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Experimental Evaluation of Artillery Projectile Impact Errors Induced by Principal-Axis Misalignment

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Analytical studies and experiments have shown that the presence of a small (less than 1 deg) principal-axis misalignment in an artillery projectile produces a proportionately large initial total transient angle of attack. It was further predicted by six-degree-of-freedom trajectory simulations that this initial transient would cause significant projectile range degradation and drift perturbation. A flight test program was conducted to investigate these transient and trajectory perturbation effects; the resulting data are presented. Confirmation of the analytical predictions of these induced trajectory disturbances was obtained. These data provide a concrete basis for illustrating the undesirable effects on ballistic similitude that can result from small differences in the principal-axis misalignment between otherwise similar projectiles.

Introduction

A SERIES of flight tests was conducted to demonstrate experimentally the decreased range and drift perturbation experienced by an artillery shell as a result of the proportionately large initial total transient angle of attack produced by the presence of a small principal-axis misalignment. Experimental verification of these predicted effects was desired to provide further validation of a recently published theory concerning the effect that principal-axis misalignment has on the ballistic similitude of similar projectiles.[1] Ballistic similitude exists between types of projectiles for equivalent launch conditions (elevation, azimuth, and velocity) if their mean impacts fall within some specified small range and drift probable errors. It was shown[1] through analytical developments and through the use of six-degree-of-freedom (6-DOF) trajectory simulations that, because of the perturbing effects indicated above, small differences in principal-axis tilt between otherwise similar types of projectiles can produce unacceptably large differences in the distance between their mean impacts.

Recently, Murphy[2] published experimental data that describe the effect that principal-axis misalignment has on initial transient angular motion. However, to the knowledge of the authors, there have been no published experimental data that describe the extremely important effects of decreased range and drift perturbation also induced by principal-axis tilt. Apparently, this paper provides the first complete description of the combined effects.

Test Equipment and Procedures

The projectiles fired during this test program were basically U.S. Army 8-in. M106 units. Inert, unfilled M106 bodies were modified with an internal ballast structure designed to provide specified levels of projectile principal-axis misalignment without introducing lateral center-of-gravity (c.g.) offset. A typical modified projectile is shown in Fig. 1. Principal-axis misalignment, relative to the assumed in-bore spin axis or X-axis of geometric symmetry, was introduced by the tungsten weights located away from the c.g. alternately above and below the X-axis. For small angles the magnitude of the principal-axis-misalignment angle is approximately equal to the product of inertia (introduced by the off-axis weights) divided by the difference between the lateral and axial moments of inertia.

The ten projectiles used in the program, each weighing nominally 205 lb (93. 2 kg), included four rounds that had 0.7 deg of principal-axis misalignment and three pairs that had 0, 0.3, and 0.5 deg, respectively. Figure 1 illustrates a projectile with a 0.7-deg misalignment. The misalignment of each round was measured on a Trebel (FED-1000) dynamic balancing machine. Prior to modification, the mean principal-axis-tilt value for these projectiles was 0.02 deg.

These projectiles, with the exception of differences in principal-axis tilt, satisfied the ballistic similitude criteria[3] (recently verified experimentally[4]); i.e., they had similar gyroscopic stability factors, ballistic coefficients (predicted impact-range variation of ± 55 m), and yaws of repose (predicted impact-drift variation of ± 25 m). Relatively large principal-axis tilts were used so that differences in impact locations would be large relative to the added normal round-to-round dispersion caused by internal ballistic and muzzle-exit effects. Therefore, differences in their impact locations are primarily affected by differences in the principal-axis misalignments. Yawsondes[5] were used to monitor the transient angular motion and spin rate of these shells during flight.

The projectiles were fired from an 8-in. M201 gun tube (1-in-20 twist, no muzzle brake) along a fixed aximuth at a 48 deg elevation angle with a nominal muzzle velocity of 2550 fps (777 m/s). The angle ϕ between the plane of the principal axis (plane passing through the projectile geometric centerline and the principal axis) and the gun-tube vertical plane (also earth vertical) was controlled and varied to assess the effect on trajectory drift. This angle is designated the muzzle-exit roll-orientation angle. For $\phi = 0$, the principal axis is in the gun-tube vertical plane and is located above the projectile geometric centerline at the nose. A muzzle-exit roll-orientation angle greater than zero is obtained by rotating the plane of the principal axis about the gun-tube centerline from the zero position in a clockwise direction looking downrange. Roll-orientation angles were restricted to values near 0, 45, 90, and 180 deg during the firing program.

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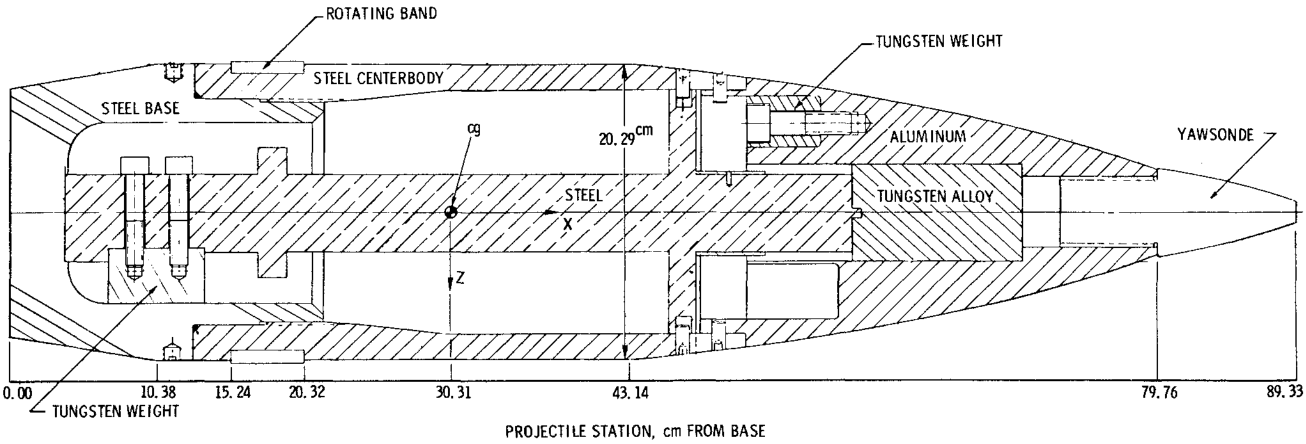

Fig. 1 Typical projectile in cross section.

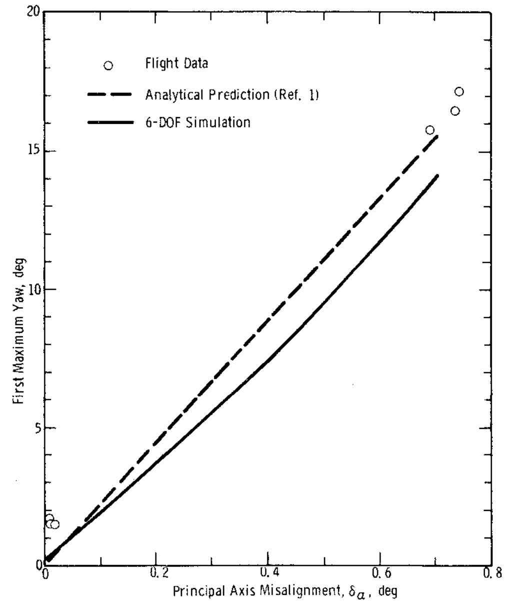

Fig. 2 First maximum yaw variation.

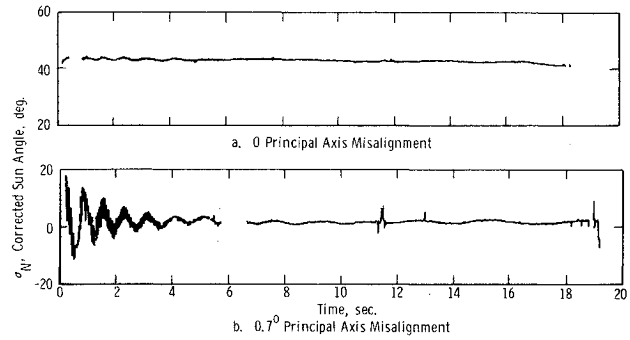

Fig. 3 Typical yawsonde records.

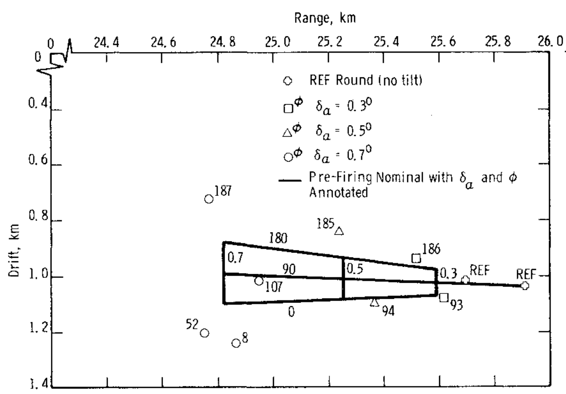

Fig. 4 Impact points.

Results and Discussion

Comparisons are given in Fig. 2 of the simulated effect, the experimentally determined effect, and the analytically predicted effect[1] that principal-axis misalignment has on first maximum yaw (maximum amplitude of initial transient motion). The simulated and experimental results confirm the analytically predicted trend; i.e., large magnifications of small principal-axis-misalignment-induced trim are present in the initial transient angular motion. The analytical estimate ignores damping and is based on linear aerodynamics; therefore, some deviation from the levels of experimental and simulated results is to be expected. Differences between the experimental data and simulated results, as evidenced by the zero principal-axis-tilt data, may be partially caused by small muzzle disturbances. Also, small errors in the aerodynamic force and moment model are possible contributors. Because of telemetry dropouts near zero time or failure of the yawsonde units, only three experimental points could be obtained for comparison. Data near zero axis tilt were obtained from an earlier experiment.[4]

A comparison of the transient angular motion of an M106 projectile with zero principal-axis misalignment to the transient motion of one with 0.7 deg is provided by the yawsonde plots presented in Fig. 3. Only the first 20 s of these approximately 90-s flights are shown. Even though the initial transient angular motion induced by the principal-axis misalignment damps rapidly for this flight condition, the resulting drag induced by the angular motion reduces the effective ballistic coefficient sufficiently to cause a large reduction in range, and the initial motion alters the flight path direction. These large effects on range and deflection are demonstrated in Figs. 4-6.

Figure 4 provides an overall view of the relative impact locations of the various test projectiles. The exit orientation ϕ of each projectile, as determined from smear camera data, is indicated. These impact data have been corrected for differences in muzzle velocity, weight, and winds. The predicted performance, as determined from 6-DOF simulations, is indicated by the solid lines. The near-vertical solid lines give the range estimates for the various principal-axis misalignments, while the near-horizontal solid lines provide the deflection predictions for $\phi = 0$, 90, and 180 deg. Note that the range effects are close to the predicted values, while the effects on deflection were somewhat larger than predicted. Data

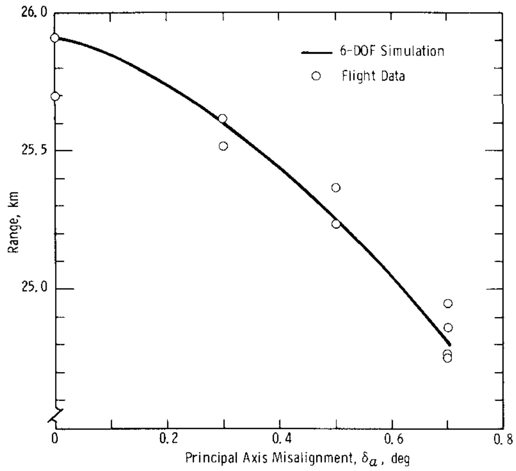

Fig. 5 Range effect.

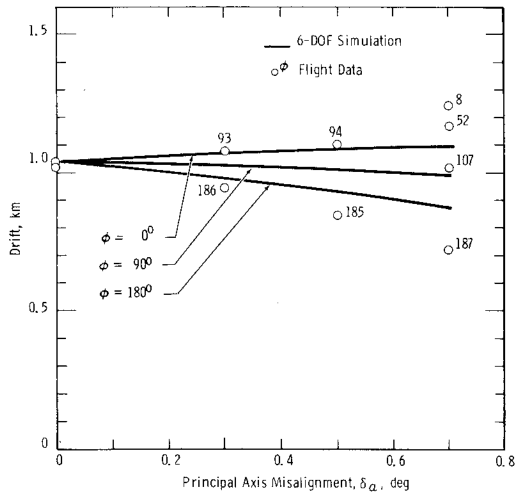

Fig. 6 Drift effect.

from this plot are presented in Figs. 5 and 6 to provide a more detailed description of the effects.

Results obtained from 6-DOF simulations are compared with flight data in Fig. 5 to demonstrate the effect that principal-axis misalignment has on projectile range. Note again the excellent agreement between the experimental data and the 6-DOF simulation. These data confirm the large effects that principal-axis misalignments have on range reduction. For this initially supersonic flight condition where, due to high gyroscopic stability, the effects of principal-axis misalignment on initial angular motion are smallest,[1] the curve in Fig. 5 indicates that differences in principal-axis tilt as small as 0.1 deg can cause differences in range of 100 m or greater. Even for this relatively long range, differences in range less than this magnitude would exceed most similitude requirements. Therefore, these data also confirm the previous conclusions[1] reached concerning the undesirable effects on ballistic similitude that even small differences in principal-axis misalignment can have.

Results obtained from 6-DOF simulations are compared with flight data in Fig. 6 to demonstrate the effect that principal-axis-misalignment-induced trajectory deflections can have on changes in drift. Here again the muzzle-exit orientation ϕ of each projectile is indicated. Because the gun elevation is near that for maximum range, a slightly altered effective elevation angle caused by trajectory deflection should have no noticeable effect on range.

With a 90 deg muzzle-exit orientation, the trajectory deflection (downward in the vertical plane) due to principal-axis tilt, as predicted by the 6-DOF simulations, should have a negligible effect on range and no effect on drift. Therefore, the drift differences between the $\phi = 0$ and $\phi = 90$ deg lines and the $\phi = 180$ deg and $\phi = 90$ deg lines reflect the maximum predicted effect on the drift that a given level of principal-axis misalignment can have for these conditions. As shown by the data near $\phi = 0$ and $\phi = 180$ deg (Fig. 6), the actual principal-axis-tilt-induced drift errors can be considerably larger than the predictions based on 6-DOF simulations. These differences may be attributable to additional muzzle-exit disturbances resulting from gun-tube motion, projectile balloting (both effects induced by the dynamically unbalanced projectiles), etc. Also, errors in the aerodynamic characteristics employed in the 6-DOF simulations may contribute. The initial conditions used for these flight simulations ignore the small additional muzzle-exit disturbances. Because of the lack of more detailed data for this projectile, a linear aerodynamic model was used for the projectile pitching moment. Deviations from this linear model; which occur at high angle of attack; could cause errors in the prediction of trajectory drift. Displacements of the impact points away from the $\phi = 90$-deg line for the $\phi = 93$ and 94-deg data (Fig. 6) are also probably caused by additional initial lateral motion effects and aerodynamic model errors.

As shown by the data in Fig. 6, small differences in principal-axis misalignment can cause relatively large differences in drift. Assuming that the muzzle-exit orientations of two types of projectiles are random, principal-axis-misalignment-induced trajectory deflection should not noticeably affect the relative location of their mean impacts but should affect the distribution of impacts about these mean values. Trajectory deflections induced by principal-axis tilt should therefore influence similitude basically through an effect on drift precision rather than through an effect on mean impact. Notice in Fig. 4 and in a comparison of Figs. 5 and 6 that for the same magnitude of principal-axis misalignment, the deflection-induced changes in drift are small compared to the reductions in range that result from reduced effective ballistic coefficient.

Conclusion

A series of flight tests was conducted and data were gathered to confirm experimentally the predicted decreased range and drift perturbations experienced by an artillery shell as a result of the proportionately large initial transient angular motion caused by the presence of a small principal-axis misalignment. These data provide a concrete basis for illustrating the undesirable effects on ballistic similitude that can result from the presence of small differences in the level of principal-axis tilt between otherwise similar types of projectiles.

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