CFD Applications and Validations in Aerodynamic Design and Analysis for Missiles

Kwang-Seop Lee and Seung-Kyu Hong
Agency for Defense Development

3rd International Symposium on Integrating CFD and Experiments in Aerodynamics

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Outline of Talk

• ADD Brief
• Numerical Method
• Applications
  - Ogive-cylinder
  - Boat tail and Spike
  - VLS Internal Flow
  - Side jet on body-tail missile
• Conclusions
Military Demarcation Line
3rd International Symposium on Integrating CFD and Experiments in Aerodynamics

US Navy LOGIR Team Visits to ADD
Cultural Exposure
Cultural Exposure
R&D and Acquisition Flow

MND
• Defense Policy
• S&T Policy

DAPA

ADD

DTQAA

Industry/ Academia/ Institute

JCS
(Defense Master Plan/ROC)

Services
(ROC/T&E)

ROC Plan

Industry Initiation

ADD Initiation

Acquisition
Procedure of Aerodynamic Design

1. Aerodynamic configuration
3. Static Stability
   - (Allowable)
4. Trajectory Simulation
5. Check Aerodynamic Performance Requirements
6. Satisfied?
   - No
   - Yes
   - Satisfied?
7. Confirm Configuration
Aerodynamic Analysis

• **Aerodynamic coefficients**
  - prediction code
  - W/T tests
  - 6DOF table (trajectory simulation, design of autopilot)

• **Aerodynamic load**
  - trim condition
  - panel code
  - CFD
  - structural test

• **Hinge moment**
  - determine hinge axis
  - hinge moment on hinge axis
  - W/T tests for hinge moment
Analysis Tools

- **Semi-empirical prediction tool**
  - for the static and dynamic aerodynamic coefficients
  - for hinge moment
  - for aerodynamic loads

- **Panel method aerodynamic prediction tool**
  - for aerodynamic coefficients
  - for aerodynamic loads

- **Computational Fluid Dynamic (CFD) aerodynamic prediction tool**
  - in-house code
  - commercial code
CFDS Numerical Method

- Flux-Difference Splitting Method
- Finite Difference Method
- 3-D Navier-Stokes Solver
- Multiple Blocks
- Characteristic Boundary Conditions
- Baldwin-Lomax Turbulence Model
- Two 1-Equation Models
\[ |\lambda| = \left( \frac{\lambda^2 + \varepsilon^2}{2\varepsilon} \right) \text{ if } |\lambda| \leq \varepsilon \]

where, \( \varepsilon = \text{constant} \)

AIAA-95-1732-CP

- \( M = 8.0 \)
- \( \text{AOA} = 0.0 \text{ deg.} \)
- \( \text{Re} = 1.9 \times 10^8 \)
- Mesh 101x50
CFDS Shock Fixing

Shock Instability

Instability Cured
Supersonic Ogive-Cylinder

- $\text{Mach}=3.0$
- $\text{AoA}=10.0 \text{ deg.}$
- $\text{Re}=6 \times 10^6$
- $\text{Grid}=84 \times 65 \times 62$
- $\text{Baldwin-Lomax Turbulence Model}$
- $\text{Degani-Schiff Modification}$
Supersonic Ogive-Cylinder

Surface pressure

Circumference pressure

Exp. (windward)  Exp. (leeward)  Present

Present(1st-order)  Present(2nd-order)  EXPERIMENT

Body Length (caliber)

$P/P_\infty$

$\phi$ (windward=0, leeward=180)
Boat-Tail Design

Mach contours, Sr=1.45, M=0.85

Drag curves
Boat-Tail Design

Jet OFF

Jet ON

Mach contours, Sr=1.45, M=0.85
Aerodynamics for Man-Portable SAM

- Spike Flow Simulation (Drag Reduction)
- Asymmetric Fin
- Roll Induced Device
- Aerodynamic Interference with Thrust Plume

Aerodynamic Analysis of Flexible Body
Spike Design

Unsteady turbulent flow, $M=1.2$
Jet Impingement onto Flat Plate

Motor Characteristics

<table>
<thead>
<tr>
<th></th>
<th>Test Motor</th>
<th>Full-Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chamber Pressure</td>
<td>1200 psia</td>
<td>1750 psia</td>
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<tr>
<td>Chamber Temperature</td>
<td>2950 K</td>
<td>2970 K</td>
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<tr>
<td>Thrust</td>
<td>330 lbs</td>
<td>1500 lbs</td>
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<tr>
<td>Throat Diameter</td>
<td>12.0 mm</td>
<td>67.0 mm</td>
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<tr>
<td>Exit Diameter</td>
<td>32.6 mm</td>
<td>182.6 mm</td>
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<tr>
<td>PR</td>
<td>1.87</td>
<td>2.33</td>
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<tr>
<td>Exit Mach</td>
<td>2.93</td>
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</table>
Jet Impingement Problems

Main Parameter

- PR (Pressure Ratio)
- Me (Exit Mach no.)
- H/D (Distance)

Test Motor
H=3, 4, 5, 6D

Full-Scale Motor
H=5.4D, 7.6D
Test Motor Simulations

Mach Contours for Varied Distance

H=3D  H=4D  H=5D  H=6D

Mach

4.00  3.73  3.46  3.19  2.91  2.64  2.37  2.10  1.83  1.56  1.29  1.01  0.74  0.47  0.20
The Motor Test

Experiment Facilities
The Motor Test
Full-Scaled Motor Test

Pressure Distribution

Pressure and Temperature Measure Locations
VLS Internal Flow Simulations

Sketch of a full scale Vertical Launching System (VLS)
Grid systems
VLS Grid System

yz-plane

xy-plane

xz-plane

yz-plane
Duct
VLS Internal Flow Simulations

Mach Contours and Velocity Vectors of yz-plane
Animation of VLS Internal Flow

VLS Internal Flow (movie)
# Frequency Comparison

<table>
<thead>
<tr>
<th>CASES</th>
<th>H/D</th>
<th>Po (psia)</th>
<th>Dominant Frequency (k Hz)</th>
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<tbody>
<tr>
<td>Test Motor</td>
<td>3</td>
<td>1,200</td>
<td>4.0</td>
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<tr>
<td></td>
<td>4</td>
<td>1,200</td>
<td>10.1</td>
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<tr>
<td></td>
<td>5</td>
<td>1,200</td>
<td>8.5</td>
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<tr>
<td></td>
<td>6</td>
<td>1,200</td>
<td>7.0</td>
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<tr>
<td>Full-Scale</td>
<td>5.4</td>
<td>1,750</td>
<td>20.0</td>
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<tr>
<td>Motor</td>
<td>7.6</td>
<td>1,750</td>
<td>2.8</td>
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<tr>
<td>VLS</td>
<td>7.6</td>
<td>1,750</td>
<td>0.7</td>
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</tbody>
</table>
VLS Test Fire

Normal Fire Test

Restrained Fire Test
VLS Test Fire

Sensor Locations of VLS Test Fire

Plenum Top Plate

Motor

P1  P2  P3  P4

P7  P6  P5

P10

P9

Plenum Top Plate
VLS Test Fire

Pressure Comparisons of VLS Flow
Side Jet Effects on Body-Tail

Jet interaction flowfield near and on body surface
Side Jet Simulation

Jet interaction flowfield near and on body surface

Vortex structure due to body and side jet
Side Jet Simulation

Effect of flight altitude on jet interaction

M0102 Body-Alone Computation Results: Aoa=5° Mach 2.3
Single Leeward Jet Cases

H=5Km (P_{jet}/P_{ref} = 67.2)
H=10Km (P_{jet}/P_{ref} = 137)
H=15Km (P_{jet}/P_{ref} = 300)
H=20Km (P_{jet}/P_{ref} = 657)
Side Jet Wind Tunnel Test

Side jet wind tunnel test (ONERA Modane)
$C_N = C_{N\text{Without Jet}} + k_{C_N} N_{\text{Jet}} \frac{T_{\text{Single Jet}}}{Q_{\text{ref}} S_{\text{ref}}}$

$C_M = C_{M\text{Without Jet}} + k_{C_M} N_{\text{Jet}} \frac{T_{\text{Single Jet}}}{Q_{\text{ref}} S_{\text{ref}}} \frac{L_{\text{Jet}}}{L_{\text{ref}}}$
Side Jet Wind Tunnel Test
April 2007 France
Conclusion

- Aerodynamic design process at ADD is introduced.
- CFD applications for cylinder ogive, boat tail and spike, VLS internal flow, side jet effect, are shown along with validation.
- Various validation techniques are devised for different flows.
- CFD contributes greatly during the missile development phase, giving insight into the flow.
- Coupling with multidisciplinary optimization is our next direction.