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The Influence of Projectile Mass upon Precision

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Precision, or round-to-round dispersion is an important parameter contributing to the accuracy of tank fire. It is typically a lot acceptance specification for ammunition, both war and target practice rounds. A kinetic energy war round is fabricated from a dense metal such as tungsten alloy while the practice round is made from steel. In an attempt to improve training round performance and lower cost, a series of designs using aluminum was examined. The test results showed a considerable degradation in precision. This paper examines the firing data for a set of rounds having widely different inertial characteristics and attempts to explain the results.

INTRODUCTION

In training, it is desirable to have a round that closely resembles the actual war round in terms of visual appearance, size, weight, and, up to a point, ballistic performance. To remain within the boundaries of military reservations, it is required that the maximum range of the training round be considerably less than that of the war round. Also, penetration should be limited in the event of an accidental impact on another vehicle in training. For the 120mm cannon, the training round is a flare-stabilized projectile made of steel. The round is launched at 1700 m/s and provides satisfactory simulation of the war round out to 3 km; however, beyond that range, the high drag of the flare provides rapid deceleration and limits the maximum range. At the high muzzle velocity, a steel core round has appreciable penetration capability. Kennedy, et al[1], attempted to provide an alternative with greatly reduced penetration. By employing a hollow aluminum flight body, they succeeded in matching the trajectory of the existing trainer, while reducing the penetration by about a factor of ten. However, precision testing showed that round-to-round dispersion grew by a factor of more than three.

In examining the possible sources of launch and flight disturbances[2], it was determined that the aerodynamic jump coefficient[3] of the aluminum round was significantly greater than that of the steel core design. One obvious way to improve the jump sensitivity was to increase the static margin. This suggested the use of higher density counter weights in the nose region. Lead, copper, and steel were all tested. Significant improvements in precision were observed; however, levels equivalent to the steel round were not achieved. The present paper examines this body of data and correlates inertial properties of the projectiles with both overall precision and the components of flight disturbance. Four fin-stabilized round types are considered: tungsten alloy, steel, aluminum, and aluminum with a steel counterweight.

EXPERIMENTS

Data is taken from three separate experiments. The tungsten alloy and steel rounds were fired in a fully instrumented[2] accuracy test conducted at the ARL Transonic Range. This experiment made use of eddy probes and strain gages to measure gun tube motion as the shot moved down the bore. External to the gun, a set of six orthogonal x-rays captured the disengagement and sabot discard dynamics while the Transonic Range recorded the projectile free flight. An impact target was placed at 1 km. All components were careful surveyed into common temporal and spatial references. The aluminum round was fired at Yuma Proving Ground[4]. Instrumentation consisted of yaw cards near the first maximum of yaw, smear cameras, and targets at 1 and 2.5 km. The final set of data was taken at Transonic Range as part of the present tests. Instrumentation consisted of three orthogonal x-rays located at 0.5, 2.5, and 4.5 m from the muzzle. Transonic Range measured the projectile flight motion and a target was located at 1 km. For all three experiments, the gun was laid using a muzzle boresight. The inertial and aerodynamic properties of the four rounds are presented in Table 1.

	m (kg)	D (m)	I_t (kg-m^2)	V_m (m/s)	C_D	$C_{L\alpha}$	$C_{M\alpha}$
Tungsten	4.43	0.038	0.048	1650	0.322	7.58	-16.9
Steel	2.73	0.038	0.034	1680	0.314	7.20	-14.2
Aluminum	0.94	0.038	0.0074	1700	0.269	8.02	-7.00
Al-Steel	0.86	0.028	0.011	1690	0.508	8.00	-41.9

Table 1. Properties of Fin-Stabilized Projectiles

The aerodynamic properties of the tungsten, steel, and Al-steel rounds were measured at the Transonic Range, while those of the aluminum round were computed using PRODAS[5]. The aluminum round with the steel counterweight is of a different family than the others. This is because this round is based on the M829 projectile while the other three are based on the M865 technology, Fig. 1. When the M829 cartridges were scheduled for demilitarization, it was of interest to determine if the heavy metal core could be removed and replaced by an aluminum core. This would serve to recover most of the components thus providing a low cost training round. For this reason, the M829 envelope was selected to extend the earlier tests of the all aluminum training round.

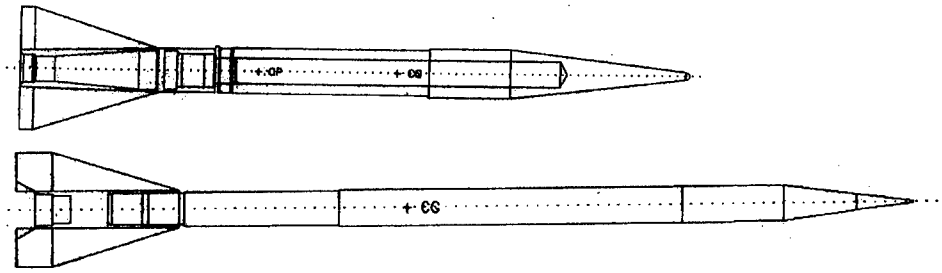

Figure 1. Test projectiles

The rounds were fired from different gun tubes, at different sites, and at different times. While these factors influence accuracy, it is hypothesized that the influence on precision is not great. Simply stated, the tank firing error budget is treated as arising from three, independent sources: tank-to-tank bias, occasion-to-occasion bias, and round-to-round dispersion. The differences in the test conditions would affect the bias, but have limited influence on the final factor that is of interest in the present study. The fact that two different families of ammunition, M865-like and M829-like, were tested does provide a potential source of variability in precision. This needs to be kept in mind as comparisons are made between experimental results; however, the program was not resourced to include heavy core results for the M829 case.

Lyon, et al[2], describe the launch disturbances as being comprised of a set of components related to the gun and projectile dynamics and aerodynamics. The gun tube pointing angle and crossing velocity at shot exit are measured and used to capture the changes in the gun attitude from its rest state. X-ray data taken over the first fifteen feet following exit provide a measurement of the projectile velocity vector which when compared to the gun data shows the influences of disengagement dynamics. A second set of x-rays another fifteen feet downrange capture the linear and angular velocity of the round after sabot separation. The measured angular velocity is used to extrapolate the trajectory downrange onto the target plane. This requires use of the expression for aerodynamic jump

$$\Theta = (I_t/mD^2)(C_{L\alpha}/C_{M\alpha})\xi_o' \qquad (1)$$

where ξ_o' is the complex yawing velocity expressed in radians per caliber of projectile travel. The methodology of dissecting the launch disturbances and extrapolating downrange to the target produces good agreement between with measured impacts, i.e., closure.

The experiments on the aluminum and Al-steel rounds could not provide such a complete evaluation of launch disturbances. An abbreviated version was employed to capture the influence of aerodynamic jump and initial projectile velocity. From the known boresight point on the target an expected impact point is computed by taking into account the known gravity drop. The difference between the expected and actual impact points gives the total jump for that individual shot. In all cases, data were taken on the angular motion of the round in sufficient detail to provide an estimate of ξ_o', providing an estimate of the aerodynamic jump, Eq. (1). Subtracting this from the total jump yields the initial projectile velocity vector:

$$(u + iv)/V_m = (x_t + iy_t)/L - (I_t/mD^2)(C_{L\alpha}/C_{M\alpha})(\beta_o' + i\alpha_o') \qquad (2)$$

where x_t,y_t and L are the horizontal and vertical components of on-target jump and the range to the target, respectively.

DATA ANALYSIS

Firings of all rounds showed structural integrity and produced first maximum yaw levels of less than two degrees, Fig. 2. To examine the statistics of the launch and impacts, the circular probable error[6] is used as defined by Mirabelle[7] for cases with unequal horizontal and vertical components

$$CPE = 1.18[(\sigma_h + \sigma_v)/2] \quad (3)$$

where CPE is the radius of the circle containing one-half of the data set and σ_h, σ_v are the horizontal and vertical standard deviations of the component of interest. For ease of comparison, all values are normalized to those of the tungsten round. Test results are summarized in Table 2.

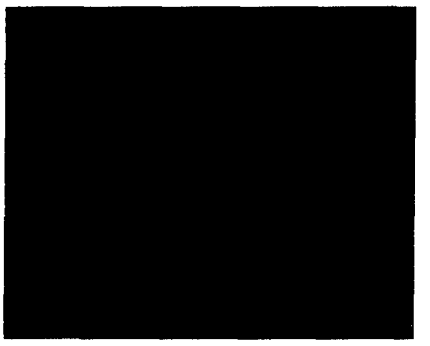

Figure 2. Smear photograph of Aluminum/Steel Counterweight Round

	CEP on Target (mr)	CEP $u,v/V_m$ (mr)	CEP Angular Velocity (rad/s)	**Aero. Jump Coef. (Θ/ξ_o')**
Tungsten	1	1	1	3.35
Steel	1.29	2.50	2.58	4.38
Aluminum	3.53	5.67	4.19	6.18
Al-Steel	2.35	5.75	3.24	5.5

Table 2. Circular Probable Errors for Various Rounds

The decay in CEP from the tungsten to the aluminum-based rounds is apparent. A number of factors are responsible. The linear and angular velocities both take on a progressively more random nature. In addition, the aerodynamic jump coefficient is roughly twice as large for the aluminum round as for the tungsten round. This serves to amplify the effects of initial angular velocity disturbances. The fact that the CEP on Target does not grow to the same extent as the CEPs in Linear and Angular Velocities, reflects the fact that the latter two can interact in a fashion to partially cancel each other. Some interesting correlations are possible between the dynamic results and the inertial properties of the rounds, Fig. 3 and 4. The CEP in initial lateral velocity decreases with increasing projectile mass. Even the data for the M829-like, Al-Steel projectile seems to follow this behavior. Similarly, the CEP in initial angular rate correlates reasonably well

with the transverse moment of inertia. Reversing the variables, i.e., correlating linear velocity with moment of inertia produces a less satisfying result.

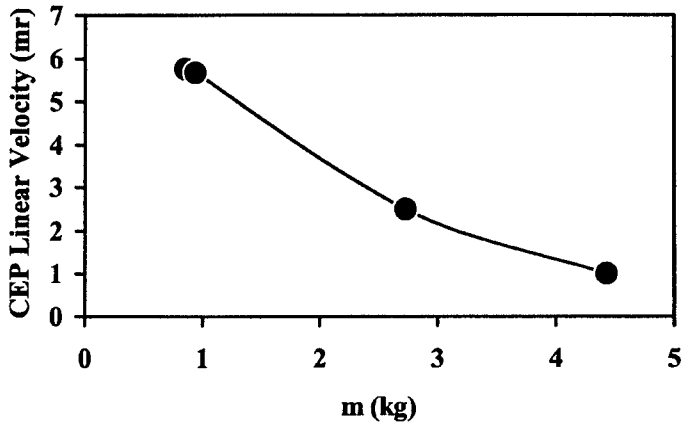

Figure 3. Correlation of flight mass with CEP in initial linear velocity

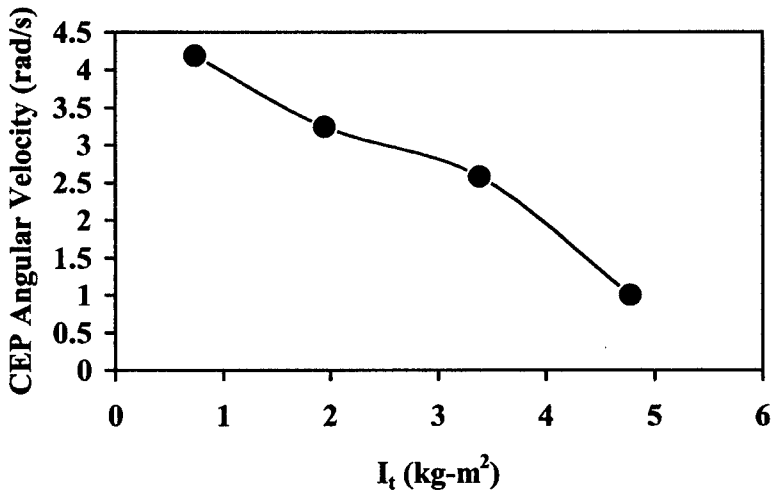

Figure 4. Correlation of transverse moment of inertia with CEP of angular velocity

Perhaps it should not be surprising that the linear and angular velocities correlate with their respective multipliers of the inertia tensor. A simple model of a spring-mass system helps to illustrate these correlations. The solution for a simple undamped oscillator responding to an initial displacement is

$$z = z_o \cos(k/m)^{1/2}\, t \tag{4}$$

with derivatives

$$dz/dt = -z_o\, (k/m)^{1/2} \sin(k/m)^{1/2}\, t \tag{5}$$

$$d^2z/dt^2 = -z_o\,(k/m)\cos(k/m)^{1/2}\,t \qquad (6)$$

The argument is made that since the CEP in lateral velocity represents the variability of this term, it should be directly related to the derivative of this term, Eq. (6), times some perturbation parameter, e.g., a variation in exit time, t_o. Thus, from Eq. (6),

$$\mathrm{CEP}\,(u/V_m,\ v/V_m) \sim 1/m \qquad (7)$$

The 1/m function is plotted in Fig. 5, where it is normalized to the value of tungsten mass. It is seen that the measured variation and that conjectured by Eq. (7) are similar. This may be fortuitous or indicative of the nature of the in-bore and separation dynamics. Consideration of Eq. (6) suggests that reduction in the stiffness (parameter, k) of the sabot could have improved the CEP of the lower mass rounds. This approach was not considered at the time. Both the M865-like and M829-like rounds were fired with existing sabots that were compatible with the high mass projectiles.

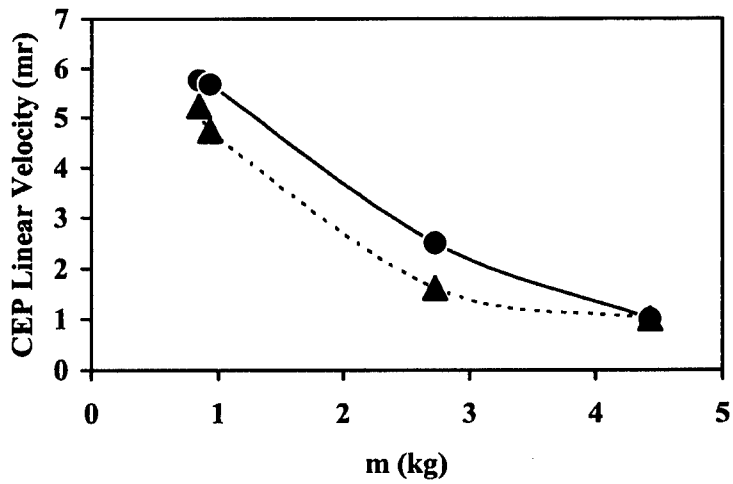

Figure 5. Comparison of measured CEP dependence (solid circles) with the parameter m_{WA}/m (solid triangles)

CONCLUSIONS

In the process of attempting to develop improved and/or low cost training rounds, accuracy firings were performed. It was found that lower mass projectiles had significantly greater round-to-round dispersion than tungsten or steel core designs. This was ascribed to larger values of the aerodynamic jump coefficient, Θ/ξ_o'. While undoubtedly a factor, careful analysis of the data indicates that variability in initial dynamics dominates. A simple dynamics argument suggests that when the inertial properties of the round are changed, it is necessary to match the sabot properties, e.g., stiffness. To better understand this behavior, higher fidelity simulations of the in-bore vibration and disengagement dynamics are required.

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