Tones encountered with a coannular nozzle and a method for their suppression

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Outline of talk:

Introduction
Experimental Facility
Experimental Results
Numerical Results
Summary
Scope of the work:

Tones were encountered in larger-scale, multi-stream nozzle tests in the Aeoacoustics Propulsion Laboratory (AAPL).

An approximately half-scale model of a 2-stream nozzle was built to study the tones and find possible remedy.

This paper presents results from the model-scale experiment.

Results of a numerical study on duct acoustic modes corresponding to the tones are also presented.
Tone problem faced in the AAPL with a 2-stream nozzle
Remedies tried

CVP42_66630
Scenario 4: Lossless Conditions / Lift Radius / Model Scale
polar = 90°

PSD (dB)

Hz

NoTab
OneTab
ThreeTab
FiveTab
SevenTab
0.46-scale model of two-stream nozzle
Sound pressure level spectra ($\theta=90^\circ$)

-- Broadband peak is due to TE shedding (frequency of peak increases with $M_j$); Strouhal number based on lip thickness is about 0.2.
-- There are sharp tones at lower $M_j$. 

0.030 lip case

BB peak freq data for all three inner nozzles
Sound pressure level spectra in low Mj range

--Frequency of tone varies with Mj in steps.
Four cases corresponding to the four stages are explored with parametric variation

Parameters varied:
- Lip thickness of inner nozzle
- Inlet length \( (L = 0.75, 2, 4.75) \)
- Flared and constricted inlets
- Lip-to-lip distance

\[ f (kHz) \]
\[ \text{SPL, dB (staggered)} \]

\( M_j = 0.427 \)
\( 0.345 \)
\( 0.260 \)
\( 0.168 \)

AIAA Aeroacoustics Conference, Denver, CO, Jun 5-9, 2017, Zaman/GRC
Effect of changed lip-to-lip distance
Changed by unscrewing inner nozzle

--Tone frequencies remained basically unchanged.
Tone frequency vs. Mj for different inlet lengths

--With parameter variations noted in last slide frequencies were basically unaffected.
-- Here data shown for inlet length variation and also with outer flow blocked.
-- Same four stages occurred in all cases.
--caps with width $w = 0.65$ (full span 0.8) took the tones out !!
-- $w = 0.3$ or 0.1 were just as effective.
SPL spectra with full-span caps on inner struts

-Tones came back at higher Mj.
SPL spectra with full-span caps on inner struts

--Two stages of tones occurred in Mj range of 0.4–0.85.
--Amplitudes were the largest in the middle of each stage.
Schlieren pictures of flow-field for full-caps on inner struts

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$M_j = 0.45$, $f = 4.13$ kHz
(shedding at 45 kHz)

$M_j = 0.67$, $f = 6$ kHz
(shedding at 65 kHz)

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-Tones excite the shear layer.
- Shedding from the inner nozzle lip can also be discerned upon inspection.
-- Obviously, shedding from the struts couples with duct resonances to generate the tones.

-- Experimental data did not shed any light on the nature of the duct modes.

-- In order to study this, numerical simulation was done using a code, ‘COMSOL Multiphysics’, for the given geometry of the nozzle and struts.
Numerical simulation

- No flow.

- Asymmetric perturbation imparted near TE of one of the four struts.

- Solves for acoustic pressure field within the domain.

- With perturbation at a given frequency maximum pressure and maximum velocity in the domain are monitored. This way a spectrum of the Response function is constructed.
Peaks at 4.46, 7.76 and 12.37 kHz are captured reasonably well!

Peak at 9.76 kHz is not but there is a hint of energy around that frequency.
‘Mode shapes’ at monitored plane just downstream of struts

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- ‘Fundamental’ involves positive and negative pressure regions in alternate intra-strut spaces, at a given instant.
- First harmonic involves pairs of positive and negative pressure regions within a intra-strut space.
- 12.52 kHz involves a complex azimuthal/radial distribution.

4.53 kHz
8.05 kHz
12.52 kHz
Pressure and velocity distribution for fundamental (4.525 kHz) in entire domain

-- Complex standing waves are set up around the struts.
-- High pressure regions (anti-nodes) occur against the duct inner wall in between pairs of struts.
-- Even though only one strut is driven, synchronized motion occurs from all four struts.
-- Struts themselves are regions of velocity anti-nodes.
Conclusions:

-- The source of the tones is traced to vortex shedding from the struts.

-- Perturbation from shedding couples with acoustic modes of the nozzle/strut, leading to step-like variation of tone frequency with Mach number.

-- Standing waves form around struts. The fundamental involves alternating positive and negative pressure regions in intra-strut spaces. The pattern is anti-symmetric about a diametral plane. With increasing frequency the shape of the standing wave become more complex.

-- A leading edge treatment of the struts in the inner nozzle eliminates the tones. This is due to a disruption of two-dimensionality of the flow that in turn disrupts organized vortex shedding.

-- It is possible a similar remedy may work in other situations, e.g., in wind-tunnel tests where tones are generated by coupling of vortex shedding from some component with tunnel acoustic modes.
Strouhal number based on local velocity and strut thickness

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<table>
<thead>
<tr>
<th>$M_j$</th>
<th>$f$ (kHz)</th>
<th>$ft/U_{in}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.168</td>
<td>4.5</td>
<td>0.30</td>
</tr>
<tr>
<td>0.260</td>
<td>7.75</td>
<td>0.33</td>
</tr>
<tr>
<td>0.345</td>
<td>9.5</td>
<td>0.31</td>
</tr>
<tr>
<td>0.427</td>
<td>12.38</td>
<td>0.32</td>
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</tbody>
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<tr>
<td>0.45</td>
<td>4.13</td>
<td>0.22</td>
</tr>
<tr>
<td>0.75</td>
<td>6.45</td>
<td>0.21</td>
</tr>
</tbody>
</table>

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- Shedding Strouhal number depends somewhat on geometry of strut
- It is apparent Karman shedding is the instigator for the observed tones

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$t=0.125$
$c=0.65$
$h=0.265$