Category 7: Slat Cove Noise

A Zonal Hybrid RANS/LES Approach to Slat Noise Simulation

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Introduction

- Propulsion related aircraft noise has decreased substantially over the last decade resulting in a larger contribution of noise attributed to the airframe.
- During takeoff and landing, the noise generated by high-lift devices (such as slats) cause large amplitude broadband (and narrow band) sound waves.
Computational Methodology

**LAVA Framework**

- Computational Fluid Dynamics Solvers
  - Cartesian, Curvilinear, and Unstructured Grid Types
  - Overset Grid and Immersed Boundary Methods
  - Steady and Unsteady RANS (Reynolds Averaged Navier-Stokes)
  - Hybrid RANS/LES (Large Eddy Simulation) Capabilities

- Computational Aeroacoustics Solvers
  - Linear Helmholtz and Ffowcs Williams – Hawkings Formulations (Frequency Domain)
  - Radiating and Scattering Capabilities (Linear Helmholtz)

**Related Publications:**

- AIAA-2014-0070
- AIAA-2014-1278
- AIAA-2014-2008
- AIAA-2015-2211
- AIAA-2015-2262
- AIAA-2016-0814
- AIAA-2016-0815
- AIAA-2016-2958
- AIAA-2016-2963
Geometry and Flow Conditions

Geometric Model

30P30N Configuration
- Stowed Chord $c = 0.457$ m
  - Slat Chord $c_s = 0.15$ c
  - Flap Chord = 0.3 c
- Model Span $b = 1.016$ m
- Simulated Span $b_{sim} = 0.0508$ m
- Periodic in Spanwise Direction

Conditions
- Mach = 0.17
- $Re_C = 1.71 \times 10^6$
- AOA = $5.5^\circ, 9.5^\circ, 14.0^\circ$

Dual Time-Stepping
- $\Delta t = 1$ $\mu s$
- 3 orders residual reduction in 3 sub-iterations
Structured Overset Grid Procedure

- Build initial coarse grid appropriate for RANS analysis, but with some intent on higher-fidelity modeling of the slat flow field
- Perform RANS based mesh convergence study (consistent family of uniformly refined meshes)
- Construct Hybrid RANS/LES grid from selected RANS mesh
  - Utilize variable spanwise spacing for different regions
  - Select ZDES “Mode” for each zone (region)

**NOTE:**
In BANC-IV the intent was to model all noise sources of the 30P30N which required:
- Many grid points to capture the main element flap cove region and flat TE
- Utilized the same spanwise spacing throughout the grid system
- Utilized high-order accurate finite differencing schemes up to 8th order in the spanwise direction

This lead to an accurate simulation for the aeroacoustics of the 30P30N, but this methodology is not computationally affordable for full airplane geometries (such as the HL-CRM)
Approach for BANC-V

3-D Structured Curvilinear Overset Grid Solver
- Zonal Detached Eddy Simulation (ZDES)
- Spalart-Allmaras turbulence model for baseline RANS model

Higher-Order Finite Difference Method
- 4th-order Hybrid Weighted Compact Nonlinear Scheme (HWCNS) used for convective fluxes and metric terms
- Numerical flux is a modified Roe scheme
- Optimal weight 4\textsuperscript{th}/3\textsuperscript{th} order blended central/upwind biased left and right state interpolation (no special treatment in span)
- Second-order accurate differencing used for time discretization and viscous fluxes

Modifications to ZDES model
- Utilizing cube root of volume as local length scale in LES regions
- Near wall functions are removed in LES mode
- Introducing “Mode 4” pure LES region (zones not connected to walls)
Structured Overset Grid System

R1.0: N_{2D}=68147
R1.4: N_{2D}=128522
R2.0: N_{2D}=258593
R2.6: N_{2D}=434720
Structured Overset Grid System

R1.0: \(d_{s1_{slat}}=2.0\times10^{-4} \text{ m}, d_{s2_{slat}}=4.0\times10^{-4} \text{ m}\)

R1.4: \(d_{s1_{slat}}=1.4\times10^{-4} \text{ m}, d_{s2_{slat}}=2.9\times10^{-4} \text{ m}\)

R2.0: \(d_{s1_{slat}}=1.0\times10^{-4} \text{ m}, d_{s2_{slat}}=2.0\times10^{-4} \text{ m}\)

R2.6: \(d_{s1_{slat}}=7.7\times10^{-5} \text{ m}, d_{s2_{slat}}=1.5\times10^{-4} \text{ m}\)
RANS Flow Field Visualization

- Steady-state RANS solution on R2.0 mesh refinement level
- Streamlines colored by normalized velocity at AOA = 5.5, 9.5, and 14.5 degrees
- Stagnation point moves upstream with increasing AOA and slat cove wake reattachment moves upstream away from slat TE
- Increased velocity region through the slat gap increases with AOA
RANS Mesh Convergence of Loads

AOA = 5.5°

Selected R2.0 based on lift and drag convergence analysis

Drag values are within 1 – 11 counts on the R2.0 mesh compared to the Richardson extrapolated values

The R2.0 mesh has N_{2D}=258593 which is between the medium and fine structured overset grids generated for the HL-CRM (N_{3D})^{2/3} (Chan AIAA-2017-0362)

AOA = 9.5°

R2.0: N_{2D}=258593

AOA = 14.5°

JAXA CFD

Selected R2.0 based on lift and drag convergence analysis

Drag values are within 1 – 11 counts on the R2.0 mesh compared to the Richardson extrapolated values

The R2.0 mesh has N_{2D}=258593 which is between the medium and fine structured overset grids generated for the HL-CRM (N_{3D})^{2/3} (Chan AIAA-2017-0362)
RANS Cp Comparison (R2.0)

AOA = 5.5°

LAVA RANS-SA

- LWT2-Kevlar2017(6.5deg)
- LWT2-Kevlar2017(7.0deg)
- LWT2-Kevlar2017(7.5deg)
- CFD(5.5deg)
- LWT2-HardWall2013(6.0deg)
RANS Cp Comparison (R2.0)

AOA = 9.5°

LAVA RANS-SA

- LWT2-Kevlar2017(10.5deg)
- LWT2-Kevlar2017(11.0deg)
- LWT2-Kevlar2017(11.5deg)
- CFD(9.5deg)
- LWT2-HardWall2013(10.0deg)
RANS Cp Comparison (R2.0)

AOA = 14.5°

LAVA RANS-SA

-11
-10
-9
-8
-7
-6
-5
-4
-3
-2
-1
0
1
2
-0.2
-0.1
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2

LWT2-Kevlar2017(16.0deg)

CFD(13.5deg)

CFD(14.0deg)

CFD(14.5deg)
Excellent agreement with RANS results from JAXA are observed using the R2.0 mesh.

Good agreement with the experiment is also observed at the shifted AOA (shift was determined in Murayama et al AVIATION 2018).

A small discrepancy is observed on the pressure side of the slat between $-0.03 < x/c < 0.01$.

AOA $= 5.5^\circ$  

AOA $= 9.5^\circ$  

AOA $= 14.5^\circ$
BANC-IV Review

- Number of Grid Points: 78.1 M
- Spanwise: 194 ($z^+ = 106$)
- Max Wall-normal stretching: 1.1
- Max Streamwise stretching: 1.175
- Triple Fringe Layers
- No Orphan Points
- $DS_{\text{plus}} = \max(x^+, y^+)$
BANC-IV Review

ZDES Grid-Zone Specification
Progress on BANC-V ZDES Simulations

- Total number of grid points: 36.7 M
  - 5.6 M Blanked
  - 5.3 M Fringe
  - 25.8 M DOF
- Double Fringe (no orphans)
- Variable spanwise spacing: 256 (red), 128 (green), 64 blue
- Maximum wall-normal and streamwise stretching 1.118
- Maximum streamwise spacing along airfoil: \( ds/c_{stowed} = 0.0055 \)
Progress on BANC-V ZDES Simulations

Three ZDES modes were selected:
- Mode 0 (RANS) blue
- Mode 1 (DES97) green
- Mode 4 (LES) red

LES using SA turbulence model with the length scale replaced by the cube root of volume as the SGS model.
Progress on BANC-V ZDES Simulations

- Simulation start-up:
  - Initially run with large-time step ($dt = C/U/10$) until loads level off
  - Reduce the time step ($dt = c/U/100$) and run until loads level off
  - Restart with aeroacoustic simulation time-step ($dt = 1.0e-6$ s)
  - Run for at least $12.75$ CTU (these started running on early Thursday and will be complete on Sunday or Monday)

- All comparisons are using data with incomplete time-histories:
  - Time averages will likely change but not by a huge amount
  - Increased overlap to 75% for PSD spectrum
  - Far-field acoustics will be completed when the full time-integrations are complete

- Since we are utilizing a different zonal strategy this year will include comparisons with our LAVA BANC-IV results for clarity
Time-averaged Spanwise Vorticity

- No major differences in time-averaged spanwise vorticity is observed between BANC-IV and BANC-V simulations (not shown for brevity)
- Slat shear-layer impingement moves upstream with increasing AOA
- Upstream movement of the impingement location reduces the region of 3D turbulent recirculating flow in the slat cove
**Instantaneous Spanwise Vorticity**

- Significant reduction in resolved turbulent content and delayed transition to 3D turbulent structures along the initial slat LE shear-layers
  - This could be related to the coarse mesh in streamwise and wall-normal spacing using for the BANC-V simulation
  - This may also be cause by the reduction in order of accuracy when using the 4\textsuperscript{th} order WCNS compared to the 6\textsuperscript{th} order WCNS
Significant reduction in resolved turbulent content and delayed transition to 3D turbulent structures along the initial slat LE shear-layers

- This could be related to the coarse mesh in streamwise and wall-normal spacing using for the BANC-V simulation
- This may also be cause by the reduction in order of accuracy when using the 4th order WCNS compared to the 6th order WCNS
Instantaneous Streamwise Vorticity Colored by Streamwise Velocity

- Upstream movement of slat LE shear-layer impingement, and reduction of recirculation region with increased AOA can also be observed in the instantaneous streamwise vorticity isocontours.
Instantaneous Density Gradient Magnitude
2D Turbulent Kinetic Energy (Resolved)

BANC-IV: AOA = 5.5°

AOA = 5.5°

AOA = 9.5°

AOA = 14.0°
2D Turbulent Kinetic Energy (Resolved)

- A reduction in resolved TKE2D is observed between the BANC-IV results and the BANC-V results at AOA = 5.5° (mesh, order of accuracy?)
- A consistent reduction in resolved TKE2D with increasing AOA in the initial part of the shear layer is also observed (physical or numerical diffusion caused by increased mesh misalignment with increasing AOA?)
3D Turbulent Kinetic Energy (Resolved)
A similar reduction in resolved TKE3D is observed between the BANC-IV and BANC-V results at AOA = 5.5°.

Analogous to the TKE2D the TKE3D are reduced along the initial portion of the slat shear-layer with increasing AOA.
Spectral Comparison P4: AOA=5.5°
Spectral Comparison P1: AOA=5.5°
Spectral Comparison P6: AOA=5.5°
Spectral Variation with AOA: P4

\[ \alpha = 5.5 \]
\[ \alpha = 9.5 \]
\[ \alpha = 14.0 \]
Spectral Variation with AOA: P5
Spectral Variation with AOA: P8
Summary

- A zonal hybrid RANS/LES method has been applied to the 30P30N configuration at three angles of attack.
- A RANS based mesh refinement study was performed to develop an initial structured overset grid system.
- Zone based spatially varying spanwise grid spacings were used to keep the number of grid points relatively low.
- Comparisons with LAVA results from BANC-IV using a different ZDES method were made:
  - Resolved TKE was reduced in the initial part of the shear-layer for the AOA=5.5° case. This may be caused by the coarser mesh or the switch from the 6th order to the 4th order WCNS.
  - Similar PSD spectrum are observed in spite of the reduction in resolution of the turbulent scales.
Summary

- A comparison of instantaneous and time-averaged flow quantities, and PSD spectrums at different AOA were also made:
  - An upstream shift of the slat LE shear-layer impingement on the slat lower-surface with increasing AOA is found.
  - A delay in resolved TKE along the shear-layer with increasing AOA is shown. This may be physical or numerical and must be further scrutinized.
  - Good comparisons between CFD and JAXA WT data at P4 and P5 were observed, and reasonable comparisons at P8 were also found.
  - PSD levels in the lower frequency range are reduced with increasing AOA which is consistent with the JAXA WT results.