Combining Experimental Data, CFD, and 6-DOF Simulation to Develop a Guidance Actuator for a Supersonic Projectile

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Outline

- Why guided bullets?
- Initial Results
- Wind tunnel results
- CFD
- Subscale Range Tests
- Comparison with CFD and Reconciliation
- Full Scale Range Tests
**Swarmers Concept for Cruise Missile Defense**

**Goal:** Defend against maneuvering cruise missiles.

**Features:**
1. High supersonic projectiles (Mach 4+)
2. High g maneuvers (50g)
3. Short Mission (4 sec)
4. Swarm of Projectiles
Guided bullets to intercept mortars
Ball M33 Lab Tests
Optical Verification of changes in flow due to mass injection at Nose and Midbody.
Measurements of mass flow required to affect flow.

40mm Scaled Ball M33
USAFA Tunnel / CFD
Mass Injection: Nose, Midbody, Boattail
Long and Short Boattail

Can Alter
Flow

Long Boattail
Best

Aft Mass Injection
Best

40mm ARL Projectile
U. Texas Tunnel / CFD – forces and moments
Aft Mass Injection: Tangential and Normal

Normal Mass Inject
Better

Projectile Unstable

GTRI Phase 1 Efforts

GTRI Second Year Efforts

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Concept of implementing flow control near fin

Actuators create shock patterns that impinge on fin and body surfaces to produce time dependent control forces.

**Roll control**
- Aft View
- 2 diametrically opposed pins
- Induce clockwise rotation

**Pitch control**
- Aft View
- 2 pins close to adjacent fins
- Induce Angle of Attack Change

**Flow parameters**
- $M = 4.0$
- $AOA = 0^\circ$
Fin Interactions

GTRI Tunnel
Measured forces generated by pins and mass injection in region near fin

Pins Near Fins
Generate Strong Turning Moment

Too Much Volume Required for Mass Injection

Input from ARL on Size, Shape, Mass Dist.

Need System Study to Define: Cg location, Fin Shape/Size, Roll or Fin Stabilized? Actuation Concept and Preliminary Design

½ Body Test Rig

3D Effects
Steering Force (Steady & Unsteady)

CFD
Understand Fluid Dynamic Interactions

Preliminary Actuators
Available Steering Force

Fire Round at ARL
Test Concept and Hardware
Understanding Fin-Body Corner Flow Interactions

Flow over fin and cylinder

Creates pressure changes on fin

Pressures used to calculate force on fin

Early results proved two things:

1) More force produced near trailing edge of fin

2) Mass flow requirements for fluid injection too high
Pin-Fin Interaction Parametric Study

**Goal:** Understand trades of pin location and pin shape

**Rationale:** Recognize likelihood of non-optimal pin placement and geometry

- Data acquired at $M = 1.7$
- Data for 4 different pin geometries
  - Round pins 0.1 and 0.2 inch diameter
  - Flat pin with same frontal area as 0.2 round pin
  - Trapezoidal pin with same frontal area as 0.2 round pin
- Pin height fixed at 0.5 in
- Spacer blocks used to position pin

<table>
<thead>
<tr>
<th>Pin Height</th>
<th>Pin Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2 Round</td>
<td>Round 0.2</td>
</tr>
<tr>
<td>0.2 Round</td>
<td>Round 0.1</td>
</tr>
<tr>
<td>Trapezoid</td>
<td></td>
</tr>
</tbody>
</table>
Parametric Study Details

Pin location test matrix

- 9 x 10 Matrix (90 locations)
- 0.55 in spanwise x 0.88 in streamwise
- Force measurements made for all pins at all points except trapezoid, which experienced structural failure
- 271 unique tests performed
- 1300 + data points (each location performed 3 times)

Forces on fin directly measured as opposed to pressure measurements
Contour plots of side force vs pin location show same trend for all pins

Clear evidence of optimal regions for pin location

- Implies there is leeway in placement of pin
- Important as mechanical/space restrictions may not allow for location at optimal location Relative force for flat pin larger than round with same frontal area
- This likely due to stronger shock (no 3-D relieving effect)

Hypothesis that optimal location should scale with pin diameter, was proven wrong (compare 0.1 and 0.2 dia pins)

The 3-D shock interactions are complex and do not lead to simple scaling
Effect of Separation Distance (between pin and fin)

- Dividing the force by the frontal area of the pin provides a 1\textsuperscript{st} order collapse of the magnitude.

- Several different parameters were explored to determine the effect of separation distance:
  - The distance from the edge of the fin to the centroid of the pin provided the best collapse.
  - Optimum separation distance appears to be about 0.41-0.42 in.

- Plots are at $Y = 0.775$ in.

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**Diagram:**

- **Gap (pin-fin):**
  - Round 0.1 \times Gap
  - Round 0.2 \times Gap

- **Dist to Centroid (Pin Diameter):**
  - Round 0.1 \times D
  - Round 0.2 \times D

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*Georgia Tech Research Institute*
Effect of Pin Geometry

- For same frontal area, rectangular pin gives most force
  - Has least 3-D relieving effect
  - Seems to outweigh additional sideforce generated on trapezoidal pin

- Optimal (X,Y) location independent of pin geometry

- Enough trapezoid data acquired (before structural failure) to demonstrate that flat pin is better
Mach 2.5 Experiments at GTRI

½ Projectile (full scale)

Ground Plane

Mach 2.5 C/D Nozzle

50 mm

Linear Air Bearing

Shaft for model rotation

Force Sensor for moment measurement

Pressure Transducer and Signal Conditioners

Force Sensors for side force measurement
Effect of Pin Height

- Force dominated by AOA of projectile
- Non linear effect of pin height on moment
- Projectile should be rotate to about 5 degrees with pin deployed
Second Generation Actuator Rotates into Flow

- Rocker Pin Hardware Installed in Wind Tunnel Scale Model
  - Rotation solves stiction problem

- Consisted of
  - Rocker Pin Assembly
  - Pneumatic Cylinder
  - Small Valve

- Further work needed
  - Not g-hardened
  - Valve still too large

- Using 90 psi
  - Very large holding force
  - Response time on order of 10 ms
  - Rotates projectile over 4 degrees
Experimental Input to CFD

- Experiments showed
  - Where to place guidance pins
  - Effects of pin geometry
    - Including material failure (not from CFD)
  - Crude force measurements
  - Mechanical design considerations (not from CFD)

- Need CFD to complete picture
  - Little flow understanding
  - Better drag and force measurements
  - Use full 3-D body

- Combine EFD and CFD to predict Range Tests
Using CFD to Predict Range Test Results

- Drag and Roll Torque Predicted using CFD
  - Allowed for estimation of performance in range
  - Fewer shots required as we knew how many rotations to expect downrange

\[ M = 4.0 \]
\[ \text{AOA} = 0^\circ \]
ARL Range Tests to Measure Roll Torque

- ½ Scale Projectiles Fired from 1 inch Gun
  - Quantify Rolling Moments
  - Provide Results for Validating CFD
  - Provide More Accurate Aero Coefficients to 6 DOF

- Total shots fired: 15 rounds
  - 3 with no pins
    - 1 at Mach 3
    - 1 at Mach 2.5
    - 1 at Mach 2
  - 3 with long pins (0.1 in height) at Mach 3
  - 9 with short pins (0.07 in height)
    - 3 at Mach 3
    - 3 at Mach 2.5
    - 3 at Mach 2

Picture of test facility
ARL Range Test Setup

- 6 Orthogonal X-ray Stations Near Muzzle
  - Showed that Sabot Separated Cleanly
- 35 Shadowgraph Stations – to 100 m Downrange
  - Generated Images that were used to determine:
    - Roll and Pitch Damping
    - Drag
    - Number of Revolutions – Spin Rate

25-mm smooth bore gun

Blast Chamber  Spark Shadowgraph Stations
Test Articles

- Projectiles ½ Scale (25 mm)
- Pins were round 1/16th in diameter on opposing fins
- Nylon Sabot
Shadowgraphs from Range – Count Rotations

- The rotation of the round as it traverses the range can be tracked via a spin pin.
- The rotation rate leads to a measurement of roll torque developed by pins.

Stations 22 and 27
6.7m to 8.2m
Little Spin Observed

Stations 295 and 300
90m to 91.4m
Over 90° rotation
Range Test Comparison with CFD

- Comparison with measured data not as good as expected
- Drag under predicted at all Mach numbers
- Roll torque prediction worse as Mach number increased
What went wrong?

- Compromises in machining small rounds led to significant differences between CFD geometry and test rounds
- New grid generated and new runs accounting for
  - Fin leading edge bluntness
  - Fillet at base of fin
  - Round pin versus Rectangular
Comparison with Updated Geometry

- Once a more accurate geometry was modeled, a much better correlation was found between the computed and measured drag and roll torques.
- Allowed us to proceed with divert test on full scale rounds.
700 ft Range Preliminary Tests

- Outdoor Range
- 75 mm smooth bore gun
- Yaw cards set up
- Problems encountered
  - Stability
  - Sabot Separation

Try doing this in CFD
Sabot and Launch Package Resolution

- New set of rounds made with increased static margin
- Cup scored more deeply
- Aluminum pusher plate
700 ft Range Tests – Divert Demonstration

Series of yaw cards show that projectile is clearly diving down due to pins deployed after launch.

Aim Point

1.9 m Downrange

4.5 m Downrange

9.1 m Downrange

27.4 m Downrange
Transonic Spark Photograph Layout

- 5 groups of 5 stations
- Each Station provides Shadowgraphs for
  - Vertical Plane – Wall
  - Horizontal Plane - Pit

Projectile
Shadowgraph

Group 1
Group 2
Group 3
Group 4
Group 5

Nominal Pin Deployment

3 m

39.5 m
45.8 m
162 m
Divert Demonstrated by Shadowgraphs

40 m

74 m

132 m

156 m

196 m

1 m
Demonstrated High G Turn on Stable Projectile

Stable projectile for testing (1.5 caliber static margin)

~14 g divert maneuver

~80 N force created by control pins

Preliminary data reduction

More data will be available in the near future

Concept promising for high g maneuvers

9.4 g horizontal acceleration

10.4 g vertical acceleration
Conclusions

- A demonstration of steering a Mach 4 projectile using the guidance pins was successful.

- The combined CFD and Experimental efforts led to a greater understanding of the effects of the pins:
  - EFD and CFD each used to get different but required forces and moments
    - Results could have been easily done without IFD
    - This in turn allowed us to better predict the results of the range tests

- Less range tests were required because once the predictions were validated, it was proven we understood the aerodynamics:
  - This saved substantial amounts of money
    - $10,000 bullets and 5 range operators and 2 PhDs add up fast
    - (As does destruction of the ADT alarm box)

Less Bullets $\rightarrow$ Less $$ $\rightarrow$ IFD=GOOD