Development of an Aeroelastic Modeling Capability for Transient Nozzle Side Load Analysis

Ten-See Wang  
*NASA Marshall Space Flight Center, Huntsville, Alabama*

Xiang Zhao  
*Alabama A&M University, Huntsville, Alabama*

Sijun Zhang  
*ESI CFD, INC., Huntsville, Alabama*

and Yen-Sen Chen  
*Applied Research Laboratory, Hsinchu, Taiwan*

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Introduction

• Lateral nozzle forces are known to cause severe structural damage to any new rocket engine in development.

• While three-dimensional, transient, turbulent, chemically reacting computational fluid dynamics methodology has been demonstrated to capture major side load physics with rigid nozzles, hot-fire tests often showed nozzle structure flexing during peak side load occurrence, leading to structural damage if structural strengthening measures were not taken. The modeling picture is incomplete without the capability to address the two-way responses between the structure and fluid.
Objective

- The objective of this study is to develop a coupled aeroelastic modeling capability by implementing the necessary structural dynamics components to an anchored computational fluid dynamics methodology.
UNIC Multidisciplinary Computational Methodology

- Fluid: unstructured-grid, pressure-based, turbulent, reacting flow

\[ \frac{\partial p}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_j) = 0 \]

\[ \frac{\partial \rho \alpha_i}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_j \alpha_i) = \frac{\partial}{\partial x_j} \left[ \left( \rho D + \frac{\mu_t}{\sigma_a} \right) \frac{\partial \alpha_i}{\partial x_j} \right] + \omega_i \]

\[ \frac{\partial \rho u_i}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_j u_i) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} \]

\[ \frac{\partial \rho H}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_j H) = \frac{\partial p}{\partial t} + Q_r + \frac{\partial}{\partial x_j} \left[ \left( \frac{K}{C_p} + \frac{\mu_t}{\sigma_H} \right) \nabla H \right] + \frac{\partial}{\partial x_j} \left[ \left( \mu + \mu_t \right) - \left( \frac{K}{C_p} + \frac{\mu_t}{\sigma_H} \right) \nabla \left( \frac{V^2}{2} \right) \right] + \theta \]

\[ \frac{\partial \rho k}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_j k) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + \rho (\Pi - \varepsilon) \]

\[ \frac{\partial \rho \varepsilon}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_j \varepsilon) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \rho \frac{\varepsilon}{k} \left( C_1 \Pi - C_2 \varepsilon + C_3 \Pi^2 / \varepsilon \right) \]
- Multiple transient inlet properties IC from engine system modeling
Conjugate heat transfer to get surface and solid temperatures for combustion chamber, nozzle, and nozzle extension.
UNIC Multidisciplinary Computational Methodology

- Structural dynamics in terms of modal analysis

\[
[M]\dddot{Y} + [C]\dot{\ddot{Y}} + [K]Y = \{F\}
\]

\[
\{Y\} = [\Phi]\{Z\}, \{\dot{Y}\} = [\Phi]\{\dot{Z}\}, \{\ddot{Y}\} = [\Phi]\{\ddot{Z}\}
\]

\[
\dddot{Z} + [\Phi]^T [C][\Phi]\dot{Z} + [\Phi]^T [K][\Phi]Z = [\Phi]^T \{F\}
\]

\[
\begin{cases}
\dddot{z}_i + 2\xi_i \omega_i \dot{z}_i + \omega_i^2 z_i = r_i \\
r = \Phi_i^T \{F\}
\end{cases}
\]

\[i = 1, 2, \ldots, n\]
Computed Major Side Load Physics for Regeneratively Cooled Engine (SSME)

<table>
<thead>
<tr>
<th>Fyz, kN</th>
<th>Dominant frequencies, Hz</th>
<th>Physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test</td>
<td>CFD</td>
<td>Test</td>
</tr>
<tr>
<td>1st jump</td>
<td>90</td>
<td>80</td>
</tr>
<tr>
<td>2nd jump</td>
<td>200</td>
<td>212</td>
</tr>
</tbody>
</table>

- **combustion wave**
- **Mach disk flow: FSS**
- **core jet flow**
- **FSS-to-RSS**
- **Mach disk flow: RSS**
- **lip RSS oscillation**
- **nozzle flowing full**
Comparison of Computed J-2X (Nozzlette) with those of LE-7A Hot-Fire Test

Comparison of the Sea Level Peak Side Loads

<table>
<thead>
<tr>
<th>Side load, kN</th>
<th>J-2X</th>
<th>LE-7A</th>
<th>physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>With extension</td>
<td>1&lt;sup&gt;st&lt;/sup&gt; peak</td>
<td>80</td>
<td>102</td>
</tr>
<tr>
<td></td>
<td>2&lt;sup&gt;nd&lt;/sup&gt; peak</td>
<td>249</td>
<td>259</td>
</tr>
<tr>
<td>Without extension</td>
<td>1&lt;sup&gt;st&lt;/sup&gt; peak</td>
<td>26</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>2&lt;sup&gt;nd&lt;/sup&gt; peak</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Effect of Out-of-Roundness (Ovalized) on Film Cooled J-2X Nozzles

<table>
<thead>
<tr>
<th>Case</th>
<th>Description</th>
<th>L/S ratio</th>
<th>Deformation, in</th>
<th>Long axis</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>baseline</td>
<td>perfectly round</td>
<td>1.0000</td>
<td>±0.00</td>
<td>-</td>
<td>19, 30</td>
</tr>
<tr>
<td>1</td>
<td>slightly out-of-round</td>
<td>1.0086</td>
<td>±0.25</td>
<td>Z</td>
<td>this work</td>
</tr>
<tr>
<td>2</td>
<td>slightly out-of-round</td>
<td>1.0086</td>
<td>±0.25</td>
<td>Y</td>
<td>this work</td>
</tr>
<tr>
<td>3</td>
<td>more out-of-round</td>
<td>1.0346</td>
<td>±1.00</td>
<td>Z</td>
<td>this work</td>
</tr>
<tr>
<td>4</td>
<td>more out-of-round</td>
<td>1.0346</td>
<td>±1.00</td>
<td>Y</td>
<td>this work</td>
</tr>
<tr>
<td>5</td>
<td>significantly out-of-round</td>
<td>1.4400</td>
<td>±11.6</td>
<td>Z</td>
<td>this work</td>
</tr>
<tr>
<td>6</td>
<td>significantly out-of-round</td>
<td>1.4400</td>
<td>±11.6</td>
<td>Y</td>
<td>this work</td>
</tr>
</tbody>
</table>
# Effect of Out-of-Roundness (Ovalized) on Film Cooled J-2X Nozzles

<table>
<thead>
<tr>
<th>Case</th>
<th>Description</th>
<th>Long axis</th>
<th>This study</th>
<th>Previous study</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Description</td>
<td></td>
<td>This study</td>
<td>Previous study</td>
</tr>
<tr>
<td>Nominal</td>
<td>perfectly round</td>
<td>-</td>
<td>2114 [19]</td>
<td>2114 [19]</td>
</tr>
<tr>
<td>1</td>
<td>slightly ovalized</td>
<td>z</td>
<td>3309 (+57%)</td>
<td>2668 (+26%) [19]</td>
</tr>
<tr>
<td>2</td>
<td>slightly ovalized</td>
<td>y</td>
<td>3376 (+60%)</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>more ovalized</td>
<td>z</td>
<td>3175 (+50%)</td>
<td>3275 (+55%) [19]</td>
</tr>
<tr>
<td>4</td>
<td>more ovalized</td>
<td>y</td>
<td>3268 (+55%)</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>significantly ovalized</td>
<td>z</td>
<td>2715 (+28%)</td>
<td>2171 (+2.7%) [19]</td>
</tr>
<tr>
<td>6</td>
<td>significantly ovalized</td>
<td>y</td>
<td>1738 (-18%)</td>
<td>-</td>
</tr>
</tbody>
</table>
Previous Aeroelastic Nozzle Modeling Studies

• Earlier Studies
  ▪ 1994 Pekkari
    ▪ Structure: equation of motion; Fluid: a simplified wall pressure distribution and separation pressure to ambient pressure ratios; Temporal: quasi-steady Vulcain
  ▪ 2004 Östlund
    ▪ Structure: equation of motion; Fluid: 3D Euler and an empirical separation criterion; Temporal: Quasi-steady Vulcain

• Recent Studies
    ▪ Structure: CFD-STRESS; Fluid: CFD-NASTRAN; Interface: MDICE; Temporal: quasi-steady J-2S, 0 s to 0.1818 s
  ▪ 2012 Blades, et al.
    ▪ Structure: Abaqus; Fluid: CHEM; Interface: CSE; Temporal: Transient SSME, 0.79 to 0.811 s, or 0.021 s time period
Transient Startup History

- Pressure (atm)
- Temperature (K)
- Equivalence Ratio

Graph showing the transient startup history of pressure, temperature, and equivalence ratio over time (t, s).
Computational Grid
First Four Modes Computed
Computed Generalized Displacement Histories
End Views of Computed Nozzle Shape and Deformation Contours
Side Views of Computed Nozzle Shape and Deformation Contours
Computed Axial Nozzle Wall Pressure Profiles

- Rigid Left $Y=0$
- Rigid Right $Y=0$
- Rigid Upper $Z=0$
- Rigid Lower $Z=0$
- Flexible Left $Y=0$
- Flexible Right $Y=0$
- Flexible Upper $Z=0$
- Flexible Lower $Z=0$

wall pressure, atm

axial distance, m

2.84600s
Computed Physical Lateral Displacement Histories

[Graph showing computed physical lateral displacement histories with specific angles indicated.]
Computed Side Load Histories
Conclusions

• Aeroelastic modeling capability is being developed for transient nozzle side load analysis.
• The analysis of a flexible, regeneratively cooled nozzle startup transient at sea level demonstrated the effect of nozzle deformation on transient side loads.
Acknowledgment

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