Dispersion analysis of the XM881APFSDS projectile

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This study compares the results of a dispersion test with mathematical modeling. A 10-round group of modified 25-mm XM881 Armor Piercing Fin Stabilized Discarding Sabot projectiles was fired from the M242 chain gun into a designated target. The mathematical modeling results come from BALANS, a product of Arrow Tech Associates. BALANS is a finite-element lumped parameter code that has the capability to model a flexible projectile being fired from a flexible gun. It also has the unique feature of an automated statistical evaluation of dispersion. This study represents an effort to evaluate a simulation approach with experiment.

1. Introduction

The US Army has a need to improve its understanding of the effectiveness of medium-caliber cannon systems. One of the methods for advancement toward this understanding is to perform experimental aerodynamic jump tests and mathematical modeling simulating the jump tests. One fielded system of major interest is the 25-mm M242 Autocannon, which is found on the Bradley Fighting Vehicle. This system is ideal for setup in a small-caliber range, like the Aerodynamics Range Facility at the US Army Research Laboratory (ARL) at Aberdeen Proving Ground (APG).

The current service round, used with the 25-mm M242 Autocannon, is the M919 Armor Piercing Fin Stabilized Discarding Sabot (APFSDS) projectile used for armor penetration. This round has a depleted uranium penetrator that would contaminate the experimental facility. Therefore the XM881, which has tungsten penetrator and was a precursor of the M919, presents itself as a suitable substitute. The XM881 has a flight vehicle that is geometrically similar to the M919 including matching threads for fitting the sabot, however, the discarding sabot of the XM881 was totally different from the M919. To better emulate the M919, it was decided to replace XM881 sabots with the sabots used on the M919.

The dynamic state of a projectile at shot exit is determined in part by the in-bore launch disturbances experienced by the projectile as it traverses the length of the barrel. A contributing factor is the initial misalignment of the projectile's principle axis and center-of-gravity (CG) offset with respect to the bore centerline. As the projectile is driven axially down bore by the propellant gas pressure, it is also forced to travel a lateral path that is determined by static and dynamic curvatures. Tube droop in the vertical plane is a gravity-induced static curve, and the bore straightness profile is a static curve due to the manufacturing processes' inability to produce a perfectly straight bore. The firing of the gun produces an array of complex interdependent events. Axial travel of the projectile and propellant gas pressure will impart forces on the gun for recoil and dynamic bending in the barrel. The projectile reacts in flexure to the massive barrel and the barrel responds to the projectile loads. The dynamic lateral motion of the barrel serves as path for projectile balloting.

The balloting analysis program, BALANS, from Arrow Tech Associates, Inc., was chosen for this study because of its multifunctional capabilities. It has the capability to perform single shot deterministic analyses as well as target impact dispersion analysis using a stochastic approach. BALANS accounts for all in-bore clearances. Balloting is defined as the process of the projectile bouncing or slapping on the bore surface as the projectile traverses down bore.

Under this mission for comparing the experimental performance of the XM881 with the modeling results from the BALANS program will point to areas that need improvement. For example, in this study both experiment and modeling show the in-bore balloting reactions to be a significant contribution to dispersion.

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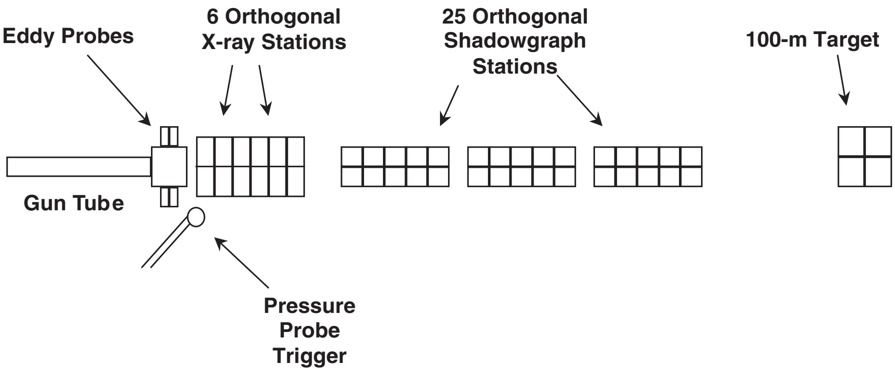


Fig. 1. Jump test instrumentation.

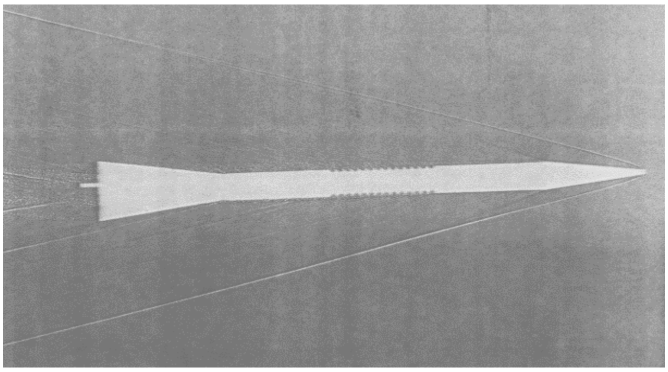


Fig. 2. XM881 flight vehicle at mach 4.0.

2. Experimental approach

2.1. Overview of the experiment

The M242 chain gun was setup at the Aerodynamics Range of the ARL, APG [1]. A schematic of the test setup is shown in Fig. 1. Two eddy probe stations that measure lateral displacements were positioned about the muzzle brake of the gun to capture the muzzle motion. A pressure probe trigger was located just outside the muzzle to start the experimental equipment. A sabot catcher plate is positioned several meters from the muzzle. Six orthogonal x-ray stations were positioned within two meters of the muzzle to capture velocity, yaw, and yaw rates. There were 25 orthogonal shadowgraph stations to measure the flight vehicle motion (see Fig. 2). At 100 meters from the muzzle, a target setup recorded shot fall. The muzzle displacements, pointing angles, transverse velocity and angular velocity were determined using data reduction analysis techniques found in reference [2].

2.2. Description of the XM881

The XM881 is a 25-mm APFSDS experimental round that has gone through a number of design iterations. The XM881 specimens available did not match the particular version of the penetrator drawings found. Therefore, detailed measurements were performed. The total length of the flight vehicle is 153.0 mm with the penetrator length of 82.8 mm and threaded length of 29.4 mm starting at 64.4 mm from the base of the flight vehicle. Refer to Fig. 2 showing a print of a shadowgraph of the flight vehicle from the test. The original sabots were removed from the flight vehicle and replaced with those found on the M919.

2.3. Bore straightness

The M242 chain gun was setup with barrel serial number (SN) 273 that was measured for centerline straightness, and bore gauged for service condition. The vertical (without gravity droop) and horizontal centerline referential to the rear face of the tube (RFT) of

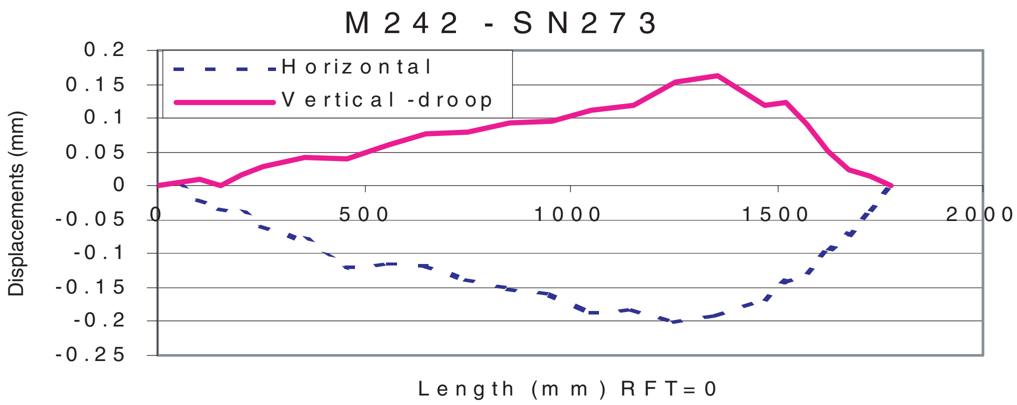


Fig. 3. M242 barrel serial number 273 for the 25-mm chain gun.

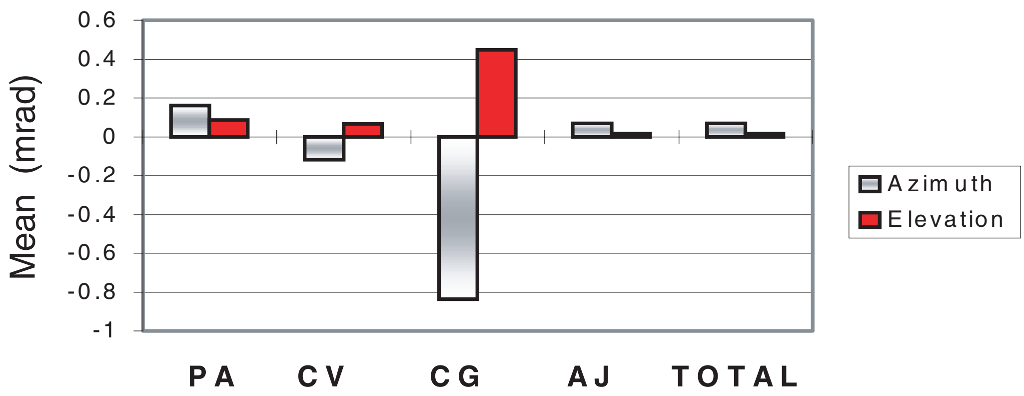


Fig. 4. The 25-mm XM881 means of jump components.

SN273 is shown in Fig. 3. The manufacturing irregularities noted in the centerline are typical with positive up and to the right as viewed from breech toward the muzzle.

2.4. *Experimental results*

The experimental results utilized the jump and dispersion models that are defined in reference [3]. The means of major angular components of jump and dispersion are displayed in Fig. 4 in milliradians. The muzzle pointing angle component is noted as "PA". The muzzle of the gun has transverse velocity noted as "CV" which is imposed on the projectile at shot exit. The angular deviation of the projectile center of gravity relative to a coordinate system attached to the muzzle at shot exit is known as projectile "CG" jump. The "CG" jump is caused by in-bore balloting, muzzle blast, and projectile mechanical disengagement. The component noted as "AJ" is aerodynamic jump which is the mean angular deviation of the projectile swerve trajectory. There was no measurable evidence of disturbance from sabot discard. The sabot discard was completed within 0.15 meters from muzzle. In Fig. 4 positive is up and to the right.

The standard deviations of the components of jump are displayed in Fig. 5. The dispersion model could be linear if the total dispersion is the result of the sum of independent individual jumps. The square of the standard deviations of the individual jump components should sum to the square of the impact dispersion; they do not. The empirical model of reference 2 appears to be suited for this type of data. This indicates that this munition dispersion is non-linear and is discussed in detail in reference 2.

3. Analytical approach

3.1. *Overview of BALANS*

BALANS [4] simulates the dynamic response and interaction of a flexible projectile and a flexible gun

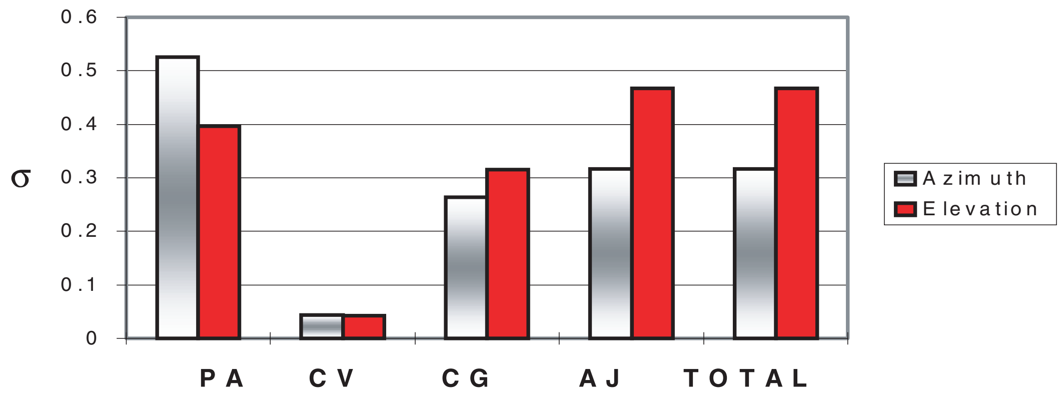


Fig. 5. The 25-mm XM881 dispersion of jump components.

tube during in-bore travel. It also includes the effects of a curved bore profile. The simulation utilizes individual models of the projectile and gun tube, in a time step iterative solution. Pertinent motion and load data are periodically saved during the analysis to produce selective summary graphical displays. BALANS takes advantage of the interior ballistics simulation and CG offset calculations of PRODAS [5] and an automatic lumped parameter modeling capability to assist in building a BALANS model.

The analytical procedure utilized in BALANS presupposes that the projectile is initially misaligned within the gun tube due to manufacturing tolerances. During firing, this misalignment produces secondary forces causing transverse displacement and yawing motion of the projectile as it travels from breech to muzzle. The resulting yaw angle, angular rate, and transverse velocity at muzzle exit are then analyzed for their effect on dispersion. It should be noted that BALANS calculates the projectile state (yaw, yaw rate, transverse velocity) at muzzle exit while the experimental setup also determines the state of the tube and bore at projectile exit.

Figure 6 contains a flow diagram of this analytical approach for predicting dispersion. Whether trying to predict dispersion on a new design or solve a dispersion related problem on a current design, the approach is very similar. It begins with gathering basic technical information such as manufacturing dimensional data, assembly drawings and/or specifications, analytical results from other analyses or tests. This information is critical to building the accurate analytical model of the projectile to be used during all analyses within this approach. From this information, a tolerance study can also be performed and its results used as additional inputs into the in-bore balloting analysis.

Another piece of information required is production history information such as Statistical Process Control (SPC) information. Even if working with a new projectile design for which there is no production history, it is valuable to obtain this information for a similar design or a projectile with similar characteristics. Since some of the inputs to this approach are statistical in nature, this historical data provides a foundation from which to derive the statistical information.

The last type of information required is test and/or measurement data. This includes bore centerline measurements, bore sight errors inherent within a test fixture or bore sight tool, known sabot discard issues from tests of similar sabots, etc.

As can be seen in Fig. 6, the drawings, production history, and results from previous analyses are used for physical modeling of the projectile which in turn is the basis for several analyses to be described in the following sections. Each of the analyses results in dispersion component sensitivities that are then used in predicting dispersion.

3.2. BALANS model of the XM881

The basic inputs for the in-bore balloting analysis are a lumped parameter model of the projectile that properly characterizes its mass properties and flexibility, a forcing function, and several distances and runouts that are used to orient the projectile within the gun tube. The lumped parameter model is generated automatically from the PRODAS geometric model.

Figure 7 is an example of the XM881 as a lumped parameter model automatically generated from PRODAS. As shown, the upper half of the model is the actual projectile as generated from PRODAS. The lower half attempts to mirror the upper half by reflecting the lumped parameter node/element model.

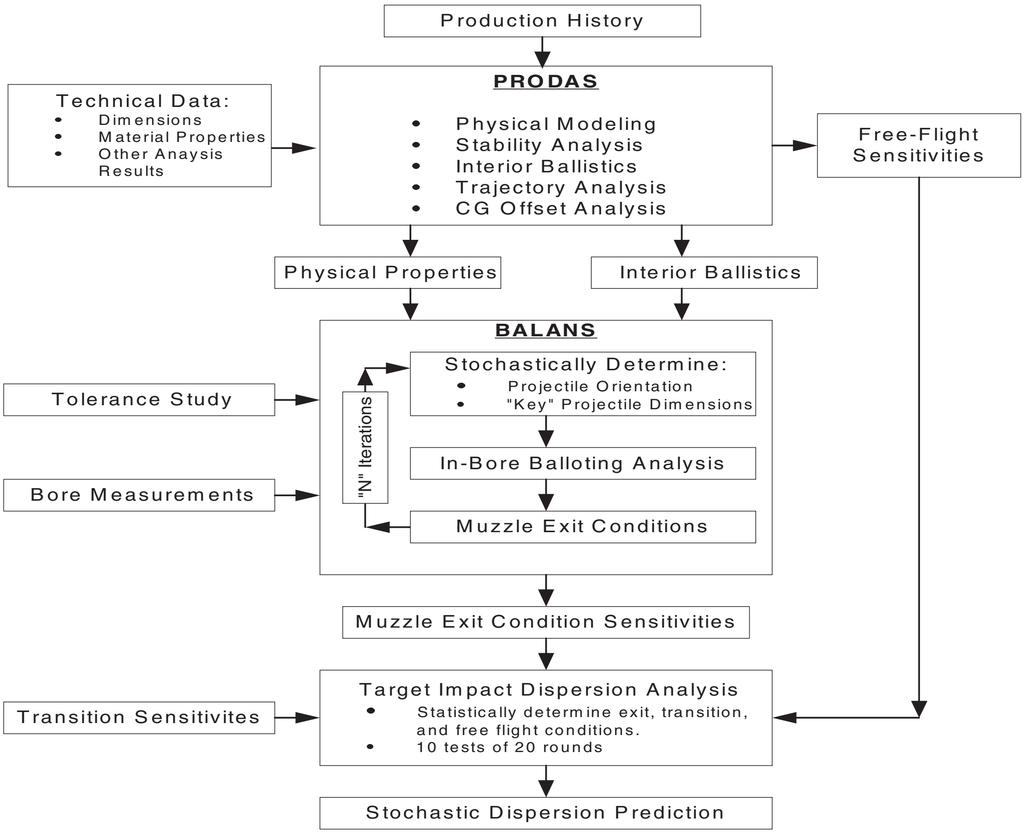


Fig. 6. Analytical approach to predicting dispersion.

The forcing function required for the balloting analysis is provided directly from the PRODAS interior ballistics analysis module. PRODAS uses the Baer-Frankl methodology [6] to simulate combustion of propellant grains and calculate the time-dependent parameters of base pressure (applied to the projectile aft of the obturator during the balloting analysis), spin velocity and acceleration (used to calculate centrifugal forces during in-bore travel), and axial acceleration (used to calculate axial forces during in-bore travel). Transverse forces are calculated from the induced balloting motion.

In addition to the lumped parameter model, the dispersion analysis requires manufacturing dimensional and tolerance information and transition and free-flight sensitivity information. The manufacturing information consists of several critical dimensions and tolerances necessary for in-bore balloting. These define the locations of the projectile / gun tube interfaces and some of the critical projectile dimensions which effect dispersion. The statistical in-bore balloting analysis uses these dimensions and their tolerances to randomly orient the projectile in the gun tube. Several hundred in-bore balloting analyses are generally required to obtain statistically valid muzzle exit yaw, yaw rate, and transverse velocity predictions [7].

The transition and free-flight sensitivity information is used to determine those components of dispersion after the projectile has left the gun tube. Transition sensitivities are separated into sabot discard and bore sight sensitivities. Errors induced by sabot discard may have significant variation from one projectile configuration to another. They have both a physical component that can occur due to asymmetric loads applied to the core during discard and an aerodynamic interference component. Sabot discard is the least well understood of the major contributors to dispersion and therefore is generally determined from test, observation, and/or experience. Bore sight errors are the error associated with pointing the gun at the target. Bore sight errors vary between calibers, gun crews, and instrumentation.

The free-flight dispersion component sensitivities include muzzle velocity, aerodynamic jump, aerodynamic trim angle, cross winds, and aerodynamic/mass asymmetries. All of these parameters are determined via trajectory analysis within PRODAS as follows:

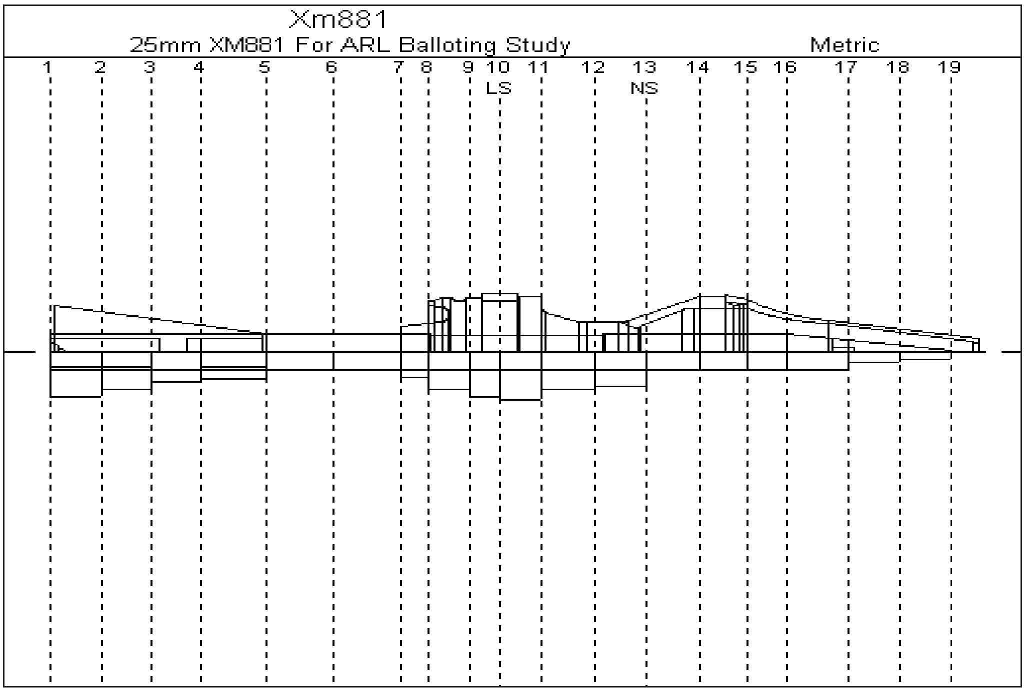
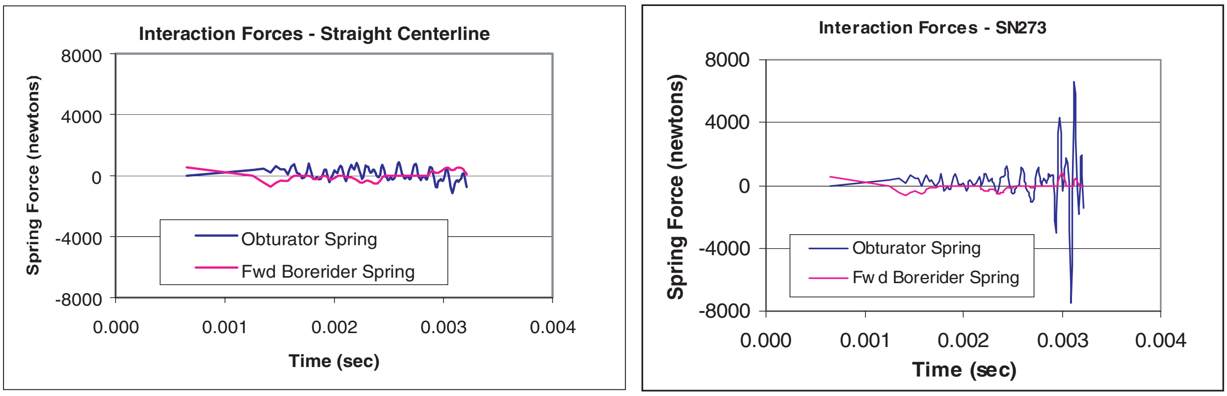


Fig. 7. Graphical representation of the XM881 lumped parameter model.



a) b)

Fig. 8. Interaction forces.

– The muzzle velocity sensitivity factor is the drop variation due to muzzle velocity variation and can be calculated by comparing the drop of trajectory simulations made by perturbing muzzle velocities.
– The aerodynamic jump sensitivity relates dispersion to the muzzle exit yaw rate of the projectile. This factor is dependent upon the physical and aerodynamic characteristics of the projectile as well as the projectile spin and velocity.
– The cross wind sensitivity of the projectile is determined by trajectory simulations of the projectile flight to the range of interest both with and without a nominal crosswind applied.
– The aerodynamic trim angle of a projectile configuration (due to manufacturing tolerances) may be calculated from PRODAS predictions of the body alone and fin alone center of pressure and normal force coefficients, and from the expected one sigma value of the angular misalignments of the nose and tail sections.
– The aerodynamic/mass asymmetries factor is determined by simulating trajectories with a trim an-

Table 1
XM881 sensitivity data

Characteristic	Value	Data source
Aerodynamic Jump Factor(dimensionless)	0.030	Analysis
Muzzle Velocity Standard Deviation(m/s)	8.419	Eng. Estimate
Muzzle Velocity Factor(dimensionless)	0.005	Eng. Estimate
Bore Sight Error(dimensionless)	0.050	Eng. Estimate
Sabot Discard Error(dimensionless)	0.050	Eng. Estimate
Miscellaneous Errors(dimensionless)	0.100	Eng. Estimate
Muzzle Velocity (m/s)	1398.4	Measured
Initial Yaw Factor (mils)	0.010	Analysis
Muzzle Spin Rate (rads/s)	2900.0	Analysis

Table 2
Manufacturing tolerance information

Characteristic	Value (mm)	Data source
Distance to Obturator	63.0941	Measured.
Distance to Forward Spring	101.143	Measured.
Distance to Bore Rider	110.236	Measured.
Bore Diameter	25.100	Measured.
Forward Bourrelet Mean Diameter	24.970	Eng. Estimate.
Forward Bourrelet Standard Deviation	0.015	Eng. Estimate.
Forward Bourrelet Runout (Mean to Penetrator)	0.025	Eng. Estimate.
Forward Bourrelet Runout Standard Deviation	0.010	Eng. Estimate.
Rear Bourrelet Runout (Mean to Penetrator)	0.025	Eng. Estimate.
Rear Bourrelet Runout Standard Deviation	0.010	Eng. Estimate.
Sabot Inside Diameter at Fwd Bourrelet	8.273	Measured.
Sabot Inside Diameter at Fwd Bourrelet Std Dev	0.000	Eng. Estimate.
Core Outside Diameter at Fwd Bourrelet	8.273	Measured.
Core Outside Diameter at Fwd Bourrelet Std Dev	0.000	Eng. Estimate.

Table 3
Simulated TID results of 10 simulations of 10 round tests

Simulation No.	Horizontal (mrads)	Vertical (mrads)
1	0.320	0.418
2	0.384	0.469
3	0.377	0.463
4	0.350	0.441
5	0.402	0.484
6	0.321	0.419
7	0.460	0.533
8	0.292	0.397
9	0.381	0.467
10	0.408	0.489
Average	0.369	0.458
Std. Dev.	0.050	0.040

gle assumed to be oriented at orthogonal and diametrically opposed orientations.

3.3. *Deterministic analysis*

The deterministic analysis provides a detailed analysis at each node in the lumped parameter model in terms of bending moments, shear forces, nodal displacements, and projectile shape at each time step as well as exit conditions. It is equivalent to performing a single shot experiment to investigate issues other than dispersion. Since the analysis presupposes an initial projectile orientation in the gun tube which is difficult to determine experimentally, the deterministic analysis has limited usefulness when trying to evaluate overall projectile performance parameters such as dispersion.

One example of using the deterministic analysis is to compare the results from a smooth straight gun tube centerline to the measured centerline SN273. Figure 8a shows the projectile lateral forces from interacting with a smooth straight centerline. Though the loads are low, it is apparent that in-bore balloting causes a high frequency disturbance. Figure 8(b) shows the projectile lateral forces from interacting with a centerline that includes manufacturing irregularities. The loads are only slightly higher except for some higher forces near shot exit.

3.4. *Stochastic analysis*

The stochastic analysis is used to investigate dispersion issues and requires some statistical information. Table 1 identifies the XM881 sensitivity values used in the analysis. The muzzle velocity comes from measurements taken during the experiment; aerodynamic jump, yaw factor and spin rate come from the other

Table 4
Components of dispersion (from simulation #3)

Dispersion component	Horizontal (mrads)	Vertical (mrads)
Yaw Rate	0.304	0.304
Muzzle Velocity	0.000	0.269
Windage	0.000	0.000
Boresight	0.050	0.050
Sabot Discard	0.050	0.050
Aero/Mass Asymmetries	0.000	0.000
Yaw Angle	0.001	0.001
Transverse Velocity	0.058	0.058
Muzzle Spin	0.204	0.204
In-Bore Total (Yaw Rate + Yaw Angle + Transverse Velocity + Muzzle Spin) = 0.371		

Table 5
Total dispersion comparison

Test	Sigma-Horizontal (mrads)	Sigma-Vertical (mrads)
Experiment (10 rounds)	0.470	0.570
Simulation (10 simulations each with 10 rounds)		
– Minimum	0.292	0.397
– Maximum	0.460	0.533
– Mean (of 10 simulations)	0.369	0.458
– Standard Deviation (of 10 simulations)	0.050	0.040

PRODAS analysis modules; bore sight, sabot discard, and miscellaneous error numbers are engineering best guess values based on experience with similar projectiles.

Table 2 contains manufacturing tolerance information required for the simulation. Generally, this data is obtained from previous simulations, testing, drawings, and/or historical SPC data collected by the manufacturer. For this simulation, the source of the data was either through measurements or from engineering estimates which are based on previous experience in simulating and testing of similar rounds.

The BALANS dispersion results presented in Table 3 are the result of 10 different simulations of 10 rounds each. The initial projectile orientations and other key dimensions as described earlier are randomized based on a normal distribution and the analysis is run to develop the muzzle exit conditions of yaw, yaw rate and transverse velocities. To perform the target impact dispersion analysis, the muzzle exit sensitivities are combined with the transition sensitivities and free-flight sensitivities. Table 4 shows the components of dispersion for one of the simulations.

4. Comparison between experimental and analytical results

The Aerodynamics Branch of ARL and Arrow Tech Associates are continuing the dialog necessary to resolve all the parameters definitions, and understand all the translations that maybe required to make BALANS output results correlate to the similar quantities that are used in the experimental arena. At the present time, we believe the bottom line quantities of horizontal and vertical standard deviations (sigma's) for total dispersion can be compared directly (see Table 5).

The difference between the experimental values and the mean of the simulation values is good considering the complexity and ammunition system. The difference between the minimum and maximum values of the ten simulations is also significant. This implies that there is variability in a modeled ten round sample size as is true for the experiment. It was shown that they are the same order of magnitude. Another source for differences is in the number of simulation parameters that had to be estimated.

5. Summary and conclusions

The full scope of correlating the individual dispersion components of the experimental work with the modeling efforts requires further investigation. However, this project, this work has brought the following insights:

– Use of this combined experimental and analytical approach can lead to more effective test plans by providing engineers with the relative magnitude of

dispersion improvement to be expected by changes in a configuration.
- The experimental approach complements the analytical approach by providing accurate aerodynamic coefficients, a necessary ingredient to determining the free-flight sensitivities for the analytical approach.
- The BALANS analytical approach is useful in the investigation of dimensional tolerances and their effect on dispersion.
- Since dispersion is a combination of random independent and interdependent events, statistics becomes an important issue. The most important issue is whether one can experimentally predict an overall projectile performance parameter such as dispersion from a ten round group.
- When combining the experimental approach with the analytical approach, the analyst and the test engineer should work together to insure an understanding of the details and physics in both methodologies.

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