographs. If the actual charge axis were misaligned from the assumed charge axis (the charge axis is assumed parallel to a set of fiducial lines on the film) by an angle of only one degree, a jet particle travelling axially at 9 km/sec would be tilted into having a drift velocity in excess of 155 m/s.

Segletes was further able to show that using just the relative drift velocities to calculate jet penetration in the PENJET model severely underestimated penetration. He believed that the discrepancy resulted from warhead tilt and was only able to remedy this with the introduction of reference particle drift velocity which tended to decrease inter-particle jet dispersion (since the reference particle of a tilted charge would appear to be drifting too). This technique was sufficient for inclusion in the PENJET model since actual warhead tilt does not affect penetration of the jet, but did nothing to differentiate what part of the drift velocity was caused by tilt and what part was inherent inter-particle dispersion.

The relative drift (i.e. transverse) velocity of all the jet particles can be broken down into x and y components ${}_jV_{tx}$ and ${}_jV_{ty}$, where j represents the index on jet particle, and can take on a value between one and the number of digitized particles in the jet. Figure 1 depicts drift velocities measured relative to the jet tip pellet (the reference particle) and in a reference frame parallel with the film fiducial lines. Let us further represent the drift velocity components of the reference particle in the assumed charge axis frame of reference (based on fiducial lines on the film) by ${}_0V_{tx}$ and ${}_0V_{ty}$. As such, the drift velocity of a jet

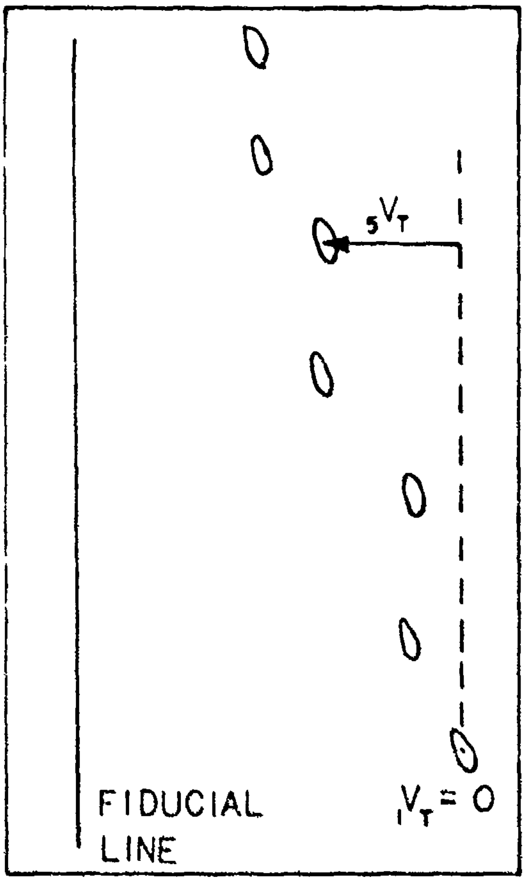

Figure 1. Calculation of Relative Drift Velocities in the Jet Tip/Fiducial Reference Frame

particle would be represented by the sum of the relative drift of that particle and the reference drift. In Figure 2, the reference particle drift velocity is shown attached to the jet tip pellet (the reference particle), though it is the case that the drift velocity of each jet particle in the fiducial reference frame has its relative drift velocity augmented by this reference drift velocity.

This composite drift (relative plus reference) seen on the film is actually made up of inherent inter-particle dispersion plus warhead tilt. One may acquire just the inter-particle dispersion by subtracting out the tilt. If the tangent of the tilt angle takes on some value K, such that the projection of that angle onto the x-z and y-z planes (the x and y axes measure transverse jet motion, the z axis measures axial jet motion) is Kx and Ky respectively, then one concludes that the x and y components of absolute drift velocity for particle j may be represented as

$$ {}_j\tilde{V}_{tx} = {}_jV_{tx} + {}_0V_{tx} - Kx\ {}_jV_a \quad \text{, and} \qquad (1) $$

$$ {}_j\tilde{V}_{ty} = {}_jV_{ty} + {}_0V_{ty} - Ky\ {}_jV_a \quad , \qquad (2) $$

where:
${}_j\tilde{V}_{tx}$ is the x component of absolute drift velocity for particle j,
${}_j\tilde{V}_{ty}$ is the y component of absolute drift velocity for particle j, and
${}_jV_a$ is the axial velocity for particle j as measured from the radiographs.

In Figure 2, the components of drift velocity resulting from the warhead tilt are proportional to the axial velocity of the particles (i.e. proportional to the distance downrange if one accepts the virtual origin approximation). When the reference velocity is added to and the tilt induced velocity is subtracted from the relative drift, the resulting absolute drift velocity, as shown in Figure 3, is measured with respect to the tilted charge axis. When used to calculate particle dispersion angles (also shown in Figure 3), the absolute drift velocities described by equations (1) and (2) give a good measure of the quality of the jet.

The four unknowns in these two equations are the two components of tilt and the two components of reference drift velocity. Because Segletes[5] noted that penetration predictions were too low unless reference velocity was added as an attempt to remove inter-particle dispersion, and because the algorithm should predict zero drift velocity for a straight jet whose charge has been tilted, the reference velocity and tilt will be solved for in a way which minimizes inherent inter-particle dispersion. This is accomplished by minimizing the sum of the squares of the dispersion angles (actually their tangents, which are nearly identical to the angle in radians for small angles) for all the jet particles. Though one can not be sure that the actual drift distribution is the one which minimizes inter-particle dispersion, Segletes[5] showed that the actual drift distribution is much more closely approximated by the minimum-dispersion drift distribution than the unmodified relative drift distribution.

The magnitude of drift velocity for particle j is

$$ |{}_j\tilde{V}_t| = ({}_j\tilde{V}_{tx}^{\,2} + {}_j\tilde{V}_{ty}^{\,2})^{1/2} \quad . \qquad (3) $$

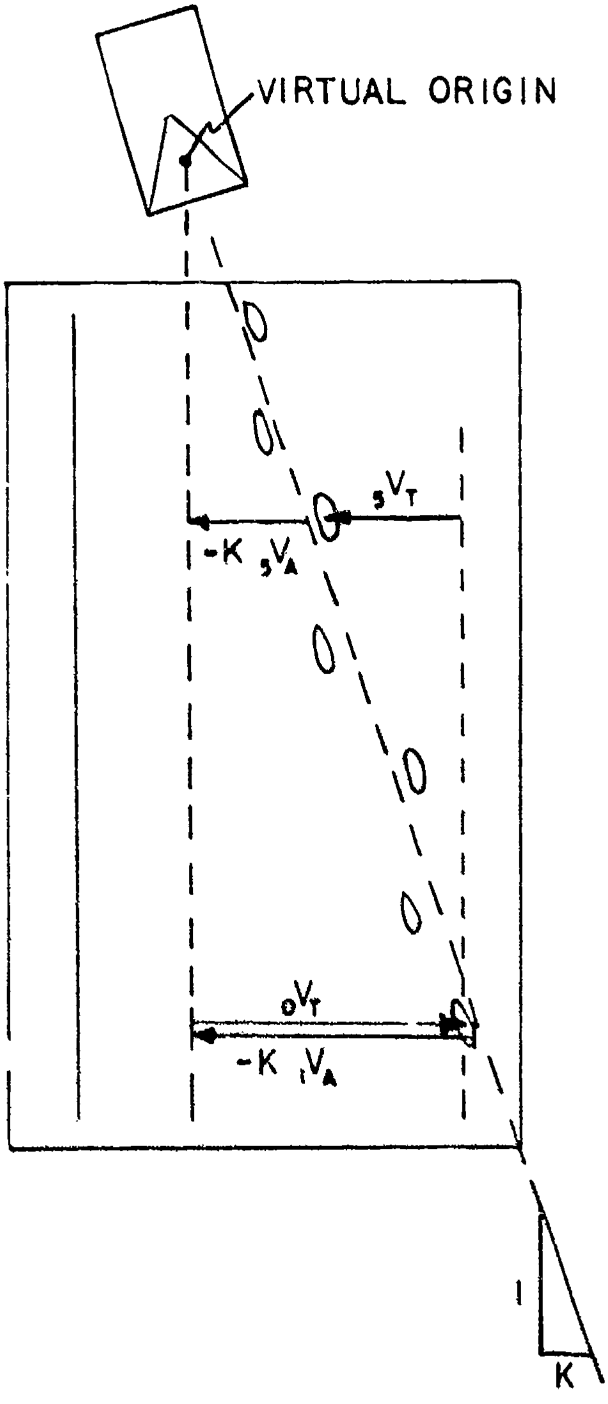

Figure 2. Estimation of Reference Drift Velocity and Jet Axis Tilt are Based on Least Squares Fit

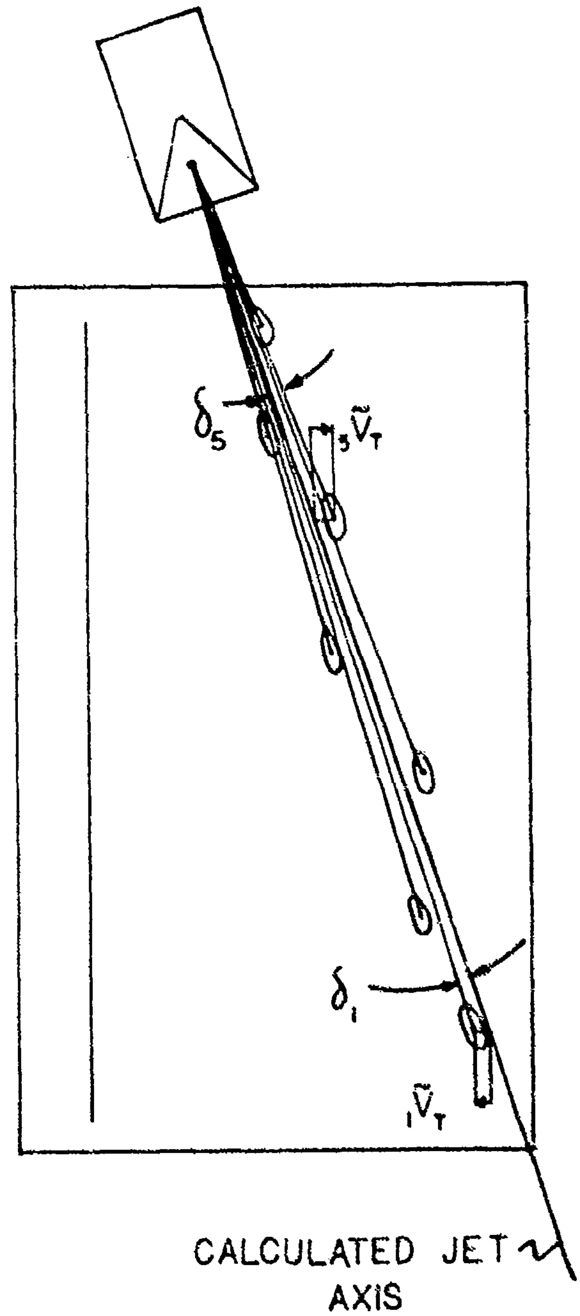

Figure 3. Absolute Drift Velocities and Particle Dispersion Angles are Based on Calculated Jet Axis Instead of the Fiducial Axis

The (tangent of the) dispersion angle is the quotient of the drift and axial velocities for a particle. Squaring this value and summing over all n particles yields

$$\Delta = \sum_{j=1}^{n} \left(\frac{{}_jV_{tx}}{{}_jV_a} + \frac{{}_oV_{tx}}{{}_jV_a} - Kx \right)^2 + \left(\frac{{}_jV_{ty}}{{}_jV_a} + \frac{{}_oV_{ty}}{{}_jV_a} - Ky \right)^2 \quad . \quad (4)$$

In order to find the values of the two unknown tilts and two unknown reference drift velocities in a way which minimizes the dispersion function Δ, merely take the partial derivative of equation (4) with respect to each of the unknowns, and set the derivatives to zero. The resulting four equations are:

$$\frac{\partial \Delta}{\partial Kx} = 0 = -2 \sum_{j=1}^{n} \left(\frac{{}_jV_{tx}}{{}_jV_a} + \frac{{}_oV_{tx}}{{}_jV_a} - Kx \right) \quad , \quad (5)$$

$$\frac{\partial \Delta}{\partial {}_oV_{tx}} = 0 = 2 \sum_{j=1}^{n} \left(\frac{{}_jV_{tx}}{{}_jV_a} + \frac{{}_oV_{tx}}{{}_jV_a} - Kx \right) \frac{1}{{}_jV_a} \quad , \quad (6)$$

$$\frac{\partial \Delta}{\partial Ky} = 0 = -2 \sum_{j=1}^{n} \left(\frac{{}_jV_{ty}}{{}_jV_a} + \frac{{}_oV_{ty}}{{}_jV_a} - Ky \right) \quad , \text{ and } \quad (7)$$

$$\frac{\partial \Delta}{\partial {}_oV_{ty}} = 0 = 2 \sum_{j=1}^{n} \left(\frac{{}_jV_{ty}}{{}_jV_a} + \frac{{}_oV_{ty}}{{}_jV_a} - Ky \right) \frac{1}{{}_jV_a} \quad . \quad (8)$$

These four equations may be solved for the four unknowns to give the following results:

$$ {}_oV_{tx} = \frac{ n \sum_{j=1}^{n} \left(\frac{{}_jV_{tx}}{{}_jV_a^2} \right) - \sum_{j=1}^{n} \left(\frac{{}_jV_{tx}}{{}_jV_a} \right) \sum_{j=1}^{n} \left(\frac{1}{{}_jV_a} \right) }{ \left(\sum_{j=1}^{n} \left(\frac{1}{{}_jV_a} \right) \right)^2 - n \sum_{j=1}^{n} \left(\frac{1}{{}_jV_a^2} \right) } \quad (9)$$

$$ Kx = \frac{ \sum_{j=1}^{n} \left(\frac{{}_jV_{tx}}{{}_jV_a^2} \right) \sum_{j=1}^{n} \left(\frac{1}{{}_jV_a} \right) - \sum_{j=1}^{n} \left(\frac{{}_jV_{tx}}{{}_jV_a} \right) \sum_{j=1}^{n} \left(\frac{1}{{}_jV_a^2} \right) }{ \left(\sum_{j=1}^{n} \left(\frac{1}{{}_jV_a} \right) \right)^2 - n \sum_{j=1}^{n} \left(\frac{1}{{}_jV_a^2} \right) } \quad (10)$$

$$ {}_oV_{ty} = \frac{n \sum_{j=1}^{n} \left(\frac{{}_jV_{ty}}{{}_jV_a^2} \right) - \sum_{j=1}^{n} \left(\frac{{}_jV_{ty}}{{}_jV_a} \right) \sum_{j=1}^{n} \left(\frac{1}{{}_jV_a} \right)}{\left(\sum_{j=1}^{n} \left(\frac{1}{{}_jV_a} \right) \right)^2 - n \sum_{j=1}^{n} \left(\frac{1}{{}_jV_a^2} \right)} \qquad (11) $$

$$ Ky = \frac{\sum_{j=1}^{n} \left(\frac{{}_jV_{ty}}{{}_jV_a^2} \right) \sum_{j=1}^{n} \left(\frac{1}{{}_jV_a} \right) - \sum_{j=1}^{n} \left(\frac{{}_jV_{ty}}{{}_jV_a} \right) \sum_{j=1}^{n} \left(\frac{1}{{}_jV_a^2} \right)}{\left(\sum_{j=1}^{n} \left(\frac{1}{{}_jV_a} \right) \right)^2 - n \sum_{j=1}^{n} \left(\frac{1}{{}_jV_a^2} \right)} . \qquad (12) $$

The components of absolute drift velocity for every particle may be acquired by substituting the two tilts and two reference drift velocities into equations (1) and (2) for each particle.

Because the above procedure minimizes the sum of the squares of the tangents of the dispersion angles of the particles, the average square of the dispersion angle tangent will equal the sum of the squares divided by the number of particles used in the calculation. As such, the average dispersion may be mathematically expressed as:

$$ \delta = \tan^{-1} \left(\left(\frac{\sum_{j=1}^{n} \left(\frac{{}_j\tilde{V}_{tx}^2 + {}_j\tilde{V}_{ty}^2}{{}_jV_a^2} \right)}{n} \right)^{1/2} \right) . \qquad (13) $$

This average dispersion angle for the jet gives a quantitative estimate for the quality of jet. Ideally, this estimate is not influenced by warhead tilt, and would approach zero for a perfectly aligned jet, regardless of tilt. In actuality, because of the fact that the complete jet is not usually radiographed, the tilt estimates based on a partial jet are incomplete, and may thus be in error.

Even with a complete jet, error may still be present since the model inadvertantly masks out uniform drift components (a drift pattern whereby all jet particles have the same drift velocity regardless of axial velocity). However, such a uniform drift distribution is not likely to result from typical warhead asymmetries[8] and in fact was only nominally achieved even when producing such a distribution was the desired goal of the study[9]. This uniform drift distribution is however, implied when a shaped charge device is operating in a fly-over mode of attack. Fly-over attack is not the intended subject of this report, though modeling of adverse effects of uniform transverse velocity has been considered by Segletes[10] and others. For the fly-over scenerio however, the projectile velocity is typically known, and need not be deduced from radiographic inspection. As such, if a sufficiently significant portion of the jet is digitized, the present modeling scheme should provide a substantial improvement over that used previously.

3. RESULTS

The proposed model has been exercised on several shaped-charge jet radiographs with good results. That is to say, rounds appearing straight (though possibly tilted) on radiographs have lower average dispersion angles than rounds appearing to be bowed or dispersed. The results for several rounds are shown in Tables 1 and 2. These tables include the drift velocities for the particles relative to the reference particle (lead pellet of the jet) and also the absolute drift velocities once reference drift and charge tilt are taken into account.

To give an idea on how the analysis is dependent on the number of particles used in the analysis (i.e., if only a partial jet is used in the analysis), Figures 4 and 5 are included. Figure 4 depicts how three of the dispersion parameters for round 3813 vary with the number of jet particles used in the analysis, namely average dispersion, tilt and tilt direction. Round 3813 consisted of a 65 mm diameter (uniform wall thickness of 1 mm), 42 degree copper cone loaded with unconfined LX-14. It produced a jet tip velocity of approximately 9.2 km/sec. Recall that a warhead tilt and a reference transverse velocity are superimposed upon the relative drift velocity distribution in such a way that the sum of the squares of the dispersion angles is minimized.

The dispersion represents the average angular deviation of a jet particle from the actual jet axis. Note that this parameter has been magnified by a factor of 100 for plotting in Figure 4, thus indicating how small the inter-particle dispersion can be with respect to warhead tilt. This fact explains why tilt must be accounted for in the assessment of jet dispersion. The tilt represents the angle between the intended axis of symmetry and the actual axis of symmetry. If one then takes the plane containing both the intended and actual axes of symmetry and intersects it with the plane normal to the intended axis of symmetry (this will be the plane of the target for normal impact), one acquires a line (in the plane of the target). The direction of this line indicates the direction of the warhead tilt. In Figure 4, the reference line was chosen for tilt direction to give an angle of zero for the analysis which included 66 jet particles.

In order for confidence in the calculation to be greatest, both tilt and tilt directions should reach steady state as the number of particles included in the analysis is increased. For round 3813, the tilt angle is still decreasing, but appears to be approaching an asymptote. However, the direction of tilt is not nearly so stationary. Nonetheless, the sensitivity of dispersion on the direction of tilt is much less than the sensitivity of dispersion on tilt itself, so that the greater variability in tilt direction should not cause undue alarm.

Figure 5 and Table 2 depict a similar analysis which has been done on round 3499. This round contained a 76.2 mm hemispherical copper liner (uniform wall thickness of 1.9 mm), loaded with unconfined 75/25 Octol of 68.9

Experimental value of penetration is 2.45 CD at 24.25 CD standoff
X, Y drift velocity of reference particle (m/s): ${}_0V_{tx}$ = 203.92 ${}_0V_{ty}$ = -91.82
X, Y tilt angles in degrees: atan(Kx) = 1.08 atan(Ky) = -0.47

Average Drift Dispersion (degrees): δ = 0.05682

PARTICLE NUMBER	+------Relative-------+ DRIFT VELOCITY (M/S)	ANGLE (DEGREES)	+------Absolute------+ DRIFT VELOCITY (M/S)	ANGLE (DEGREES)
1	0.0	0.0	34.7	332.3
2	18.6	153.2	16.2	331.3
3	23.3	154.2	14.2	330.1
4	26.8	153.2	11.5	331.4
5	28.7	154.1	11.1	329.6
6	31.0	156.1	10.0	323.2
7	33.5	153.4	9.7	332.2
8	36.6	154.7	7.5	326.0
9	38.2	155.2	5.8	319.9
10	39.9	154.9	7.0	324.9
11	44.0	152.8	5.5	339.2
12	46.1	152.7	4.7	342.9
13	46.9	152.7	4.7	342.8
14	51.4	153.0	2.6	348.6
15	52.6	153.3	2.4	345.0
16	55.7	154.4	1.9	320.5
17	57.8	154.1	1.0	328.1
18	60.1	153.7	1.0	358.1
19	62.0	154.3	0.6	172.4
20	64.7	154.2	0.5	152.4
21	67.4	152.7	1.9	78.3
22	68.3	153.9	1.2	129.4
23	71.[illegible]	154.0	2.9	147.4
24	73.6	153.9	3.1	143.6
25	76.8	154.9	3.7	164.4
26	78.8	153.8	5.4	145.1
27	83.0	154.2	6.0	149.9
28	85.2	154.4	6.9	152.0
29	88.1	152.9	7.3	132.6
30	89.9	154.5	7.1	152.0
31	90.8	155.1	4.4	152.1
32	93.7	154.3	5.3	146.9
33	98.2	154.4	6.1	147.5
34	100.7	154.7	7.9	152.8
35	103.1	155.6	7.0	167.9
36	103.8	155.0	7.4	155.4
37	105.6	155.1	7.8	157.6
38	106.1	154.9	7.7	154.3
39	106.7	154.6	6.9	149.3
40	109.7	154.8	7.5	152.5

Table 1. Jet Particle Dispersion Summary for Round 3813

	+------Relative-------+		+------Absolute------+	
PARTICLE NUMBER	DRIFT VELOCITY (M/S)	ANGLE (DEGREES)	DRIFT VELOCITY (M/S)	ANGLE (DEGREES)
41	110.7	154.8	7.8	151.4
42	112.6	155.3	7.7	158.5
43	114.0	154.5	6.0	143.6
44	115.5	154.4	5.5	139.7
45	116.8	154.5	5.1	140.9
46	117.3	154.6	3.5	136.2
47	119.0	154.4	3.5	128.4
48	120.8	154.4	3.6	128.0
49	122.4	154.9	3.5	143.4
50	122.8	154.8	2.8	136.6
51	121.3	156.0	2.0	217.1
52	122.6	156.0	1.7	246.1
53	122.0	155.7	1.1	282.8
54	124.6	156.0	2.1	283.1
55	126.8	155.8	1.4	286.3
56	129.0	155.6	1.5	313.1
57	130.7	155.6	1.0	302.8
58	131.5	155.5	1.9	324.5
59	131.4	155.5	2.6	327.4
60	134.9	155.4	1.2	335.6
61	136.9	155.8	2.9	314.9
62	139.7	155.8	3.3	319.6
63	142.5	155.6	3.5	329.0
64	144.6	155.4	4.2	336.3
65	145.3	155.2	5.2	342.2
66	146.6	155.1	5.4	345.6

Table 1 (cont.)

Experimental value of penetration is 0.61 CD at 20.0 CD standoff
X, Y drift velocity of reference particle (m/s): ${}_0V_{tx}$ = -658.96 ${}_0V_{ty}$ = 0.00
X, Y tilt angles in degrees: atan(Kx) = -6.70 atan(Ky) = 0.00

Drift Dispersion Factor (degrees): δ = 0.20103

PARTICLE NUMBER	Relative DRIFT VELOCITY (M/S)	Relative ANGLE (DEGREES)	Absolute DRIFT VELOCITY (M/S)	Absolute ANGLE (DEGREES)
1	0.0	0.0	48.6	180.0
2	18.8	0.0	28.3	180.0
3	44.6	0.0	15.3	180.0
4	74.7	0.0	4.9	180.0
5	97.8	0.0	5.7	0.0
6	106.8	0.0	12.5	0.0
7	127.8	0.0	10.7	0.0
8	147.1	0.0	12.9	0.0
9	156.8	0.0	20.9	0.0
10	173.9	0.0	15.4	0.0
11	193.9	0.0	6.4	0.0
12	208.2	0.0	4.5	0.0
13	217.8	0.0	6.2	0.0
14	222.5	0.0	11.6	0.0
15	236.5	0.0	9.9	0.0
16	241.4	0.0	12.3	0.0
17	252.2	0.0	1.8	0.0
18	254.9	0.0	3.2	0.0
19	261.9	0.0	9.7	180.0
20	269.1	0.0	9.4	180.0
21	274.9	0.0	7.2	180.0
22	273.8	0.0	16.8	180.0

Table 2. Jet Particle Dispersion Summary for Round 3499

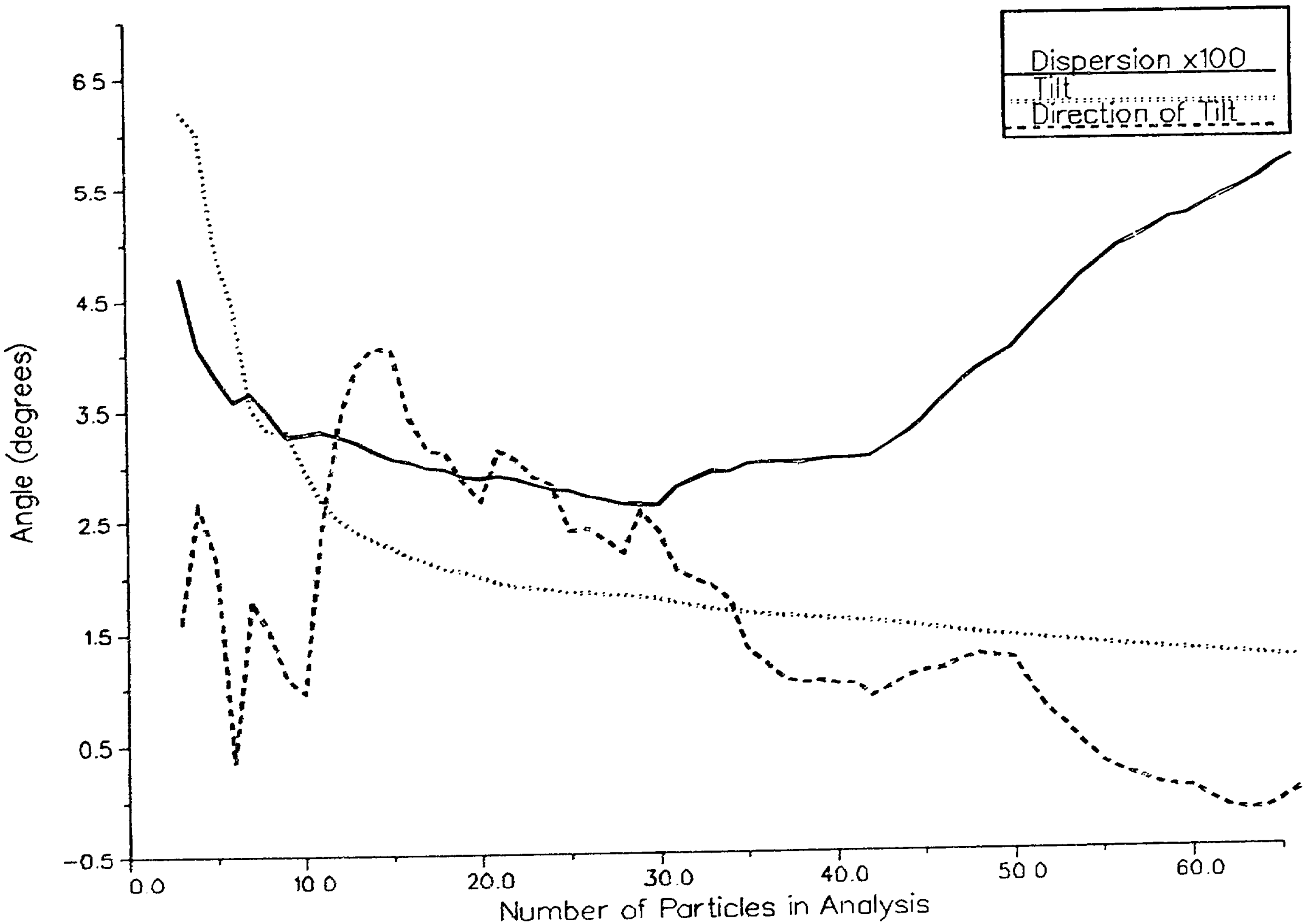

Figure 4. Dispersion Information for Round 3813

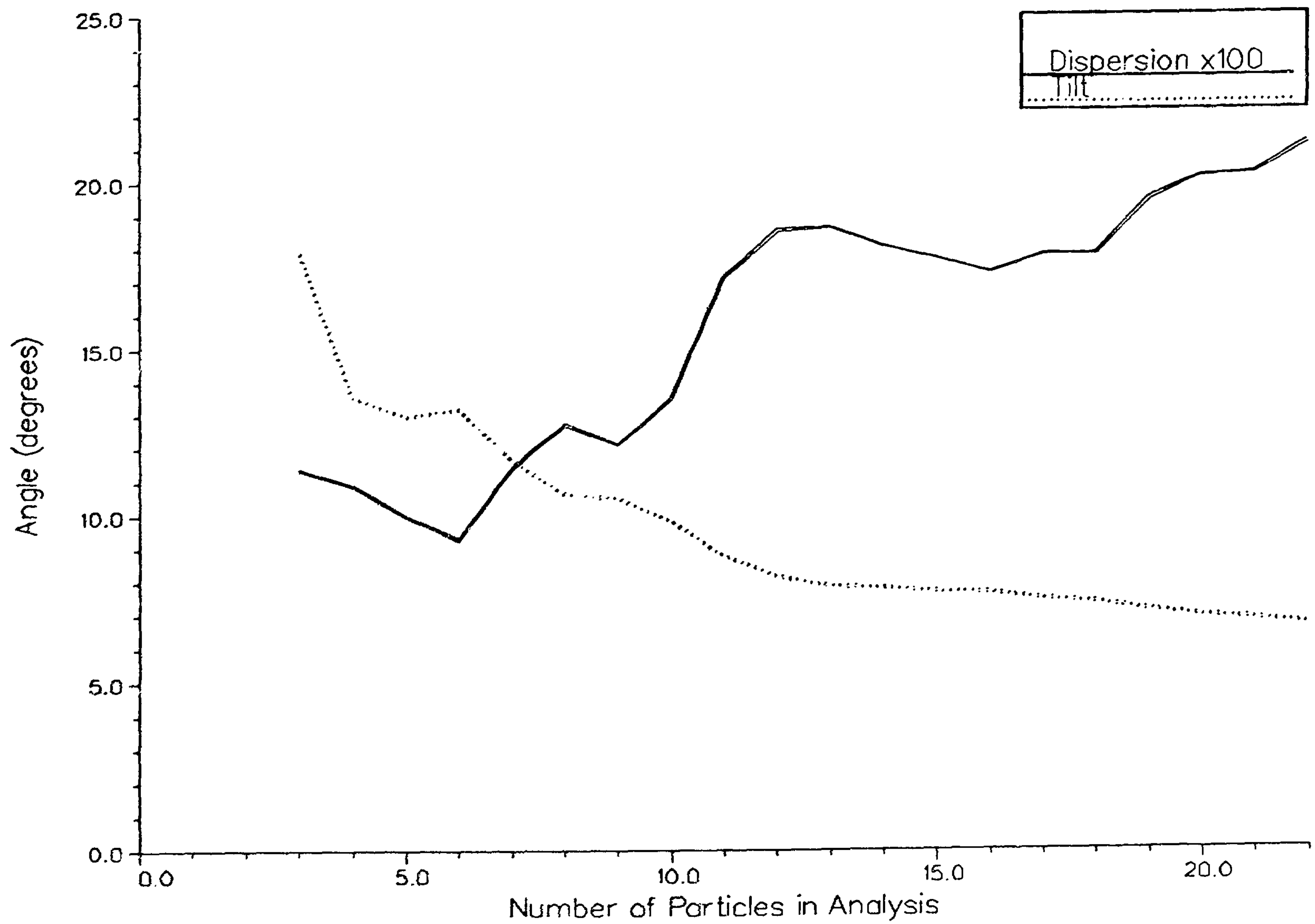

Figure 5. Dispersion Information for Round 3499

mm diameter. The jet tip velocity was 5.2 km/sec. What makes this round unique is that the explosive was intentionally detonated off of the axis of symmetry[11]. The offset was such that the line through the detonation point and the center of the hemisphere formed a six degree angle with respect to the axis of symmetry of the charge. The experimental apparatus was limited in such a way that the jet could be viewed from a single angle only. As such, it was necessarily assumed that jet dispersion was confined to the plane of the film (since both the charge axis of symmetry and the detonation point lay in the plane of the film).

Like round 3813, the average dispersion angle for round 3499 is a fraction of the tilt angle. Note however that the magnitude of dispersion is roughly three times that of round 3813. This larger dispersion is not unreasonable considering that round 3499 was detonated in an asymmetric manner. The penetration of round 3499 was approximately one quarter that of round 3813 at similar charge diameter standoffs. Also of great interest is the fact that the tilt angle for round 3499 appears to be approaching six degrees in somewhat of an asymptotic fashion. Considering the geometry of the explosive initiation, one would expect the jet axis to be nominally tilted six degrees from the original charge axis.

4. CONCLUSIONS

The ability to compute drift velocities for the particles of a jet is one way to ascertain the quality of the jet formation. Such knowledge provides a means to better predict the subsequent penetration performance of the jet.

The new technique which has been devised to calculate the drift velocities of shaped-charge jets offers substantial improvements over a technique originally proposed by Segletes[5]. Segletes' original formulation calculated jet particle drift velocities which were biased by warhead tilt, and was thus of limited value in assessing the quality of the shaped-charge jet. The new technique is able to predict the magnitude and direction of the reference particle drift velocity and warhead tilt in a way which minimizes inter-particle dispersion. Though one can not be sure that the actual drift distribution is the one which minimizes inter-particle dispersion, Segletes[5] showed that the actual drift distribution is much more closely approximated by the minimum-dispersion drift distribution than the unmodified relative drift distribution. As a consequence of being able to remove the tilt bias from the computation, a measure more closely related to the quality of the jet may be determined.

The quantification of jet quality from a radiograph is an important central link between nonideal penetration and imperfections in the warhead construction. Analyses of this type will reveal alignment and precision of assembly requirements necessary to maximize warhead performance.

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