Comparison of Experiments and OVERFLOW Modeling of Store Release from a Cavity at Mach 3

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Impetus

The AFIT of Today is the Air Force of Tomorrow.

- Defense Trends
  - Precision Guided/Low Yield
  - Reduced Signature
  - Supersonic
Store Certification Process

- Computational Fluid Dynamics (CFD)
  - Parametric flexibility
  - Computational resources
  - Verification/Validation
- Experimental Fluid Dynamics (EFD)
  - Freedrop:
    - Captive trajectory system: Steady state flowfield
    - Scale-up is challenging
- Flight testing
  - Provides the “true solution”
  - Unsteady flow
  - Untenable during R and D
Project Research Objectives

- Develop robust freedrop test capability at AFIT
- Utilize advanced CFD software (OVERFLOW) to model the wind tunnel experiments
  - Simple sphere model released from a cavity into Mach 3 flow
  - Multiple stagnation pressures
- Freedrop test realistic geometry (Mk-82)
- Characterize how a flow control device (spoiler) affects cavity flow and store separation at Mach 3
Cavity Flow

- Supersonic cavity flow\(^1\)
- Open cavity pressure resonance\(^2,3\)
  - Frequency prediction
- Cavities pose challenges for store release\(^4\)

\[
Str = \frac{fL}{U_\infty} = \frac{n - \beta}{M_\infty} + \frac{1}{k_c} \sqrt{1 + \frac{1}{2} (\gamma - 1) M_\infty^2}, n = 1, 2, 3, \ldots
\]

\(^1\)Stallings and Wilcox (1987)
\(^2\)Rossiter (1964)
\(^3\)Heller, Holmes, and Colvert (1970)
\(^4\)e.g. Bjorge et al. (2003)
Store Release Scaling

Often difficult to scale wind tunnel tests to flight tests (Marshall, 1977)
- Forces due to pressure and shear scale with area ratio
- Weight scales with volume ratio
- Froude scaling works for incompressible (but not compressible) flows

Heavy Mach scaling
- Often increase wind tunnel model density (e.g., weighted with lead)
- Trajectory information attained
- Conservative for scale-up
- Generally preferable to light Mach scaling

Light Mach scaling
- Ejector force common, sometimes used for moments/store dynamics

Large-scale tunnel tests are generally preferred.
Store Release Method

One may minimize stagnation pressure for supersonic freedrop tests (Marshall, 1977)
  • Instead of raising material density for tunnel models
  • Vacuum chamber at tunnel exit
    • Can pose an added challenge for drop testing

Our approach utilized ice models released at Mach 3
  • Stagnation pressures from 4 psia up to 20 psia
    • Effectively changes “scale” without changing model

Small tunnel (2.5” by 2.5” cross-section)
  • WICS bay (scaled down by 0.375) to L=6.75” and D=W=1.5”

CFD used to compare to (and extend) experimental results using sphere-shaped stores
  • Using a sphere greatly simplifies scaling
OVERFLOW 2.1

- Overset solver with 6-DOF relative motion capability
- Background grids from Dr. Robert Nichols
  - Assistance from Maj. Andrew Lofthouse and CDR Neal Kraft (US Naval Academy)
- Capabilities
  1) Overset structured grids
  2) Used extensively for unsteady/turbulent flow
  3) Robust solver with current numerical methods and turbulence modeling
- Other keys to success
  - Proper non-dimensionalization
  - Management of overset grids, blanked-out regions/X-rays, fringe/donors/orphans
OVERFLOW 2.1 Settings

- Numerical Method
  - Hartax Lax van Leer Contact (HLLC) upwind scheme with van Albada flux limiters
  - 5th-order spatial flux algorithm
  - Symmetric Successive Over-Relaxation (SSOR) scheme
  - 2nd-order time with Newton sub-iterations used on temporal terms

- Turbulence Model
  - Delayed Detached Eddy Simulation/ Shear Stress Transport Hybrid RANS/LES model
    - RANS in boundary layer
  - Time step of 5 *10^-6 seconds
CFD Methodology

• Weapons Internal Carriage and Separation (WICS) bay (Nichols, 2008)
• Two overlapping C-type grids (Yin and Yang) set up about the sphere [after Kageyama and Sato (2004)].

<table>
<thead>
<tr>
<th>Block</th>
<th>Name</th>
<th>Cells</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Plate</td>
<td>5600000</td>
<td>351x201x81</td>
</tr>
<tr>
<td>2</td>
<td>Bay</td>
<td>1920000</td>
<td>201x81x121</td>
</tr>
<tr>
<td>3</td>
<td>Yin</td>
<td>140000</td>
<td>41x71x51</td>
</tr>
<tr>
<td>4</td>
<td>Yang</td>
<td>140000</td>
<td>41x71x51</td>
</tr>
</tbody>
</table>
CFD Methodology

- Grid sizing
- Grid relative movement
Bay/“Yin” Grid Overlap

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## CFD Parameters

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<table>
<thead>
<tr>
<th>Run</th>
<th>CT1B</th>
<th>CT4B</th>
<th>CT2B</th>
<th>CT3B</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_T$ (Psia)</td>
<td>4</td>
<td>12</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>$Re_{ft}$ (million)</td>
<td>0.64</td>
<td>1.93</td>
<td>0.32</td>
<td>0.16</td>
</tr>
<tr>
<td>$\Delta t$ (sec)</td>
<td>$5.0 \times 10^{-6}$</td>
<td>$5.0 \times 10^{-6}$</td>
<td>$5.0 \times 10^{-6}$</td>
<td>$5.0 \times 10^{-6}$</td>
</tr>
<tr>
<td>$M$</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>$Re_{gridunit}$</td>
<td>20000</td>
<td>60300</td>
<td>10000</td>
<td>5030</td>
</tr>
</tbody>
</table>
Tunnel and Test Section

- Supersonic (M= 2.94) variable density blowdown tunnel
- Two high-speed cameras
  - One conventional and one with Schlieren visualization setup
- Piezo-resistive pressure transducers
Model Fabrication

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(a) (b) (c)
(d) (e) (f)
## Test Conditions

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<table>
<thead>
<tr>
<th>P\textsubscript{T,sc} (Psia)</th>
<th>4</th>
<th>12</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>T\textsubscript{T,sc} (°R)</td>
<td>536</td>
<td>540</td>
<td>544</td>
</tr>
<tr>
<td>P\textsubscript{∞} (lb/ft\textsuperscript{2})</td>
<td>17</td>
<td>52</td>
<td>86</td>
</tr>
<tr>
<td>V\textsubscript{∞} (ft/s)</td>
<td>2021</td>
<td>2027</td>
<td>2034</td>
</tr>
<tr>
<td>ρ\textsubscript{∞} (slug/ft\textsuperscript{3})</td>
<td>5.11x10\textsuperscript{-5}</td>
<td>15.2x10\textsuperscript{-5}</td>
<td>25.1x10\textsuperscript{-5}</td>
</tr>
<tr>
<td>Re\textsubscript{ft} (million)</td>
<td>0.65</td>
<td>1.93</td>
<td>3.18</td>
</tr>
</tbody>
</table>
Results and Analysis
Frequency Spectra

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- Experimental data shows that resonant frequency is essentially independent of pressure.
- Consistent with literature
- Low signal-to-noise ratio for low pressure data.
CFD/EFD Spectra

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- Computational spectral data is comparable but not a precise match to experimental spectra for a clean cavity.
- Based on 17,000 iterations (Welch’s method)
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CFD/EFD Visualization

Shear Layer EFD/CFD
16000 Hz Capture
30 Hz Playback
2000 Slower

FASTCAM-X 1280PC...
320 x 32
Start
16000 fps
frame: 1
+00:00:00.000000sec

Run 630C3
M = 2.94
Sehleren
20 Psia Stag Press

Run CT11B_XL
M = 3
Centerline
Density
4 Psia Stag Press
Cavity Flow: Stationary Sphere
Sphere Drop (4 psia)

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Sphere Drop (12 psia)
Sphere Drop CFD

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Sphere Drop Overlay

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Sphere EFD/CFD
2000 Hz Capture
30 Hz Playback
4 Psia Stag Press
60x Slower

Run 529S4
M = 2.94
Schlieren

Run CT1B_D
M = 3
Centerline Density®
EFD/CFD Sphere Drop

The AFIT of Today is the Air Force of Tomorrow.
CFD Sphere Drop

Run CT2B_D
2 Psia Stag Press

Run CT3B_D
1 Psia Stag Press

Sphere CFD
Mach 3
Coord: Centerline
Color: Density*

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View of Recirculation

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Mk-82 Shaped Store

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Sphere Separation

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4 Psia Stag Press
2000 Hz Capture Rate
30 Hz Playback
Sphere Separation

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12 Psia Stag Press
2000 Hz Capture Rate
30 Hz Playback
Mk-82/Spoiler Combination

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Summary

• OVERFLOW 2.1 used to compare to Mach 3 store separation events for spheres
• “Reasonable” correlation between predicted and measured Rossiter tones
• Successfully demonstrated the capability to conduct freedrop testing at Mach 3 in the AFIT supersonic tunnel
• Very good matching of the sphere dynamics between experiment and CFD results.
Flow Control
Passive Flow Control

- Tab Design
- Short Sawtooth (SST): $1\delta$
- Long Sawtooth (LST): $2\delta$
Spoiler Spectra

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Sphere Heavy Mach Scaling

Sphere Drop
40k Release
Mach 3

Titanium
Rubber
Pine
Spoiler Spectra

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Outline

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Mk-82 Model
Mk-82 Model

- 1/20\textsuperscript{th}
- Ogive nose/conical fin
Mk-82 Shaped Store
Scaling Laws Applied
Heavy Mach Scaling

- Test gravity = 32.2 ft/s² $\left( \frac{g'}{g} = 1 \right)$
- $V'_\infty$
- Translation – Representative
- Rotation – Too large

\[
m' = m \left( \frac{q'_\infty}{q_\infty} \right) \lambda^2
\]

\[
I' = I \left( \frac{q'_\infty}{q_\infty} \right) \lambda^4
\]
Sphere Heavy Mach Scaling

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- 40k release, Mach 3

<table>
<thead>
<tr>
<th>$P_{T,sc}$ (Psia)</th>
<th>1</th>
<th>4</th>
<th>12</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q_\infty'/q_\infty$</td>
<td>0.011</td>
<td>0.044</td>
<td>0.13</td>
<td>0.22</td>
</tr>
<tr>
<td>Weight (lb)</td>
<td>550</td>
<td>138</td>
<td>46</td>
<td>28</td>
</tr>
<tr>
<td>Density (lb/ft$^3$)</td>
<td>225</td>
<td>69</td>
<td>23</td>
<td>14</td>
</tr>
<tr>
<td>Material</td>
<td>Titanium</td>
<td>Rubber</td>
<td>Pine</td>
<td>Balsa</td>
</tr>
</tbody>
</table>
**Heavy Mach Scaling**

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- **1 Psia stagnation pressure**

<table>
<thead>
<tr>
<th>Simulated Altitude (ft)</th>
<th>20k</th>
<th>40k</th>
<th>57625</th>
<th>60k</th>
</tr>
</thead>
<tbody>
<tr>
<td>(q'<em>{\infty} / q</em>{\infty})</td>
<td>0.0044</td>
<td>0.011</td>
<td>0.0248</td>
<td>0.028</td>
</tr>
<tr>
<td>Weight (lb)</td>
<td>2813</td>
<td>1136</td>
<td>500.0</td>
<td>436</td>
</tr>
<tr>
<td>(I_{yy} ) (lb·ft²)</td>
<td>218</td>
<td>88</td>
<td>38.7</td>
<td>34</td>
</tr>
</tbody>
</table>

- **4 Psia stagnation pressure**

<table>
<thead>
<tr>
<th>Simulated Altitude (ft)</th>
<th>20k</th>
<th>27905</th>
<th>40k</th>
<th>60k</th>
</tr>
</thead>
<tbody>
<tr>
<td>(q'<em>{\infty} / q</em>{\infty})</td>
<td>0.018</td>
<td><strong>0.0248</strong></td>
<td>0.044</td>
<td>0.11</td>
</tr>
<tr>
<td>Weight (lb)</td>
<td>703</td>
<td>500.0</td>
<td>284</td>
<td>109</td>
</tr>
<tr>
<td>(I_{yy} ) (lb·ft²)</td>
<td>54</td>
<td><strong>38.7</strong></td>
<td>22</td>
<td>8</td>
</tr>
</tbody>
</table>
Conclusions
Conclusions

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• Good correlation between predicted and measured Rossiter tones
• Pretty reasonable comparison of pressure spectra between experimental runs and CFD model
• Successfully demonstrated the capability to conduct quick, inexpensive freedrop testing at Mach 3 in the AFIT lab
• Good matching of the sphere dynamics between experiment and CFD results.
  • Demonstrated ability to validate the CFD run with in-house experiments.
Conclusions (cont.)

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• Determined that the spoiler design used detuned the Rossiter modes in the cavity yet significantly raised the broadband tones
• Demonstrated the positive influence of the spoiler on the separation from a spherical store from a cavity
• Demonstrated the capability to conduct ice freedrop testing of shapes representative of actual stores
• Developed the case that if the stagnation pressure could be sufficiently reduced, heavy Mach scaling laws can be attained with this freedrop test method.
Acknowledgements

• Sponsor – AFRL Air Vehicles
  - Jim Grove
  - Rudy Johnson

• ENY Labs
  - Jay Anderson
  - John Hixenbaugh
  - Chris Zickefoose
  - Sean Miller

• Model Shop
  - Brian Crabtree
  - Chris Harkless

• CFD support
  - Dr. Robert Nichols
  - CDR Neal Kraft
  - Dave Doak
  - Maj Andrew Lofthouse
Questions?

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Cavity Flow

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EFD/CFD Sphere Drop

Sphere EFD/CFD
2000 Hz Capture
30 Hz Playback
12 Psia Stag Press
60x Slower

Run 601S2
M = 2.94
Schlieren

Run CT4B_D
M = 3
Centerline Density
HIFEX

- Long Range Strike Aircraft
- High speed separation
- Active flow control devices
- Acoustic testing
- Separation testing
- Full-scale sled tests
Release Mechanism

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Scaling Laws

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- Governing equations

\[
\frac{\ddot{Z}}{g} = 1 - \left[ C_{N_{\alpha}} \left( \theta + \frac{\dot{Z}}{V_{\infty}} + \Delta \alpha \right) \cos \theta - C_A \sin \theta \right] \left( \frac{qS}{mg} \right) + \left( \frac{F_{ej}}{mg} \right) \cos \theta
\]

\[
\dot{\theta} = \left[ C_{m_{\alpha}} \left( \theta + \frac{\dot{Z}}{V_{\infty}} + \Delta \alpha \right) \right] + C_{m_{q}} \left( \frac{d\dot{\theta}}{2V_{\infty}} \right) \left( \frac{qSd}{I} \right) + \left( \frac{F_{ej}X_{ej}}{I} \right)
\]

- Freedrop scaling laws*

  - Aerodynamic scaling →  \[ M_{\infty}' = M_{\infty} \]

  - Dynamic scaling →  \[ M_{\infty}' = M_{\infty} \sqrt{\lambda \frac{g'}{g} \frac{T_{\infty}'}{T_{\infty}}} \]

*Marshall (1977)
Dynamic Scaling

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- \( M_{aero} \neq M_{dynamic} \)
- Subsonic
  - Froude scaling
- Transonic/Supersonic
  - Heavy Mach scaling
  - Light Mach scaling

\[
Z' = Z\lambda \\
\theta' = \theta \\
m' = m\left(\frac{\rho'_\infty}{\rho_\infty}\right)\left(\frac{V'_\infty}{V_\infty}\right)^2 \lambda^2 \left(\frac{g}{g'}\right) \\
I' = I\left(\frac{\rho'_\infty}{\rho_\infty}\right)\left(\frac{V'_\infty}{V_\infty}\right)^2 \lambda^4 \left(\frac{g}{g'}\right) \\
F_{ej}' = m\left(\frac{\rho'_\infty}{\rho_\infty}\right)\left(\frac{V'_\infty}{V_\infty}\right)^2 \lambda^2 \\
X_{ej}' = X\lambda \\
V'_\infty = V_\infty\sqrt{\lambda \left(\frac{g'}{g}\right)} \\
t' = t\lambda \left(\frac{V'_\infty}{V_\infty}\right)
\]
Heavy Mach Scaling

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- Test gravity = 32.2 ft/s² \( \left( \frac{g'}{g} = 1 \right) \)
- \( V_\infty' \)
- Translation – Representative
- Rotation – Too large

\[
m' = m \left( \frac{q'_\infty}{q_\infty} \right) \lambda^2
\]

\[
I' = I \left( \frac{q'_\infty}{q_\infty} \right) \lambda^4
\]
Light Mach Scaling

The AFIT of Today is the Air Force of Tomorrow.

- Augmented gravity \((g' \neq g)\)
- Translation – Vertical displacement under predicted
- Rotation – Representative

\[
m' = m \left( \frac{\rho'}{\rho_\infty} \right) \lambda^3
\]

\[
I' = I \left( \frac{\rho'}{\rho_\infty} \right) \lambda^5
\]
Sphere Freedrop

- Simple shape
- Consistent mass properties
- No pitch considerations
- Tractable grid generation