Fluid Structure Interaction in a Cold Flow Test and Transient CFD Analysis of Out-of-Round Nozzles

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Two Related Topics Presented

- A cold flow nozzle test with fluid-structure interaction when the nozzle had separated flow
- CFD analysis for nozzle flow and side loads of nozzle extensions that are out-of-round.
First Topic: Fluid Structure Interaction

Material From:

Joint Propulsion Conference
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Dr. R. Keanini of UNC Charlotte
The FASTRAC engine was an LOX-RP1 engine designed in-house at MSFC in the mid 1990’s.

Stub nozzle test shown, full nozzle was longer as it was an altitude engine.

The stub did not flow full at sea level. Flow separation clearly identified.

Flow separated for the full duration of the test.

Strain-gauge measurements taken on nozzle during hot fire test.
Nozzle 2ND mode dominated the nozzle’s response.

Strain gages were at 16 circumferential locations.

- Not conclusive evidence of fluid structure interaction since combustion excites all modes.
- Clear that further testing, study, analysis required to produce useful design and analysis methodologies.
Ground tested rocket engine nozzles generally operate in overexpanded condition.

Overexpansion causes boundary layer separation of low-pressure internal fluid flow from inner wall of nozzle.

Separation is not axisymmetric. Asymmetric loads are generated.

These asymmetric “side loads” have caused problems most liquid rocket engines at some point.

Side loads typically a large factor in the design of the nozzle and interfacing hardware.
Side load for FASTRAC nozzle were estimated with an empirical extrapolation.

Conservative assumptions in the side load estimate lead to predicted hardware failure.

Hypothesis: Loading caused by self-excited vibration of 2ND mode interacting with flow separation from wall.

Research program initiated that included a cold flow test of a nozzle.
Cold flow test of FASTRAC nozzle contour

- Two test articles were fabricated.
  - One ‘rigid’, with a thick wall, ~25mm.
  - One ‘flexible’, with a wall that tapered to ~0.6mm
- Both had Ideal nozzle contour.
- Test articles were instrumented with static pressures, high frequency pressure, strain gages and accelerometers.
Results

Thin wall test article vibrated so hard it caused a strain gage ‘red-line’ cut off.

- At $P_c = 12.2$ atm, (180 psia), NPR=110.
- Video and other data indicate extremely large vibration of 2ND mode.
Possible Fluid Dynamics Forcing Function

- Overexpanded flow produces radial inward forces on the aft end.
- With separated flow the radial inward force changes significantly.
- When the shape of the nozzle changes, the separation location moves forward or aft.
- A system of non-restoring forces arise that could couple with the structural dynamics.

Wall pressure profile from axisymmetric CFD for different amounts of wall deflection.

Normalized forces at difference azimuths.
Material From:
“Transient Three-Dimensional Side Load Analysis of Out-of-Round Film Cooled Nozzles”,
AIAA-2010

Joint Propulsion Conference
Aug, 2010

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Side loads and Motivations

• UNIC CFD code has been used to calculate J-2X flow evolution and resulting nozzle side loads under various operating conditions and environments. One of the potential issues currently being explored is the effect of deformation of the nozzle.

• Liquid rocket engine nozzles, being large with relatively light weight structures, are probably never truly round. The cause of out-of-roundness could be, but are not limited to, the following:
  • asymmetric loads induced by hardware attached to the nozzle
  • asymmetric material internal stresses induced in previous tests, and nozzle wall material deformation, such as creep, incurred in previous engine tests
  • In a round nozzle, side forces arise from asymmetric shock evolutions.

• Questions were raised about how nozzle deformation would affect the nozzle side load characteristics.
Objective and Approach

• Objective:
  To gain insight into side load characteristics of out-of-round nozzles

• Approach:
  Transient 3D UNIC CFD analyses were performed of the J-2X nozzle flow during the transient startup process on ovalized nozzles with a back pressure equivalent to 100,000 ft. Four nozzles with different degrees of ovalization were used to study the effect of out-of-roundness:
  • a perfectly round, or nominal nozzle,
  • a slightly ovalized nozzle,
  • a more ovalized nozzle, and
  • a significantly ovalized nozzle.
Circular separation line
## Computational Grid Layout for Round Nozzle

<table>
<thead>
<tr>
<th>Engine</th>
<th>Grid size</th>
<th>Number of Azimuthal Planes</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSME</td>
<td>1,275,120</td>
<td>72</td>
</tr>
<tr>
<td>J-2X</td>
<td>4,421,166</td>
<td>120</td>
</tr>
</tbody>
</table>

![Diagram of a round nozzle with computational grid layout](image)
# Cases Run

<table>
<thead>
<tr>
<th>Case</th>
<th>Description</th>
<th>L/S</th>
<th>Deformation at end of Nozzle, in</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Perfectly round</td>
<td>1.0000</td>
<td>±0.00</td>
</tr>
<tr>
<td>2</td>
<td>Slightly out-of-round</td>
<td>1.0086</td>
<td>±0.25</td>
</tr>
<tr>
<td>3</td>
<td>More out-of-round</td>
<td>1.0346</td>
<td>±1.00</td>
</tr>
<tr>
<td>4</td>
<td>Significantly out-of-round</td>
<td>1.4400</td>
<td>±11.6</td>
</tr>
</tbody>
</table>

Case 1: L/S = 1.0000  
Case 2: L/S = 1.0086  
Case 3: L/S = 1.0346  
Case 4: L/S = 1.4400
Transient Startup Inlet Flow Properties

- **Pressure (P, atm)**
  - MCC and TEG curves over time (t, s).

- **Temperature (T, K)**
  - MCC and TEG curves over time (t, s).

- **Species Mass Fractions**
  - main combustion chamber flow:
  - turbine exhaust gas flow:
<table>
<thead>
<tr>
<th>Event</th>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSS</td>
<td>0.400s</td>
</tr>
<tr>
<td>TEG pumping</td>
<td>0.820s</td>
</tr>
<tr>
<td>FSS --&gt; RSS</td>
<td>0.865s</td>
</tr>
<tr>
<td>Sep line jump</td>
<td>0.929s</td>
</tr>
<tr>
<td>RSS --&gt; FSS</td>
<td>1.010s</td>
</tr>
<tr>
<td>Flowing full</td>
<td>1.490s</td>
</tr>
</tbody>
</table>

**Computed Side Load History**

![Graph showing Mach Contours for the Nominal Case]
Animation of Mach Contours for Round Nozzle
Mach Contours for the More Out-of-Round Case

<table>
<thead>
<tr>
<th>Event</th>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSS</td>
<td>0.3900s</td>
</tr>
<tr>
<td>TEG pumping</td>
<td>0.8300s</td>
</tr>
<tr>
<td>FSS --&gt; PRSS</td>
<td>0.8653s</td>
</tr>
<tr>
<td>1st sep line jump</td>
<td>0.9191s</td>
</tr>
<tr>
<td>2nd sep line jump</td>
<td>0.9481s</td>
</tr>
<tr>
<td>PRSS --&gt; FSS</td>
<td>0.9865s</td>
</tr>
<tr>
<td>Flowing full</td>
<td>1.4950s</td>
</tr>
</tbody>
</table>
Computed Side Load Histories

Slightly out-of-round case

More out-of-round case
Computed Side Load Histories for the Significantly Out-of-Round Case

Sickle-shaped separation line at 0.70 s

<table>
<thead>
<tr>
<th>Event</th>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSS</td>
<td>0.38000s</td>
</tr>
<tr>
<td>TEG pumping</td>
<td>0.70000s</td>
</tr>
<tr>
<td>FSS --&gt; PRSS</td>
<td>0.88420s</td>
</tr>
<tr>
<td>1st half SLJ</td>
<td>0.91387s</td>
</tr>
<tr>
<td>2nd half SLJ</td>
<td>0.94883s</td>
</tr>
<tr>
<td>PRSS --&gt; FSS</td>
<td>1.02223s</td>
</tr>
<tr>
<td>Flowing full</td>
<td>1.49500s</td>
</tr>
</tbody>
</table>
Computed Side Load Histories for the Significantly Out-of-Round Case

100k ft, 0.0109 atm

asy TEG pumping
1st & 2nd halves of sep. line jump

core jet flow FSS Mach disk flow RSS FSS nozzle
flowing full
## A Comparison of the Computed Peak Side Loads

<table>
<thead>
<tr>
<th>Nozzle shape</th>
<th>Peak Fyz, N</th>
<th>Physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perfectly round</td>
<td>2114</td>
<td>Separation line jump</td>
</tr>
<tr>
<td>Slightly out-of-round</td>
<td>2668</td>
<td>Separation line jump</td>
</tr>
<tr>
<td>More out-of-round</td>
<td>3275</td>
<td>Separation line jump</td>
</tr>
<tr>
<td>Significantly out-of-round</td>
<td>2171</td>
<td>FSS-to-RSS transition</td>
</tr>
</tbody>
</table>
Conclusions

Peak side load physics for the round, slightly out-of-round, and more out-of-round cases is the separation line jump, and that the peak side load increased as the degree of out-of-roundness increased.

For the significantly out-of-round case, the separation line jump was split into two parts. The peak side load was reduced to a level comparable to that of the round nozzle. This peak side load reduction mechanism, splitting the peak side load in azimuth, is consistent with experimental results reported for non-round polygon nozzles.
BACKUP SLIDES
Nozzle Fluid Dynamics Responsible for Side Loads

Side Loads in a TIC
- FSS to qRSS early in the transient.
- Oscillation of the separation line

Side Loads in a TOC
- Transition FSS to RSS
- Transition RSS to FSS
Experimental Approach

♦ The test facility available was a vacuum test chamber, MSFC’s cold flow Nozzle Test Facility (NTF). Normal use was for measurement of axial thrust of nozzle test articles.

♦ Measured the moments induced by off-axis forces with an instrumented strain tube.

♦ Designed two nozzle test articles
  • truncated ideal contour (TIC)
  • thrust optimized contour, specifically a parabolic (PAR) contour,
In periods of increasing NPR, the chamber fills with air from the ejector pipe which is only inches from the end of the nozzle test article. This air impacts on the test article inducing strain in the strain tube. This backwash induced strain corrupts the SL moment measurement.

The backwash’s impact on the test data:
- invalidates nozzle shutdown transients.
- the ‘up ramp’ transients have to be assessed for continuously favorable dNPR/dt.
Schematic of the previous test article support system. The old support system, intended for axial thrust measurement, could not be stiffened significantly.
Schematic of the new test article support system.

- 2” thick seal face replaced with a 2” thick “Stiffener Plate”.
- Dynamic analysis showed the plate provided the equivalent of a ‘fixed end’ for the strain tube.
- Test data later confirmed.

2” thick steel plate fits where the Seal Face was.
Transient 3-D Nozzle Side Load Computational Methodology

- Multidisciplinary computational methodology
  - UNIC time-accurate, unstructured-grid, pressure-based, reacting flow, CFD & heat transfer code
  - Engine system modeling for transient inlet properties (to simulate hot-firing tests)
  - Thermal modeling of wall temperatures for combustion chamber, nozzle, and nozzle extension (to simulate hot-firing tests)

- Benchmark or comparing results with available, actual rocket engine hot-firing
  - Benchmarked with a regeneratively cooled engine – SSME (side load physics captured: combustion wave, FSS-to-RSS and RSS-to-FSS transitions, cold wall promoted Coanda effect, RSS shock breathing)
  - Compared J-2X sea level results with another film cooled engine – LE-7A (side load captured: separation line jump)
Benchmark with the Regeneratively Cooled SSME nozzle during Sea Level Startup

Combustion wave

FSS-to-RSS transition

Shock breathing frequency
Benchmark with the Regeneratively Cooled SSME nozzle during Sea Level Startup

<table>
<thead>
<tr>
<th>Fyz, kN</th>
<th>Dominant frequencies, Hz</th>
<th>Physics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test</td>
<td>CFD</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>
<tr>
<td></td>
<td>275</td>
<td>275</td>
</tr>
</tbody>
</table>