Test Options & Analysis Techniques: Aerodynamic Coefficients: What’s Important & How Can I Measure Them?

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Outline

• What’s Important & Why?
• Data Acquisition Options
• Accuracy & Cost Comparison
• Summary and Conclusions
### What’s Important & Why?

#### Aerodynamic Coefficient / Item

<table>
<thead>
<tr>
<th>Description &amp; Affects</th>
<th>Symbol</th>
<th>Description &amp; Affects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero Yaw Drag Force</td>
<td>$C_{X0}$</td>
<td>Acts along projectile axis; Deceleration &amp; retained velocity, minor affect on dispersion</td>
</tr>
<tr>
<td>Yaw Drag Force</td>
<td>$C_{X2}$</td>
<td>Added drag factor along proj. axis; Decel. &amp; retained velocity of yawing bullet</td>
</tr>
<tr>
<td>Normal Force Derivative</td>
<td>$C_{N\alpha}$</td>
<td>Acts in plane of angle of attack; Causes swerve motion of yawing bullet, dispersion. Influences dynamic stability</td>
</tr>
<tr>
<td>Magnus Force</td>
<td>$C_{Y\alpha}$</td>
<td>Out of plane force from spin; source of the destabilizing Magnus moment</td>
</tr>
<tr>
<td>Pitching Moment Derivative</td>
<td>$C_{m\alpha}$</td>
<td>Acts in the plane of angle of attack; influences Gyroscopic Stability &amp; Dispersion</td>
</tr>
<tr>
<td>Pitch Damping Moment</td>
<td>$C_{mq}$</td>
<td>Acts counter to pitching moment; affects Dynamic Stability</td>
</tr>
<tr>
<td>Spin Damping Moment</td>
<td>$C_{lp}$</td>
<td>Acts counter to projectile spin; affects down range gyroscopic stability</td>
</tr>
<tr>
<td>Roll Moment Product</td>
<td>$C_{ldD}$</td>
<td>Roll moment coefficient x fin cant angle: Increases/maintains projectile spin rate</td>
</tr>
<tr>
<td>Magnus Moment</td>
<td>$C_{np\alpha}$</td>
<td>Acts perpendicular to the plane of the angle of attack; affects Dynamic Stability</td>
</tr>
<tr>
<td>GN&amp;C Forces &amp; Moments</td>
<td>$CN_{\alpha}/Cm_{\alpha}$</td>
<td>Typically Increases Angle of Attack to provide maneuver authority</td>
</tr>
</tbody>
</table>

- **What can you afford to ignore?**

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2012 NDIA Joint Armaments
What’s Important & Why?

- **Jump Equation (Dispersion)**
  \[
  \Theta_j = \left[ \left( \frac{C_{N\alpha} - C_D}{C_{m\alpha}} \right) \left( I_y - I_x \right) \left( \frac{d}{V_m} \right) \left( \alpha_g \cdot p_m \right) \right]^2 + \left[ \Delta_{CG} \cdot \frac{p_m}{V_m} \right]^2 \right]^{1/2}
  \]

- **Gyroscopic Stability Equation**
  \[
  S_{gp} = \frac{(2)(I_X^2)(\rho^2)}{(\pi)(\rho_o)(I_Y)(C_{m\alpha})(\rho^3)(V_m^2)}
  \]

- **Dynamic Stability Damping Exponents**
  \[
  \lambda_F = \frac{\rho A}{4m} \left[ -C_{N\alpha} \left( 1 - \frac{1}{\sigma} \right) + \left( k^{-2} / 2 \right) \left( 1 + \frac{1}{\sigma} \right) C_{mq} + \left( k^{-2} / \sigma \right) C_{np\alpha} \right]
  \]
  \[
  \lambda_S = \frac{\rho A}{4m} \left[ -C_{N\alpha} \left( 1 + \frac{1}{\sigma} \right) + \left( k^{-2} / 2 \right) \left( 1 - \frac{1}{\sigma} \right) C_{mq} - \left( k^{-2} / \sigma \right) C_{np\alpha} \right]
  \]
What’s Important & Why?

• Deceleration

\[ \frac{dV}{dX} = \frac{1000 \rho V A C_x}{2m} \]

• Steady State Roll Rate (Statically Stable Bullets)

\[ -C_{l\delta\delta} = (\rho d/2V)C_{lp} \quad \text{or:} \quad -2 \frac{C_{l\delta\delta}}{dC_{lp}} = p_{\text{steady state}} \quad (\text{rad/m}) \]
What are my Aero Data Acquisition Options?

- Witness & Yaw Cards
- Doppler Radar
- Wind Tunnel (& Variants)
- Spark Range
- On-Board Telemetry (Yawsonde, Magsonde, etc..)
- Data “Fusion”
Witness Cards

Simple paper target at convenient distance from gun
- Aim point & projectile impact points
- Limited examination of projectile angle of attack info

Provides:
- Dispersion & MPI distance from Aim Point estimates
- Evidence of in-flight stability or projectile damage
- Point value angle of attack not recorded by acoustic targeting systems…
  (verification of stable, low yaw flight)
Witness Card Example

- Record of aim point and impact point of various shots...

- Impact in upper right was aimed at center of adjacent target, exhibits large angle of attack @ 50 yards
Series of target cards

- Record total angle of attack & pointing vector change vs. distance from muzzle

Advantages:
- Simple technique
- Low cost “instrumentation”

Provides:
- Pitching moment, pitch damping, Magnus moment, roll moment, roll decay moment
- Is yaw causing dispersion or only MPI shift?

Drawbacks:
- Need sufficient yaw to allow observation (Yaw Inducer Needed?)
- Yaw card impact affects projectile motion
Yaw Card Data

Reference Line (e.g. Plumb Line w/ Chalk)

Aft View
(Yaw Card Imprint)

Hole Length

Projectile Angle of Attack (AoA) can be interpolated from hole length measurements or from yaw card template overlays.
“Planar” Motion
Caused by In-Bore Disturbances

Coning Motion
External Disturbance Source
Doppler Radar Testing

(Radar image courtesy of Infinition, Inc.)
Radar Testing

- Point-point initial solution
- Simulate Trajectory via 4 DoF.
- Compare Vel-Time of Simulation to Experimental Data.
- Iteratively Adjust Drag Coeff Until Difference between Simulation & Experiment is minimized.
- Assess groups of like projectiles to determine statistical behavior (Mean & sigma of MV & Drag).
Various flight dynamic problems have characteristic signatures that can be rapidly categorized & diagnosed w/ Doppler Radar.

Spin reflector can be used to obtain $C_{lp}$, $C_{ldDelta}$...
Range from “home made” subsonic to precision supersonic blow-down or steady state tunnels

Provides: Normal force coeff., pitching moment, roll moment, roll decay moment.

Drawbacks:
– Pitch damping moment, Roll moment, roll damping moment determination are contaminated by bearing friction….
– “Sting” or support muddles base flow subsonically
“Captive Free Flight”

- Fasten model to low friction bearing (e.g. sailboat “windex”)
- Affix to appropriately modified vehicle
- Drive (moderately fast)
- Disturb model & record oscillation frequency (time base on video..)
- Pitching moment, pitch damping moment can be extracted from data
Aeroballistic Range

• Concept:
  – Orthogonal Photographs of Projectile Shadow from “Spark” Sources
  – Fit 6 DoF Coefficients to Observed Flight Motion in Series of Photos
Aeroballistic Range

If you can’t get a bigger target...

• Positive Aspects
  – Full Scale Testing (5.56mm to 200mm)
  – Excellent Mach Number Control
  – Reynolds Number Match
  – Direct Observation of Angular-Translational Motion
    > Motion Growth - Damping
  – Initial Conditions / Initial Motion Match Real World

• Negative Aspects
  – Exact Angle of Attack, Roll Orientation cannot be precisely controlled
  – Apogee / Terminal Conditions (Spin/Velocity) not matched
  – Low Velocity Tests of High Velocity Projectiles do not match rotating band wear conditions
On-Board Telemetry Hardware

Aeroballistic Diagnostic Fuze

Instrumented 2.75-inch Rocket

In conjunction with Doppler Radar
The INERTIAL SENSOR SUITE BOARDS are mounted within the FUZE bodies so that the field of view of SLIT #1 lies in the I,+K half-plane.

+I

+J Axis is into the slide.
### What Methods for Which Coefficients?

<table>
<thead>
<tr>
<th>Aerodynamic Coefficient/ Item</th>
<th>Symbol</th>
<th>Yaw Card</th>
<th>Doppler Radar</th>
<th>Wind Tunnel</th>
<th>Spark Range</th>
<th>On Board Telemetry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero Yaw Drag Force</td>
<td>C(_X_0)</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Yaw Drag Force</td>
<td>C(_X_2)</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Normal Force Derivative</td>
<td>C(_N\alpha)</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Magnus Force</td>
<td>C(_Y\alpha)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Pitching Moment Derivative</td>
<td>C(_m\alpha)</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Pitch Damping Moment</td>
<td>C(_m\varphi)</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Spin Damping Moment</td>
<td>C(_l\varphi)</td>
<td></td>
<td>X (Finner)</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Roll Moment Product</td>
<td>C(_l\varphi D)</td>
<td></td>
<td>X (Finner)</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Magnus Moment</td>
<td>C(_n\varphi\alpha)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>GN&amp;C Forces &amp; Moments</td>
<td>C(_N\alpha)/C(_m\alpha)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

- Combinations of non-spark range techniques can provide all aeros
- Limitations (size, cost, range availability, etc) determine choices…
### Aero Data Acquisition Options
#### Cost & Accuracy Summary

<table>
<thead>
<tr>
<th>Measurement Option</th>
<th>Caliber Applicability</th>
<th>Goal</th>
<th>Accuracy</th>
<th>Data Acquisition Cost / Shot or run</th>
</tr>
</thead>
<tbody>
<tr>
<td>Witness Card</td>
<td>All</td>
<td>Dispersion &amp; MPI</td>
<td>~ Location, 0.010&quot;</td>
<td>Pennies</td>
</tr>
<tr>
<td>Yaw Card</td>
<td>All</td>
<td>Static &amp; Dynamic Stability</td>
<td>~±15-25%</td>
<td>$2-$10 depending on setup &amp; shots fired</td>
</tr>
<tr>
<td>Doppler Radar Data</td>
<td>All</td>
<td>Drag &amp; Muzzle Velocity</td>
<td>+ 1.5% on drag, +0.1 m/sec on MV</td>
<td>$20-$100/shot if equipment/operator is leased, less if owned.</td>
</tr>
<tr>
<td>Wind Tunnel</td>
<td>Med &amp; Large</td>
<td>Normal Force, Pitching Moment</td>
<td>± 3-5% on most aeros, 15-25% on Pitch damping, roll damping, Magnus moment</td>
<td>$10-$50 and up, + setup fees</td>
</tr>
<tr>
<td>Captive Flight</td>
<td>All, limited Mach Numbers</td>
<td>Normal Force, Pitching &amp; Pitch Damping Moments</td>
<td>± 1-20% low subsonic Pitching &amp; Pitch damping moments</td>
<td>$5-$25/ run</td>
</tr>
<tr>
<td>Spark Range</td>
<td>All</td>
<td>The whole smash</td>
<td>Best available…</td>
<td>$2000-$2500/shot</td>
</tr>
<tr>
<td>On-Board Telemetry</td>
<td>Med &amp; Large</td>
<td>Everything but Normal Force Coeff.</td>
<td>Good for everything but Normal Force Coeff.</td>
<td>$800-$25000/shot depending on infrastructure, etc. required for test. Radar coverage req’d.</td>
</tr>
</tbody>
</table>

**What are my aero coeff. collection requirements?**
Summary & Conclusions

• Numerous options available to all munitions engineers to measure actual aerodynamic coefficients, regardless of caliber

• Coefficient measurement accuracy is generally proportional to cost, but good measurements can be made inexpensively in a wide variety of cases

• “Cut-and-try”, especially with small caliber ammunition, is no longer cost effective for schedule reasons; scientific methods can be brought to bear at reasonable costs

• “Simulate the test” can prevent test repeats

• Competent testing early in the program can uniquely identify specific function problems, helping ensure project stays on schedule & under budget

• “Right Sized” test program provides the Right Response