Simulation-Based Aircraft Noise Certification: Challenges and Opportunities

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Acknowledgements

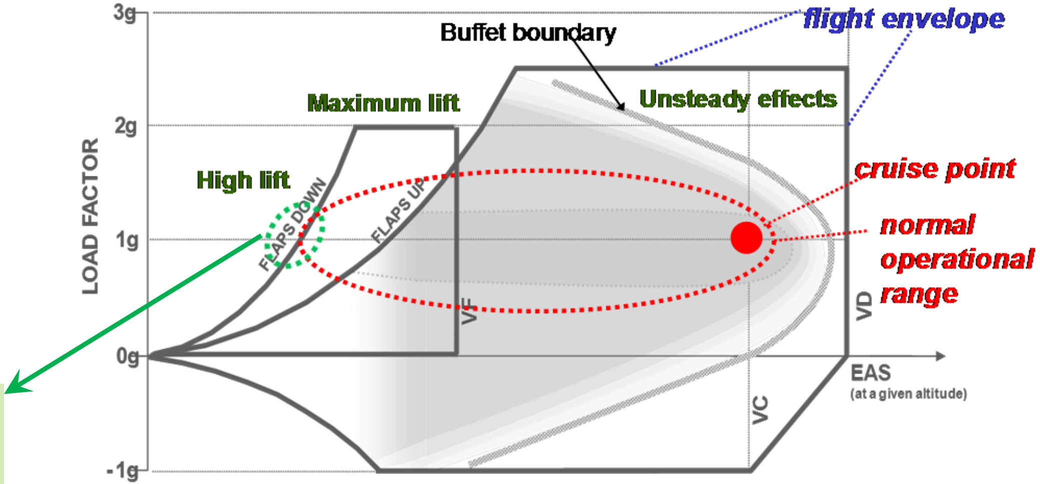
- **Results from sustained twelve-year effort**
  - Sponsored by several NASA projects (ERA, FDC, CST, AATT, and EPFD)
  - All simulations conducted with Dassault Systèmes PowerFLOW
- **Small, dedicated, and enthusiastic team**
  - Part-time involvement for all members
- **Current team members**
  - NASA: Mehdi Khorrami and Edmane Envia
  - Analytical Mechanics Associates: Scott Brynildsen
  - Dassault Systèmes: Andre Ribeiro, Benedikt König, Ryan Ferris, and Ankita Mittal
  - AVEC, Inc: Patricio Ravetta
- **Past team members**
  - Ehab Fares and Jason Appelbaum (formerly of Exa), Benjamin Duda and Damiano Casalino (Dassault), and David Lockard (NASA)

Background

❑ Certification by Analysis and Digital Twins

- Latest “buzz” words?
- Can be viewed as aspirational, distantly achievable goals
- Imply multidisciplinary analysis for full (powered) aircraft
- Numerous challenges to overcome

Flight Envelope



Noise certification region

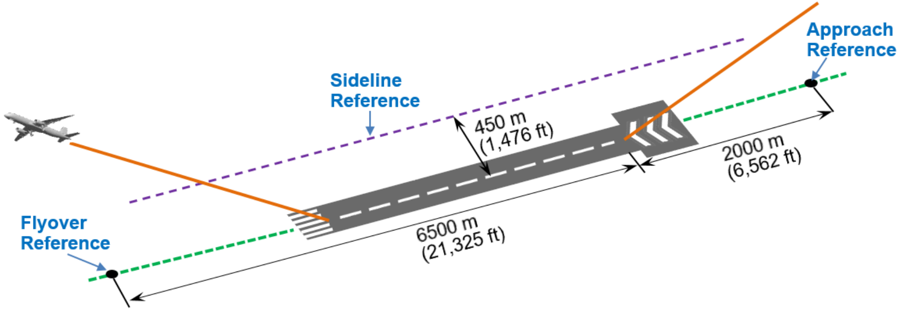
Noise Certification

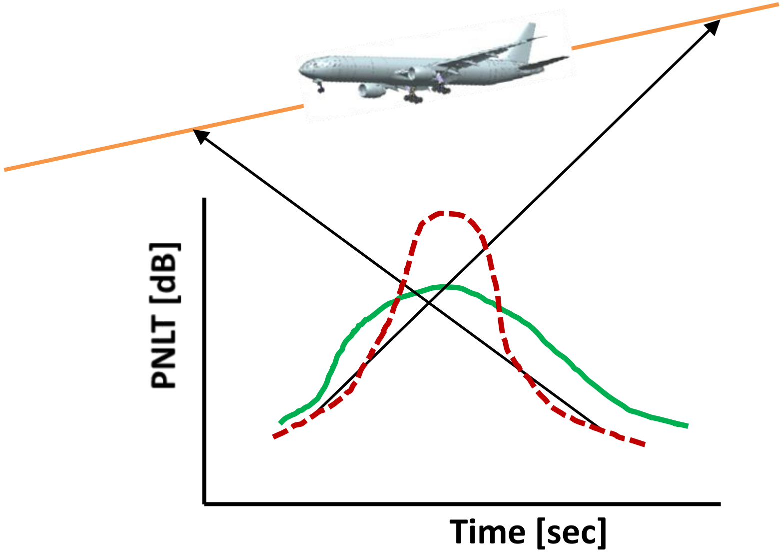
❑ Certification process

- Single-microphone certification points and standards (FAA, ICAO)
- Generate Perceived Noise Levels (PNL)
- Integrate to determine EPNdB levels

❑ Simulation-based noise prediction

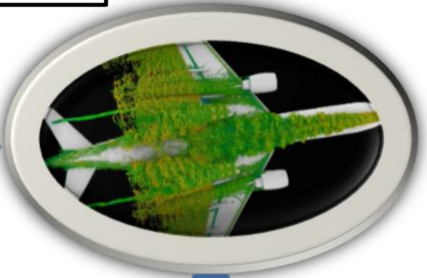
- Must be tailored for broadband noise
- For certification, 100Hz – 10,000Hz freq. range (6,000 Hz is good)
- Small time steps and long record length to ensure converged spectra





Simulation-Based Noise Prediction

Scale-resolving simulations: near-field flow



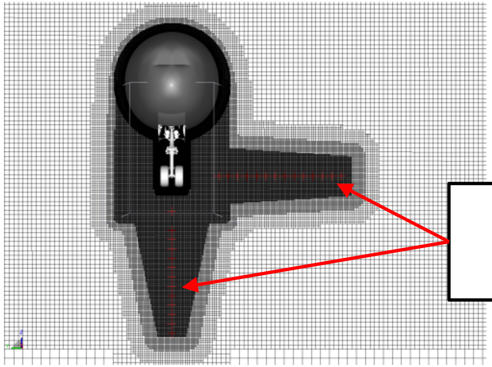
Propagation: FWH formulation solid or permeable surface

Far-field p’(t) at receiver locations
a) Certification points
b) Phased microphone arrays

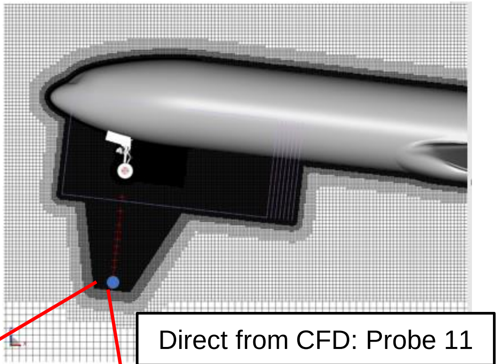
- **Outlook**
  - Direct CFD propagation not feasible in foreseeable future
  - Increase in computational power will be used to improve source (frequency) resolution
  - Integral (FWH/Farassat) formulation is key to noise prediction/certification

Issues with Solid Data Surface

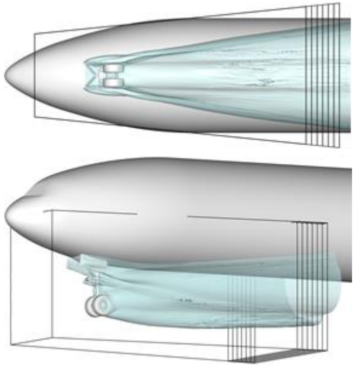
Full-scale Boeing 777-300ER nose landing gear

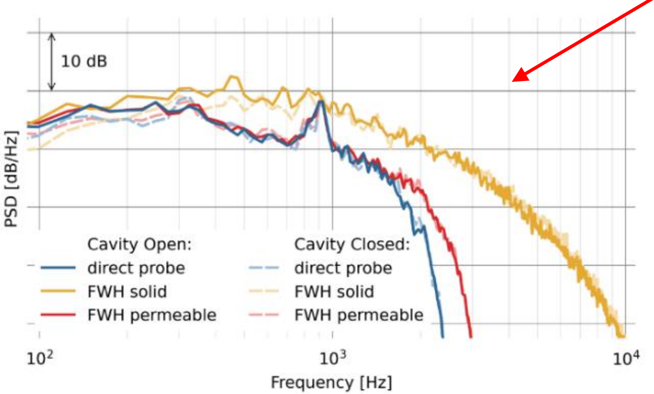


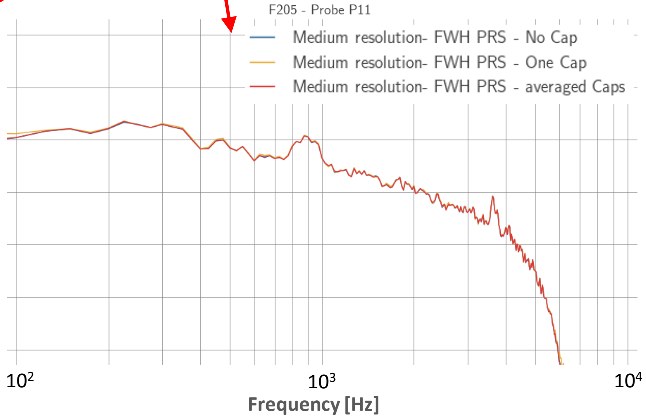
Maintain high resolution
(for direct probes)



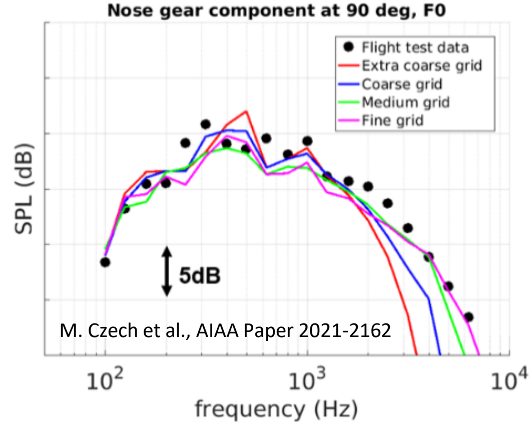
Direct from CFD: Probe 11





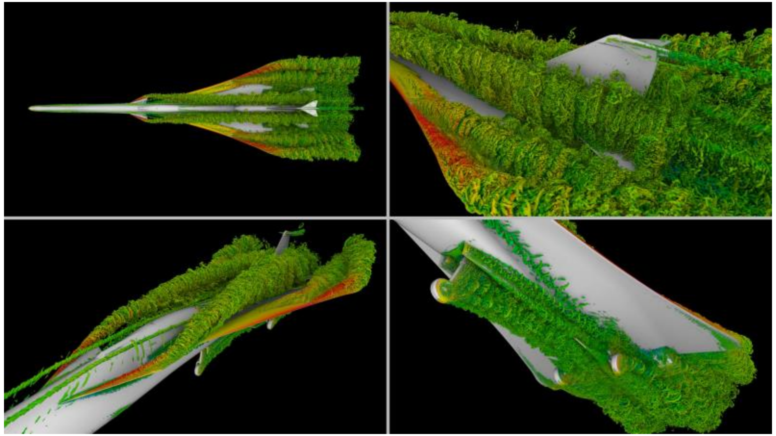


Simulation vs. QTD-II flight test data

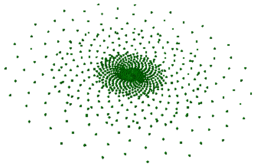


M. Czech et al., AIAA Paper 2021-2162

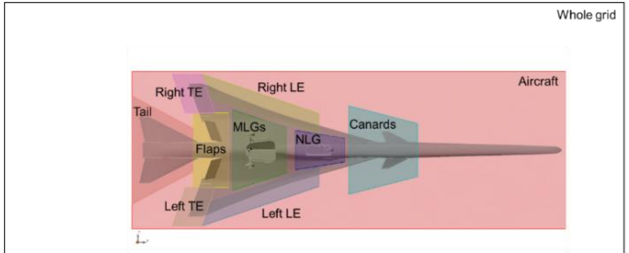
Issues with Solid Data Surface



800-element synthetic phased microphone array

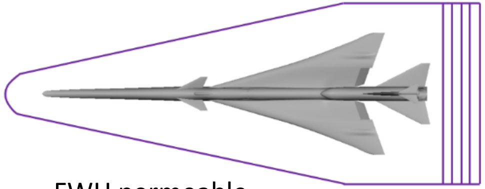


Generic Low Boom Concept (GLBC)

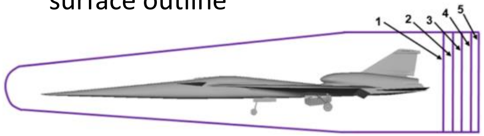


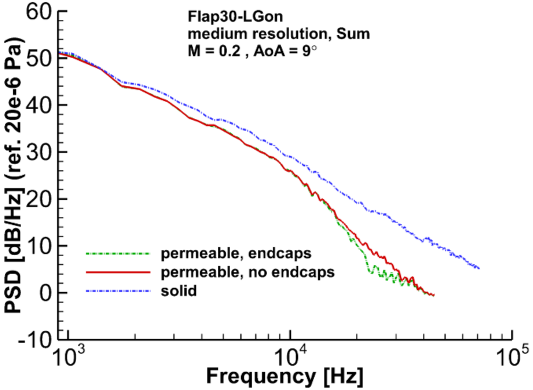
Integration regions

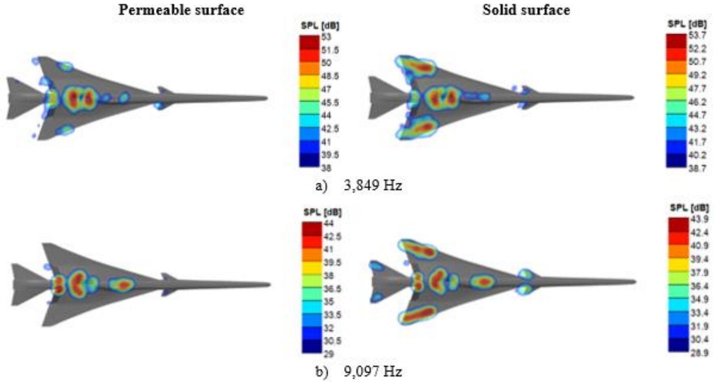
F. P. Ribeiro et al., *AST*, Vol. 135, (2023), 108202



FWH permeable surface outline





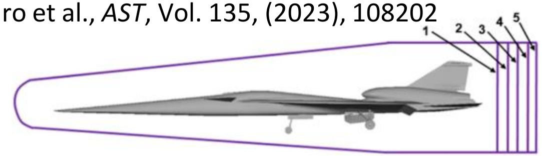


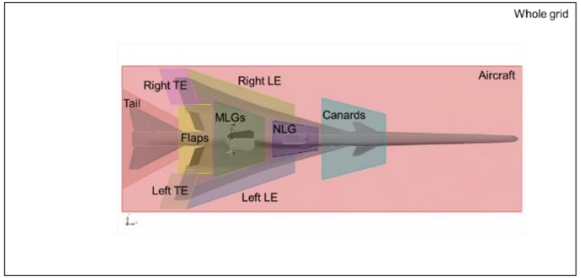
Sample beamform maps (landing configuration)

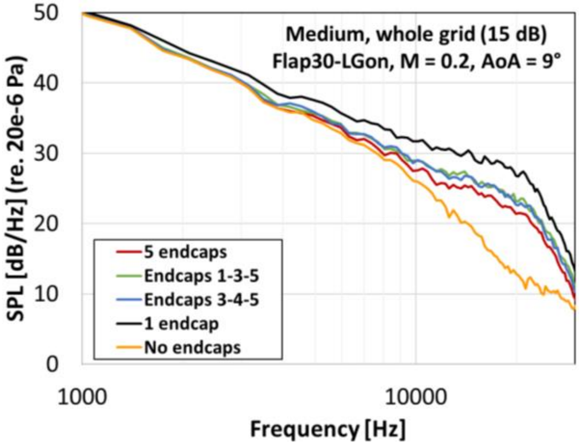
End Cap (Wake) Effects

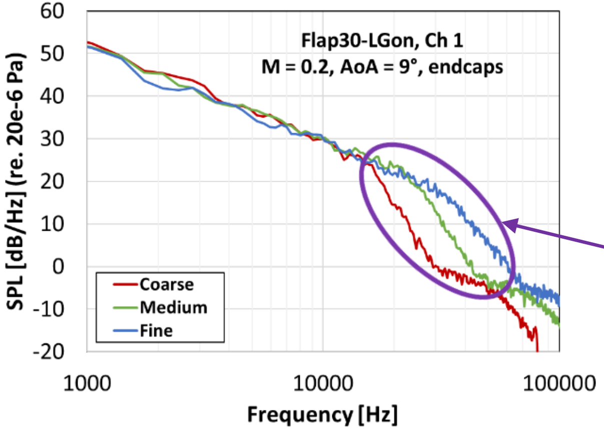
- ❑ **All wakes are different**
- ❑ **End cap effects are case-dependent**
  - Universal approach for end cap setup does not exist
  - End cap surface removal may not alleviate some problems
- ❑ **Strong streamwise vortices are problematic**

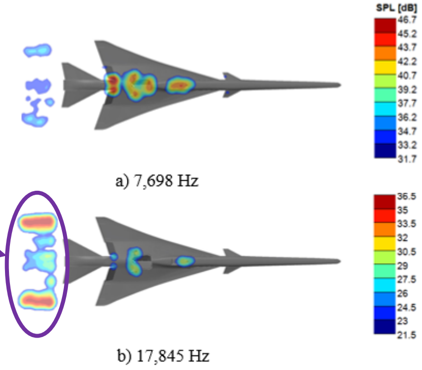
F. P. Ribeiro et al., *AST*, Vol. 135, (2023), 108202







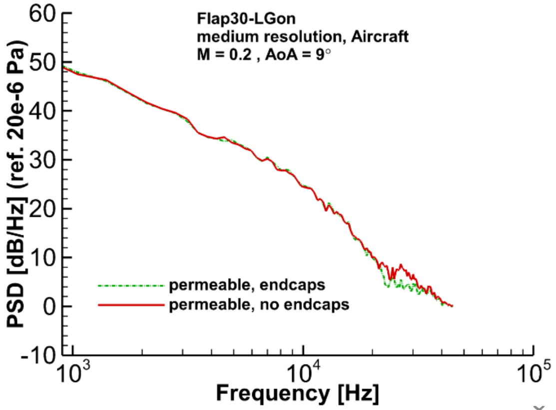




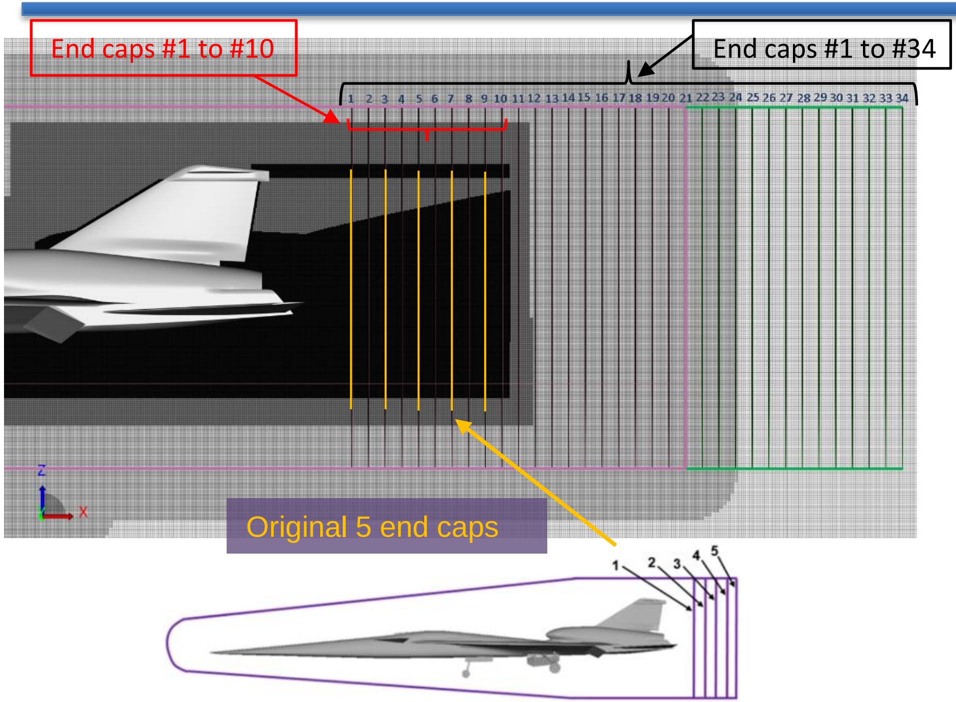
a) 7,698 Hz

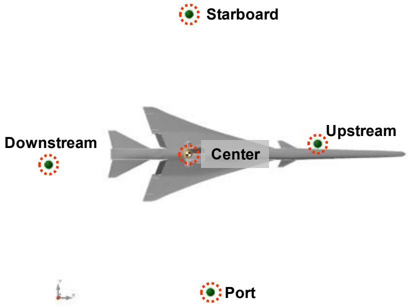
b) 17,845 Hz

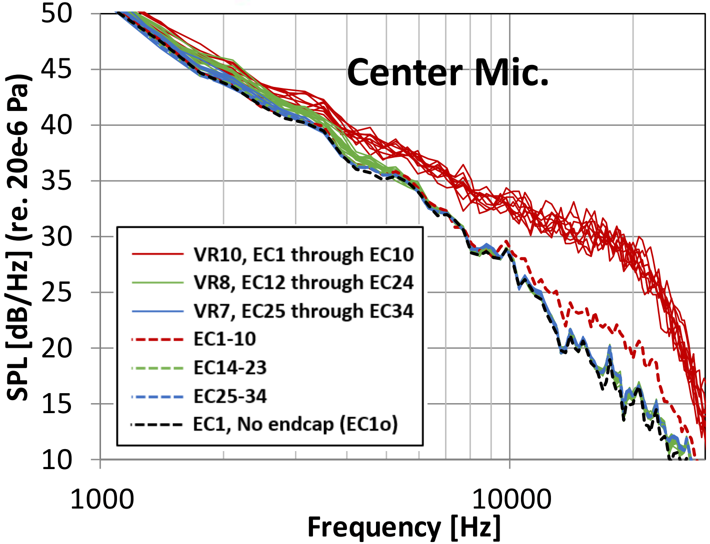
Sample beamform maps (landing configuration)



End Cap (Wake) Effects – Current Effort





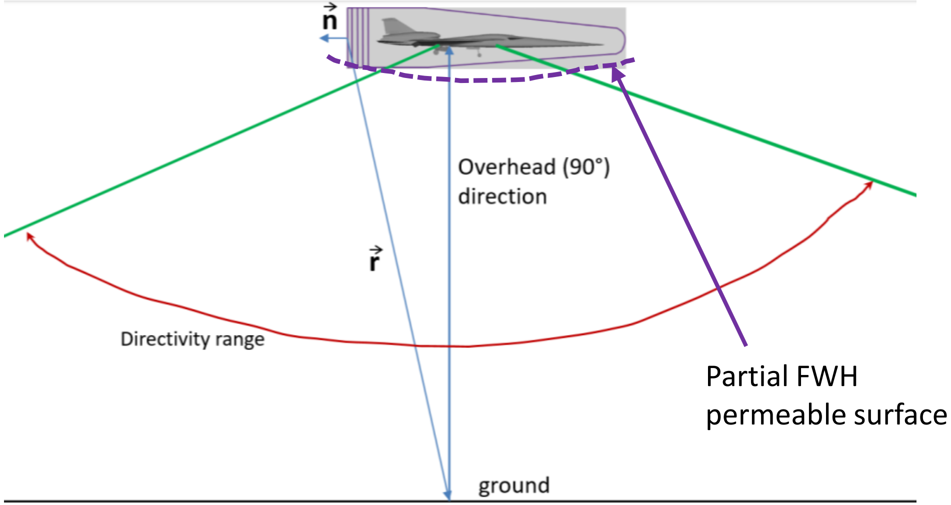


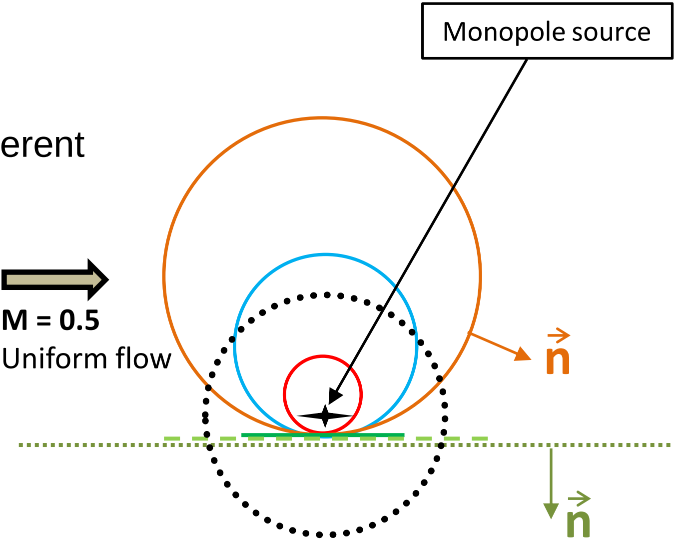
- ❑ Spurious noise sources at VR transition regions have been observed
  - ▪ Evident in GLBC maps
  - ▪ Strong presence in maps for another aircraft studied

Incomplete FWH Permeable Data Surface

❑ Partial permeable data surface

- A good first try
- Not sure why M = 0.5 was chosen for airframe noise
- Only very low frequencies were examined
- Mid- and high-frequency trends may be significantly different





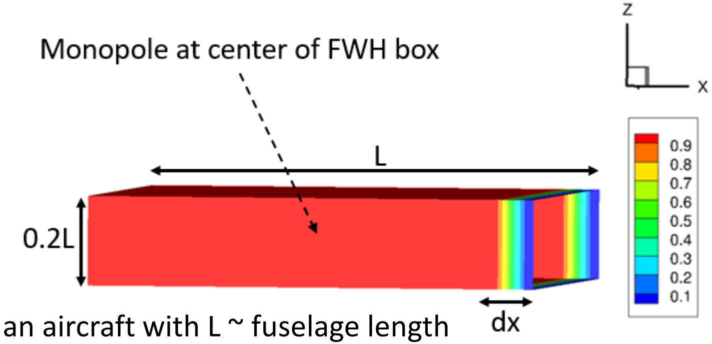
Ricciardi, T. R., Wolf, W. R., and Spalart, P. R., “On the Application of Incomplete Ffowcs Williams and Hawkings Surfaces for Aeroacoustic Predictions,” Technical Notes, AIAA J., Vol. 60, No. 3, pp. 1971-1977, March 2022

Windowing for Incomplete FWH Surface

- **S. Woodruff and D. Lockard, NASA Langley, unpublished**

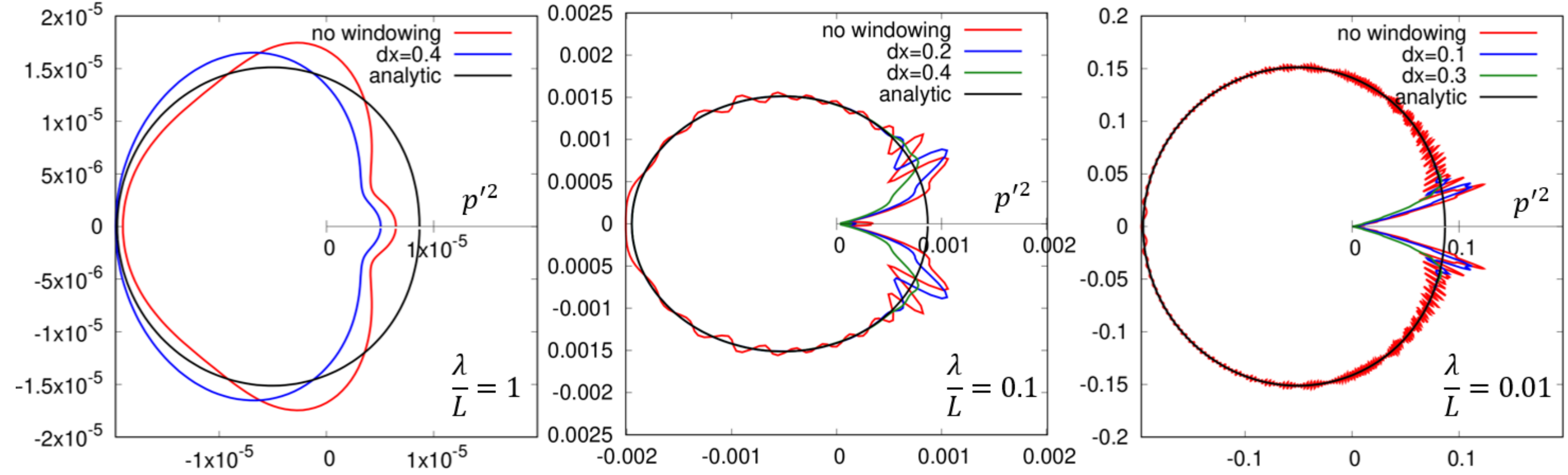
Directivity plots of radiated power from monopole, at circle of radius 10L in x-z plane.

$M_\infty = 0.2$



Monopole at center of FWH box

Box dimensions meant to correspond with a perm. surface around an aircraft with L ~ fuselage length



Windowing for Incomplete FWH Surface

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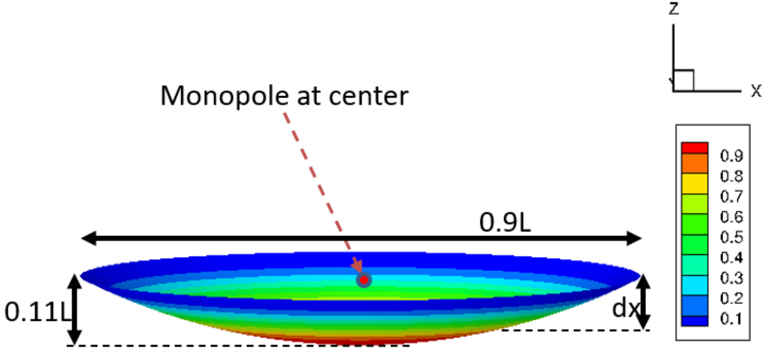
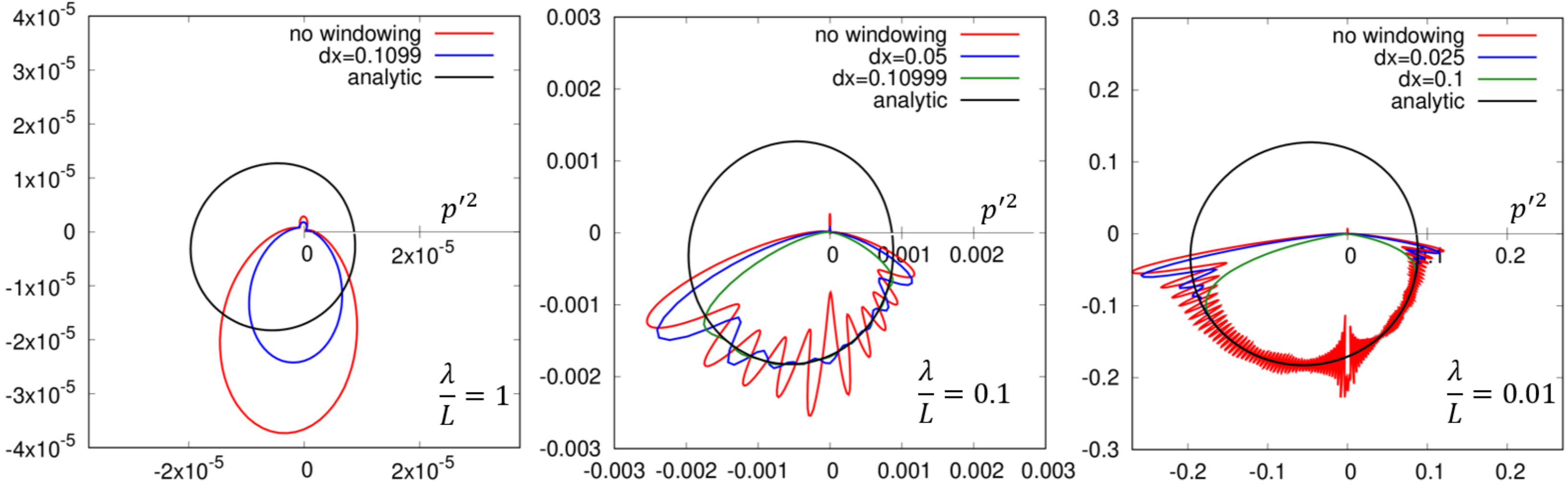


Directivity plots of radiated power from monopole, at circle of radius 10L in x-z plane.

$M_\infty = 0.2$

Surface is cap from sphere of radius L.



Simulation-Based Noise Prediction

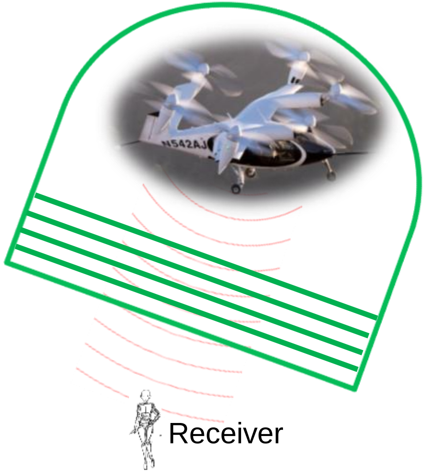
❑ UAM

- Solid data surfaces are not an option
- Cannot drop end caps
- Mesh coarsening in endcap region diminishes true signal
- How many caps in average?
- What other options do we have?

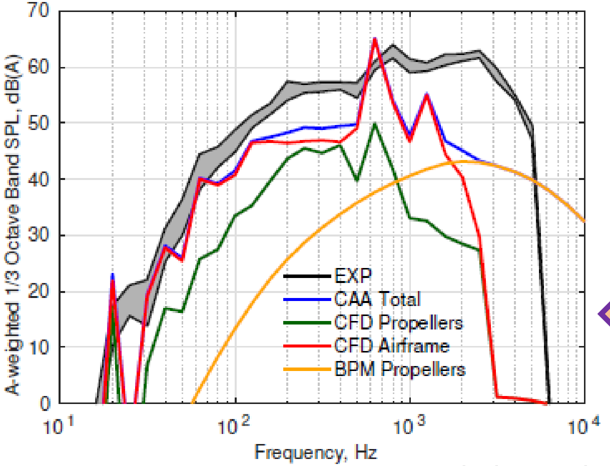
Thrustborne flight

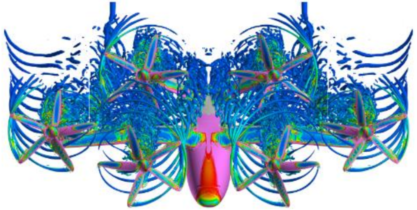
Semi-thrustborne flight

Wingborne flight

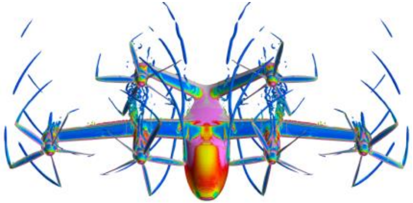


NASA Overflow code, solid surface results





60 Kts, shaft angle = 47°



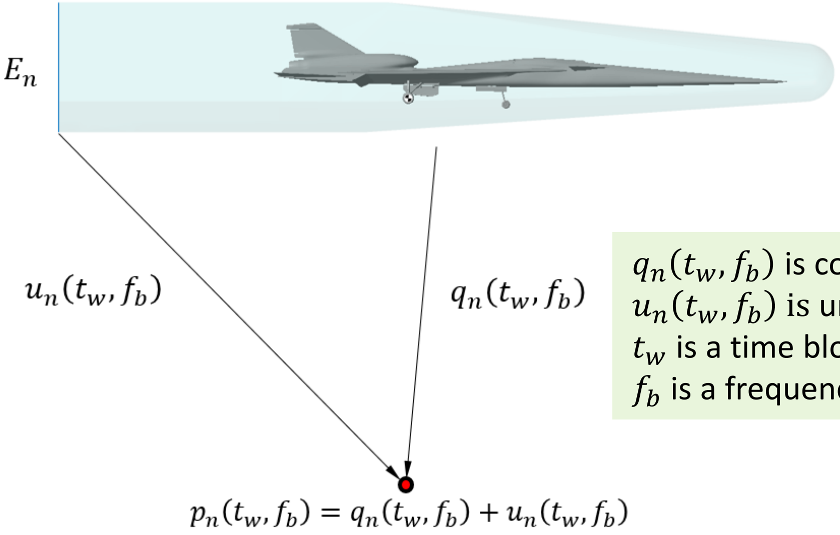
100 Kts, shaft angle = 0°

Results and images courtesy of Joby Aviation

A. Thai, J. Bain, G. V. Mikic, and A. Stoll
Vertical Flight Society Paper 79-2023-1345-2

Mitigation of End Cap Effects

- ❑ **Underlying idea and formulation of Adaptive Beamforming (AB): Robert Dougherty (OptiNav)**
- ❑ **Expanded formulation, implementation of Conventional Beamforming (CB) and AB with Diagonal Removal (DR), and data processing/analysis: Patricio Ravetta (AVEC, Inc.)**
- ❑ **Beamforming (AB and CB) used to obtain acoustic signal at a single observer**
  - ▪ Should not be confused with phased microphone array beamforming
  - ▪ Current effort is a first step, as many aspects of this approach remain to be studied and understood



$$p_n(t_w, f_b) = q_n(t_w, f_b) + u_n(t_w, f_b)$$

$q_n(t_w, f_b)$ is correlated signal
$u_n(t_w, f_b)$ is uncorrelated signal
t_w is a time block
f_b is a frequency bin

Mitigation of End Cap Effects: Expanded Formulation

- Output for each FWH surface with a single endcap used to define element n, m of the sample-averaged $N \times N$ cross−spectral matrix (CSM):

$$C_{n,m} = \frac{1}{TB} \sum_{w=1}^{T} \sum_{b=1}^{B} p_n(t_w, f_b) p_m^*(t_w, f_b)$$

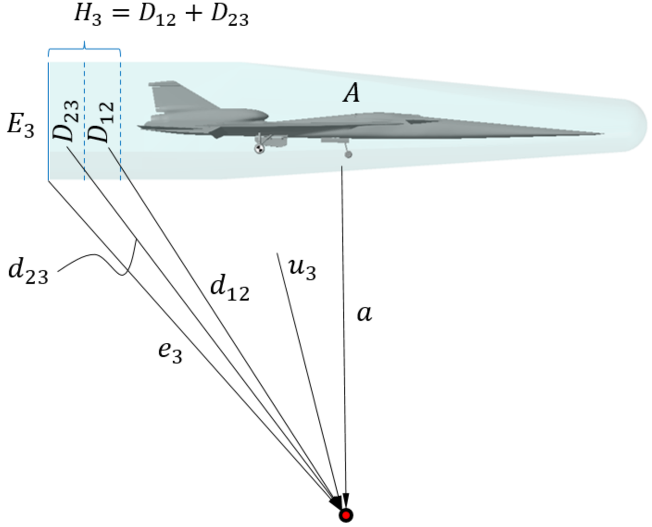
$$\begin{bmatrix} C_{11} & \cdots & C_{1N} \\ \vdots & \ddots & \vdots \\ C_{N1} & \cdots & C_{NN} \end{bmatrix}$$

- Dougherty's general formulation was "expanded" for FWH surfaces with multiple end caps and intersurfaces.
- The expected value, $\mathrm{E}[x]$, of the sample-averaged CSM element is:

$$\mathrm{E}\big[C_{n,m}\big] = \mathrm{E}[p_n p_m^*] = \mathrm{E}[(a + h_n + e_n + u_n)(a + h_m + e_m + u_m)^* \,]$$

- Assuming u is uncorrelated with q (and hence with a, h, and e):

$$\mathrm{E}\big[C_{n,m}\big] = \mathrm{E}[aa^*] + \mathrm{E}[h_n h_m^*] + \mathrm{E}[e_n e_m^*] + \mathrm{E}[a h_m^*] + \mathrm{E}[h_n a^*] \\ + \mathrm{E}[h_n e_m^*] + \mathrm{E}[e_n h_m^*] + \mathrm{E}[e_n a^*] + \mathrm{E}[a e_m^*] + \mathrm{E}[u_n u_m^*]$$



$$p_3 = q_3 + u_3 = a + h_3 + e_3 + u_3$$

$$h_n = \textstyle\sum_{i=0}^{n-1} d_{ij}\,, \; j = i + 1, \; d_{01} = 0$$

- This expanded formulation does not change the actual data processing involved.
- The full derivation (not shown here) can be used to better understand the CB output in terms of the correlated content among surfaces (main, endcap, or intersurface).

Mitigation of End Cap Effects (AB and CB)

- AB uses a data-dependent weighting vector to remove the effect of end caps
- *C* (the CSM) is ill-conditioned, with or without DR
- Elaborate scheme needed to ensure *C* is invertible

- CB uses DR to eliminate most of the uncorrelated signal (end cap effects)
- Removes the need to invert *C*
- Results from CB **without DR** are identical to endcap averaging

$$\boldsymbol{w} = \frac{C^{-1}\boldsymbol{g}}{\boldsymbol{g}'C^{-1}\boldsymbol{g}} \qquad \boldsymbol{g} = \frac{1}{\sqrt{N}}\begin{bmatrix}1\\ \vdots\\ 1\end{bmatrix}$$

	Conventional	Adaptive
Endcap-combined time history for a single virtual microphone	$\frac{1}{\sqrt{N}}\boldsymbol{g}'\boldsymbol{p}(t_j, f_b)$	$\frac{1}{\sqrt{N}}\boldsymbol{w}'\boldsymbol{p}(t_j, f_b)$
Spectral estimate for a single virtual microphone	$\frac{1}{N}\boldsymbol{g}'C\boldsymbol{g}$	$\frac{1}{N}\frac{1}{\boldsymbol{g}'C^{-1}\boldsymbol{g}}$

Un-normalized steering vector: $\hat{\boldsymbol{g}} = \begin{bmatrix}1\\ \vdots\\ 1\end{bmatrix}$

$$q_{CB} = \frac{1}{N^2}\hat{\boldsymbol{g}}'C\hat{\boldsymbol{g}} = \frac{1}{N^2}\hat{\boldsymbol{g}}'S\hat{\boldsymbol{g}} + \frac{1}{N^2}\hat{\boldsymbol{g}}'U\hat{\boldsymbol{g}}$$

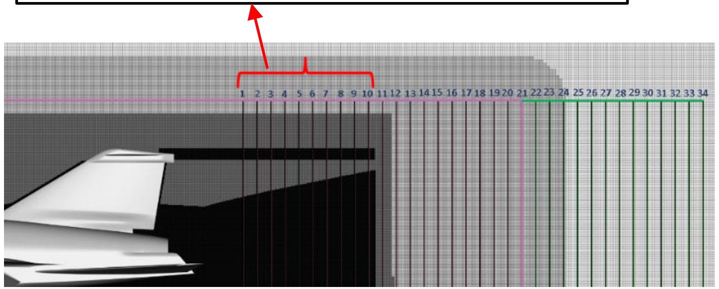
≈ 0

$$q_{CBDR} = \frac{1}{N^2 - N}\hat{\boldsymbol{g}}'\tilde{C}\hat{\boldsymbol{g}} = \frac{1}{N^2 - N}\hat{\boldsymbol{g}}'\tilde{S}\hat{\boldsymbol{g}} + \frac{1}{N^2 - N}\hat{\boldsymbol{g}}'\tilde{U}\hat{\boldsymbol{g}}$$

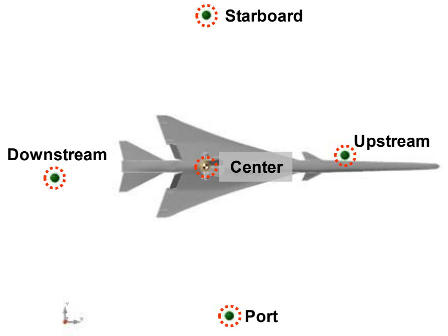
$$\tilde{C} = C - \mathrm{diag}(C)$$

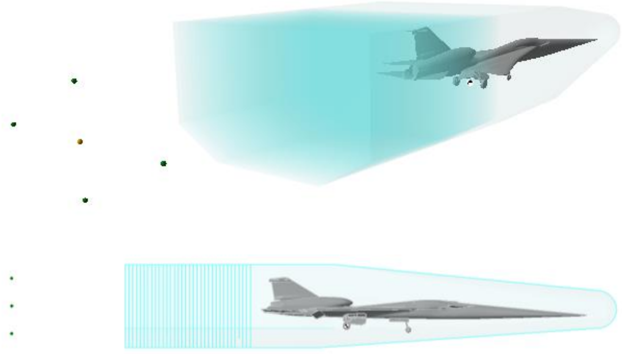
Adaptive and Conventional Beamforming Results

End caps 1-10 in finest resolution region

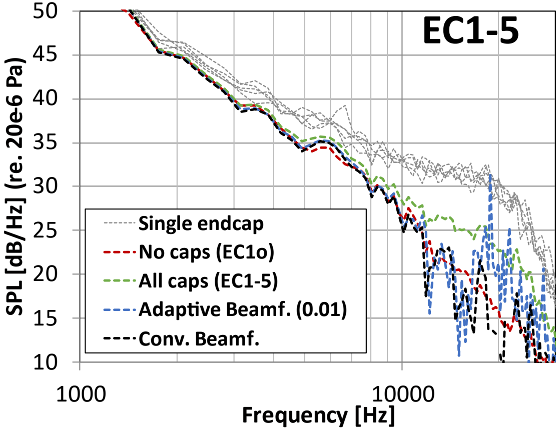


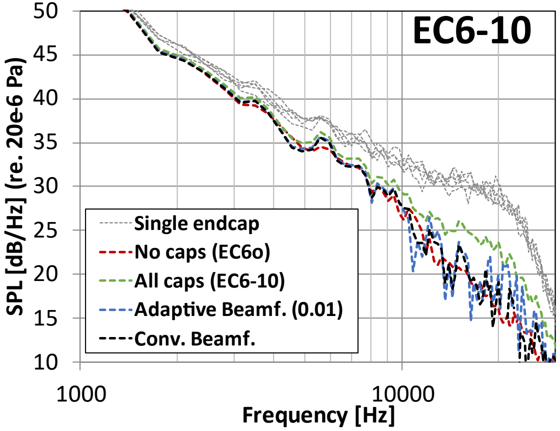
Spectra from Center Mic.

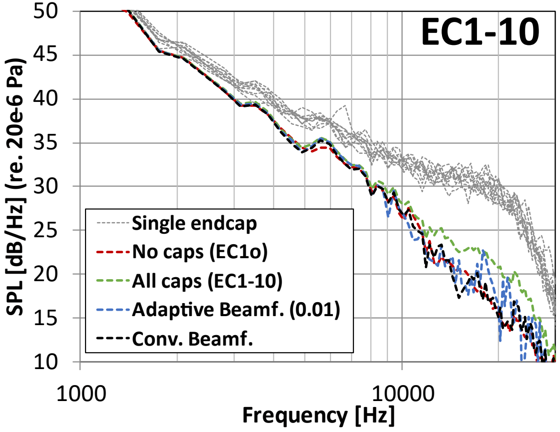




*AB and CB with DR

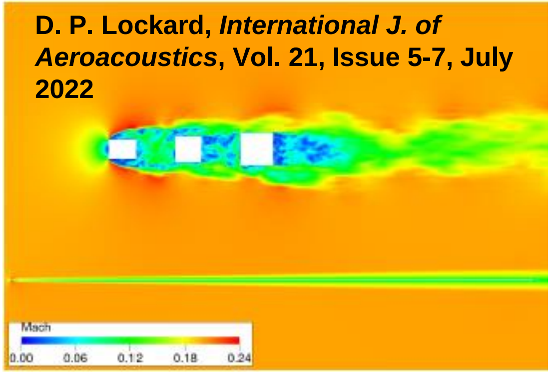






FWH/Farassat Integral Formulation (Permeable Surface)

- **Challenges**
  - Passage of a strong turbulent wake through surface very problematic
  - Standard end cap averaging insufficient to remove spurious noise fully
  - Full ramifications of a partially open surface not well understood
    - Removal of endcap may work best over a narrow range of directivity angles
    - Removal of endcap may introduce other artifacts
  - Urgent need for a more systematic study
- **Opportunities**
  - Targeted community effort to develop complementary/alternative mitigation strategies (e.g., adaptive beamforming)
  - Proposed new strategies vetted via application to realistic problems
  - Development of canonical/benchmark problems for use by wider community
    - Simple geometries that produce complex flow physics
    - Easy setup in ground facilities for aeroacoustic testing
  - Foster collaborations among applied mathematicians, acousticians, fluid dynamicists (i.e., usher in the new FWs and Farassats)


D. P. Lockard, *International J. of Aeroacoustics*, Vol. 21, Issue 5-7, July 2022

Development of Surrogate Full-Scale Aircraft for Noise Certification Purposes

Total Aircraft Noise with Electrified Propulsion (TANEP)

Sponsored by NASA Electrified Powertrain Flight Demonstrator project

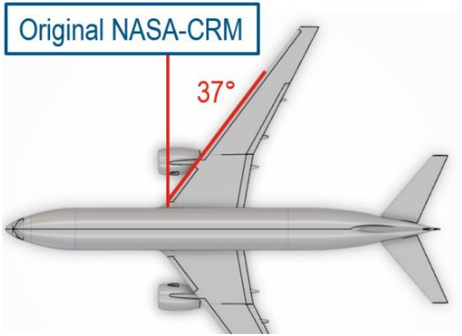
Development of Full-Scale Surrogate Aircraft

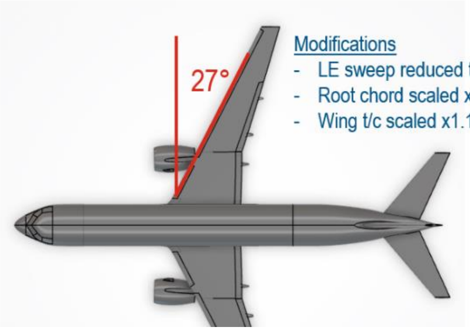
❑ Airframe attributes

- Representative of single-aisle, 150-160 passenger aircraft
- Nonproprietary geometry
- Address all prominent airframe noise sources

❑ NASA Common Research Model (CRM)

- Starting point for surrogate airframe
- Representative of twin-aisle, long range, large aircraft ($M_{cruise} = 0.85$)





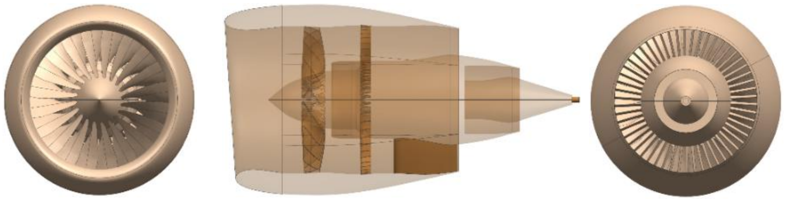
Modifications
- LE sweep reduced to 27°
- Root chord scaled x0.9
- Wing t/c scaled x1.15

❑ Engine attributes

- Nonproprietary geometry
- Address only fan and core jet noise
- Provides desired thrust, FPR, and BPR
- Direct drive and geared drive designs

❑ Baseline Direct-drive engine (DDE)

- Scaled-up Source Diagnostic Testbed (SDT)
  - ➢ Reduced number of fan blades by two
  - ➢ Introduced core flow (jet)
  - ➢ Introduced inlet droop



Full-scale direct-drive turbofan

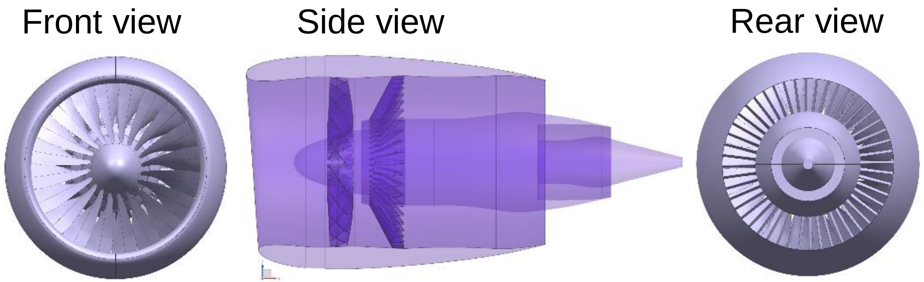
Fan blades	Fan blade diameter	Stator vanes	Core flow	Inlet droop
20	78 inches	54	Yes	4°

Development of Full-Scale Surrogate Turbofan Engine

- ❑ **Geared-drive engine (GTF)**
  - Direct-drive engine as starting geometry
  - Increased fan blade diameter
  - Reduced number of stators by six
  - Shortened rotor-stator distance
  - Added stator sweep
- ❑ **Initial high-fidelity aero simulations**
  - Near completion
  - Used to fine-tune engine flow-field
  - Future simulations to include liner geometry in nacelle walls

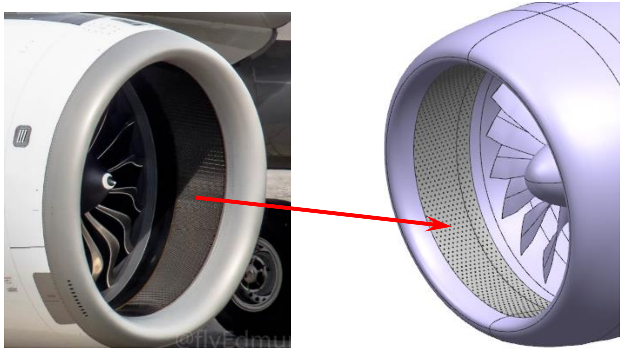
Geared-drive engine conditions

Core exhaust Temp	Total thrust	Core exhaust thrust	BPR	FPR
800K	24.6k lbf	2.2k lbf	12.0 –12.1	1.39

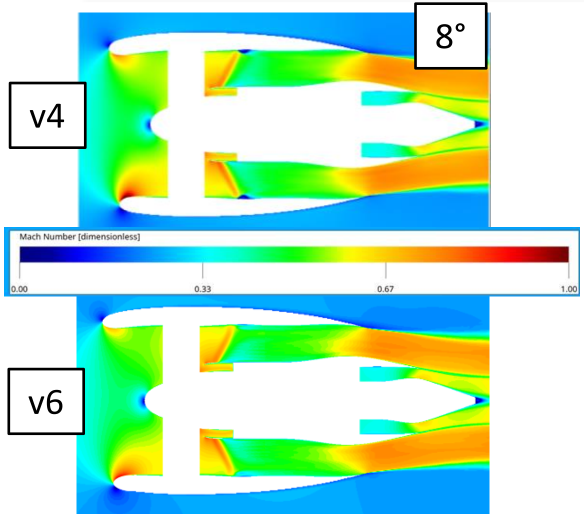

Front view Side view Rear view

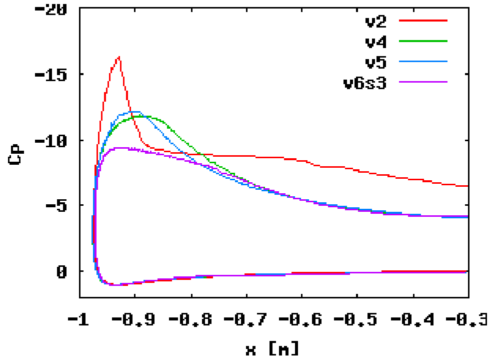
Full-scale geared-drive turbofan

Fan blades	Fan blade diameter	Stator vanes	Stator sweep	Core flow	Inlet droop
20	81 inches	48	28°	yes	4°



Development of Surrogate Turbofan Engine (GTF)



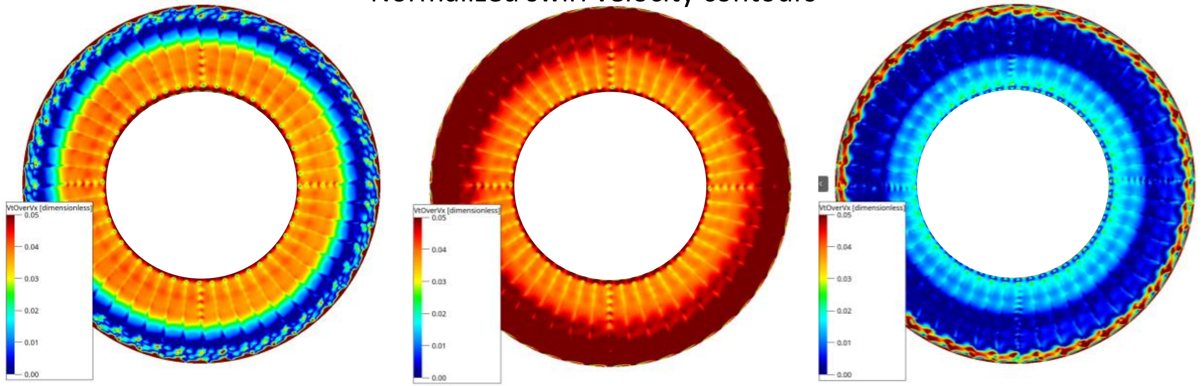


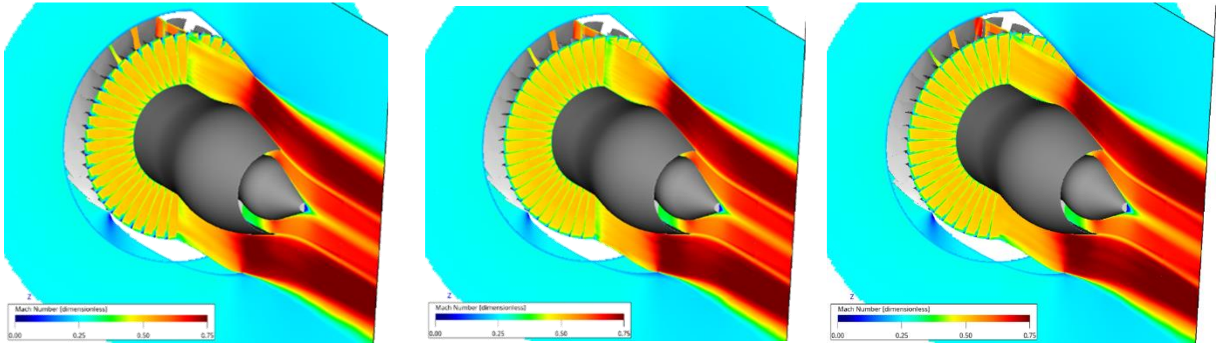
v6s3 ~ 2.7%

v6s7 ~ 5.4%

v6s10 ~ 1.3%

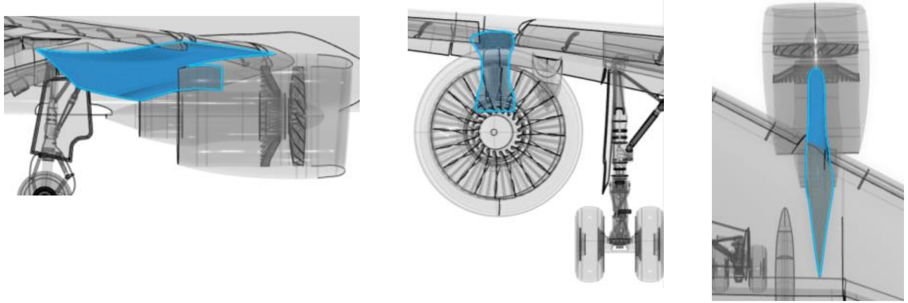
Normalized swirl velocity contours





Development of Surrogate Aircraft with GTF Engines

- ❑ **Initial airframe simulations with DDE**
  - Ensure acceptable cruise performance, fine-tune high-lift system, and evaluate the effect of slat and flap brackets
- ❑ **Propulsion-airframe integration**
  - Pylon–engine interface from NASA geometry
    - ➢ Rebuilt using Subdivision Surfaces Technology for maximum surface quality
  - Pylon–wing interface
    - ➢ Initial design completed
    - ➢ Detailed design pending flow analysis



Animation of surrogate aircraft with GTF engine

Development of Full-Scale Surrogate Aircraft

❑ Challenges

- Considerable effort by NASA and Boeing to develop a relevant airframe (CRM)
    - More than 15 years to create an ecosystem around CRM for evaluation of aeroacoustic tools
- Similar effort for a common turbofan engine does not exist
- NASA’s SDT model is over 20 years old
    - GE designed fan blades based on older generation of high BPR engines
    - Missing core
- Engine manufacturers uncooperative due to extremely competitive environment

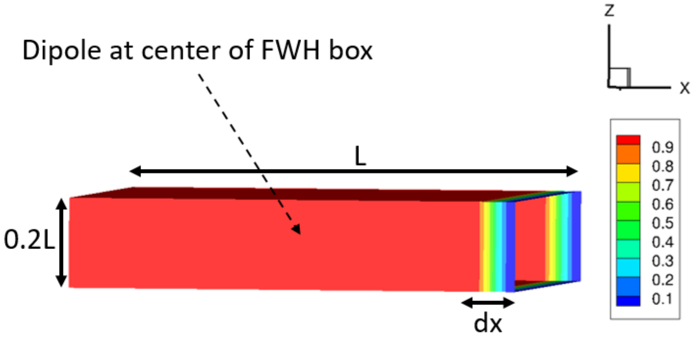
❑ Opportunities

- Cohesive community effort to develop a common engine model for tool validation
    - Create a roadmap to develop advanced fan blades representative of current engines
    - Achieve consensus on who will build the common engine
    - Collective agreement on where such an engine would be tested and what data should be collected
    - Vigorously pursue engine companies so that they become stake holders
- Build consensus on who should lead the development of a common, complete aircraft model
- Could the current surrogate aircraft developed by NASA be turned into such a model?

Backup slides

Windowing for Incomplete FWH Surface

D. Lockard and S. Woodruff, NASA Langley, unpublished

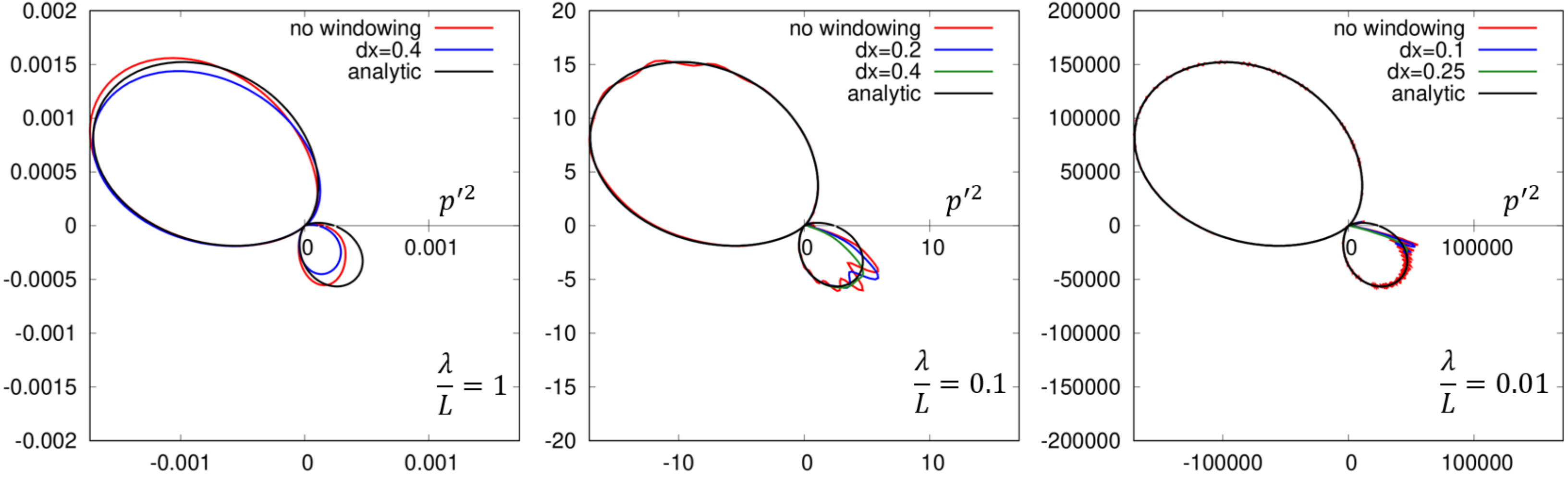


Dipole at center of FWH box

Directivity plots of radiated power from dipole, at circle of radius 10L in x-z plane.

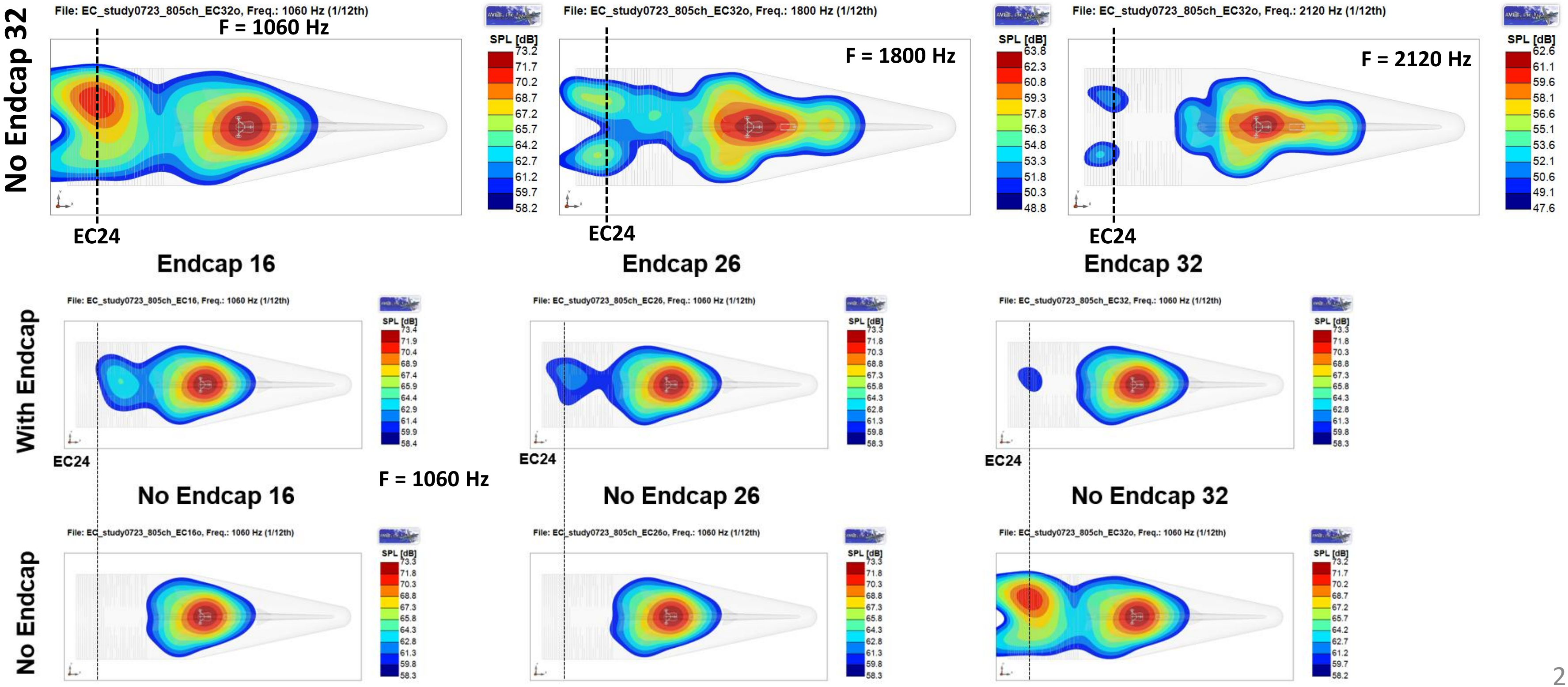
$M_\infty = 0.2$

Dipole axis in x-z plane, oriented 45^o to x axis.



End Cap (Wake) Effects – Current Effort

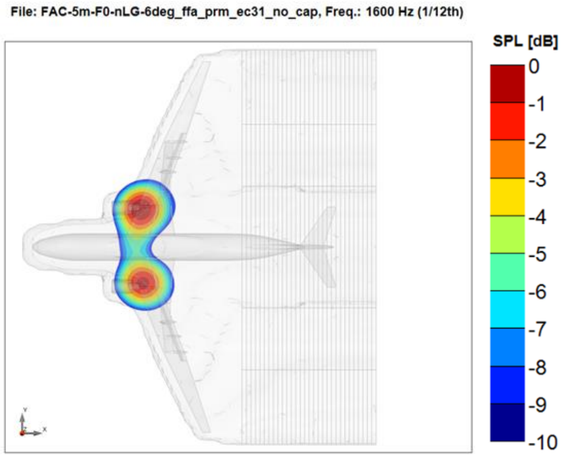
- **Spurious sources present at VR transition interfaces**



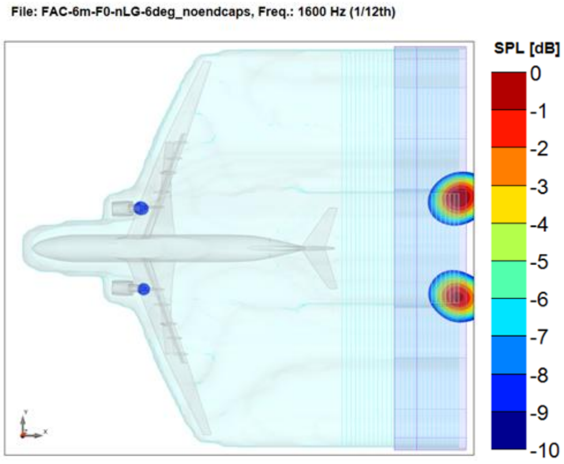
End Cap (Wake) Effects

- ❑ Transonic Truss Brace Wing (TTBW)
- ❑ Cruise configuration with LG retracted

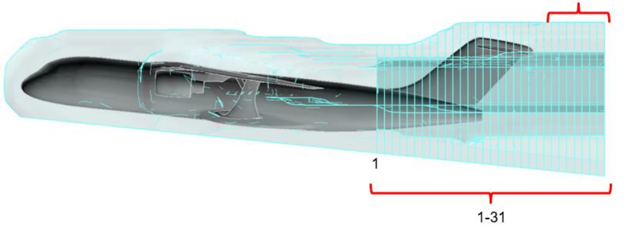
5m, CB, 1.6 kHz, No Endcaps



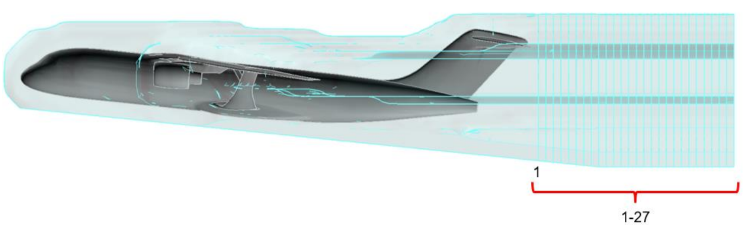
6m, CB, 1.6 kHz, No Endcaps

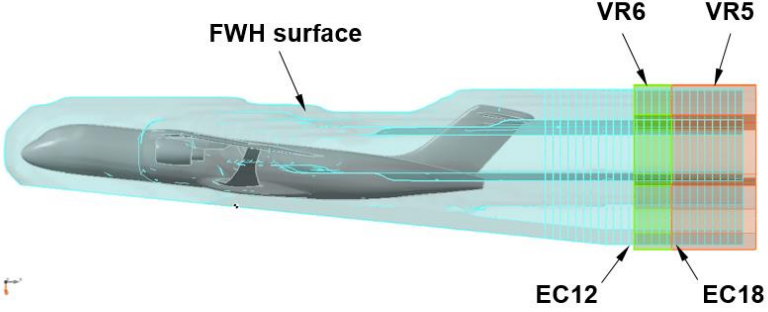


FWH Surface for Setup 5



FWH Surface for Setup 6

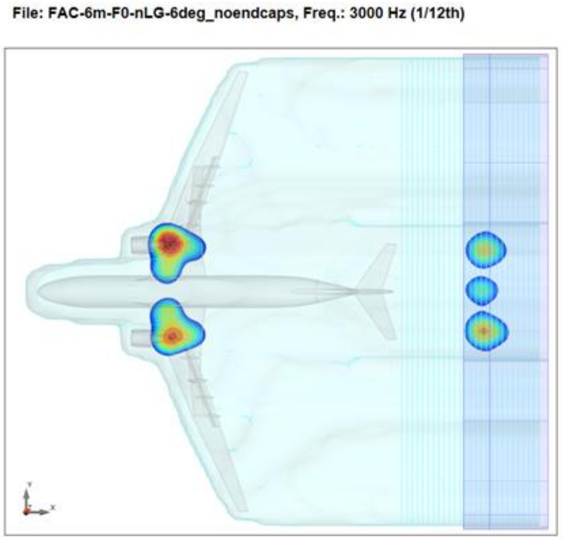




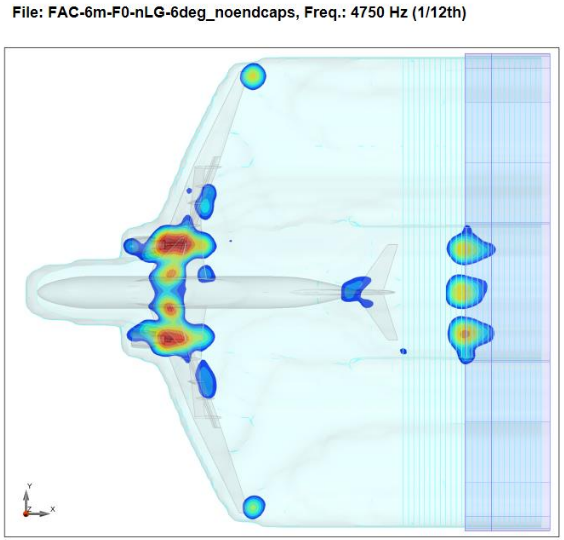
End Cap (Wake) Effects

- ❑ Transonic Truss Brace Wing (TTBW)
- ❑ Cruise configuration with LG retracted

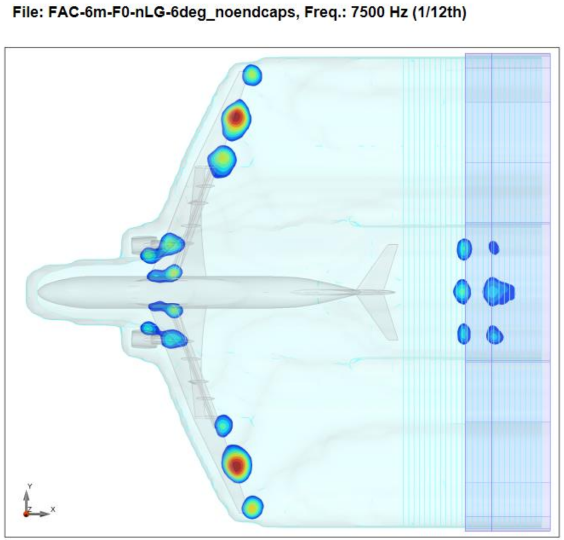
6m, CB, 3.0 kHz, 10dB cutoff



6m, CB, 4.75 kHz, 15 dB cutoff



6m, CB, 7.5 kHz, 15 dB cutoff



Mitigation of End Cap Effects: Original Formulation

- The first step is to define the cross-spectral matrix (CSM). Using the output for each FWH surface with a single endcap, element n, m of the sample-averaged $N \times N$ CSM is given by:

$$C_{n,m} = \frac{1}{TB} \sum_{w=1}^{T} \sum_{b=1}^{B} p_n(t_w, f_b) p_m^*(t_w, f_b)$$

- The expected value, $\mathrm{E}[x]$, of the sample-averaged CSM element is:

$$\mathrm{E}[C_{n,m}] = \frac{1}{TB} \sum_{w=1}^{T} \sum_{b=1}^{B} \mathrm{E}[p_n(t_w, f_b) p_m^*(t_w, f_b)]$$

$$= \mathrm{E}[p_n p_m^*] = \mathrm{E}[(q_n + u_n)(q_m + u_m)^*]$$

$$= \mathrm{E}[q_n q_m^*] + \mathrm{E}[q_n u_m^*] + \mathrm{E}[u_n q_m^*] + \mathrm{E}[u_n u_m^*]$$

- Assuming q_n and u_m are uncorrelated, $\mathrm{E}[q_n u_m^*] = 0$, this becomes:

$$\mathrm{E}[C_{n,m}] = \mathrm{E}[q_n q_m^*] + \mathrm{E}[u_n u_m^*] = s + \mathrm{E}[u_n u_m^*]$$

- Where the narrowband spectral power s is given by:

$$s = \mathrm{E}[q_n q_m^*] = \mathrm{Var}[q] \quad \text{(assume } \mathrm{E}[q] = 0)$$

- **This is the original formulation proposed by Dougherty with some minor notation changes.**

CB for Endcap Noise Removal, CB-ENR

- The conventional beamforming output can be rewritten as:

$$q_{CB} = \frac{1}{N^2}\hat{\boldsymbol{g}}'C\hat{\boldsymbol{g}} = \frac{1}{N^2}\hat{\boldsymbol{g}}'S\hat{\boldsymbol{g}} + \frac{1}{N^2}\hat{\boldsymbol{g}}'U\hat{\boldsymbol{g}}$$

- Where the uncorrelated noise contribution to the CSM is given by the matrix: $U = \mathrm{E}[u_i u_k^*]$
- Since the matrix S is Hermitian, manipulating and grouping terms it can be demonstrated that:

$$\hat{\boldsymbol{g}}'S\hat{\boldsymbol{g}} = \underbrace{N^2 aa^*}_{\text{Noise from “main” surface } (A)} \underbrace{+ 2N\Re\left(a\sum_{i}^{N} h_i^*\right)}_{\text{Correlated noise between main surface and intersurfaces}} \underbrace{+ 2N\Re\left(a\sum_{i}^{N} e_i^*\right)}_{\text{Correlated noise between main surface and endcaps}} \underbrace{\underbrace{+ \sum_{i}^{N} h_i h_i^*}_{\text{In diagonal}} \underbrace{+ \sum_{\substack{i,j\\ i\neq j}}^{N} h_i h_j^*}_{\text{Off-diagonal}}}_{\text{Noise from intersurfaces } (D_{ij})} \underbrace{+ 2N\Re\left(\sum_{i,j}^{N} h_i e_j^*\right)}_{\text{Correlated noise between main intersurfaces and endcaps}} \underbrace{\underbrace{+ \sum_{i}^{N} e_i e_i^*}_{\text{In diagonal}} \underbrace{+ \sum_{\substack{i,j\\ i\neq j}}^{N} e_i e_j^*}_{\text{Off-diagonal}}}_{\text{Noise from endcaps } (E_n)}$$

- In this equation, each term has been associated with the corresponding surfaces (main, endcap, or intersurface).
- Some elements were broken down into diagonal and off-diagonal elements for use/reference in upcoming slides.
- This equation clearly shows that the beamformed output contains correlated content between each of the surfaces (main, endcap, or intersurface).

Note: $\Re(x)$ is the real part of x

CB-ENR with Diagonal Removal

- When diagonal removal (DR) is used, we have:

$$q_{CBDR} = \frac{1}{N^2-N}\hat{\boldsymbol{g}}'\tilde{C}\hat{\boldsymbol{g}} = \frac{1}{N^2-N}\hat{\boldsymbol{g}}'\tilde{S}\hat{\boldsymbol{g}} + \frac{1}{N^2-N}\hat{\boldsymbol{g}}'\tilde{U}\hat{\boldsymbol{g}} \qquad \text{where: } \tilde{S} = S - \mathrm{diag}(S)$$

- As mentioned before, off-diagonal terms in U are negligible if enough averages are taken when computing C
- Again, since $\tilde{S}$ is Hermitian, manipulating and grouping terms it can be demonstrated that:

$$\hat{\boldsymbol{g}}'\tilde{S}\hat{\boldsymbol{g}} = \underbrace{(N^2-N)aa^*}_{\text{Noise from “main” surface } (A)} \underbrace{+\,2(N-1)\Re\left(a\sum_{i}^{N} h_i^*\right)}_{\text{Correlated noise between main surface and intersurfaces}} \underbrace{+\,2(N-1)\Re\left(a\sum_{i}^{N} e_i^*\right)}_{\text{Correlated noise between main surface and endcaps}} \underbrace{+\sum_{\substack{i,j\\ i\neq j}}^{N} h_i h_j^*}_{\text{Noise from intersurfaces } (D_{ij})} \underbrace{+\,2(N-1)\Re\left(\sum_{\substack{i,j\\ i\neq j}}^{N} h_i e_j^*\right)}_{\text{Correlated noise between main intersurfaces and endcaps}} \underbrace{+\sum_{\substack{i,j\\ i\neq j}}^{N} e_i e_j^*}_{\text{Noise from endcaps } (E_n)}$$

- Note that all terms/contributions shown in the previous slide are still present.
- Although the “weights” for each term seem different, keep in mind that all terms still need to be divided by $N^2 - N$.
- Therefore, the relative contribution from each term to the total output q_{CBDR} is still the same.

Note: $\Re(x)$ is the real part of x