

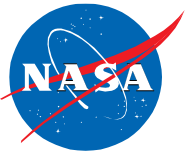
Acoustic Simulations of Two-stage Fans Behind a Supersonic Inlet

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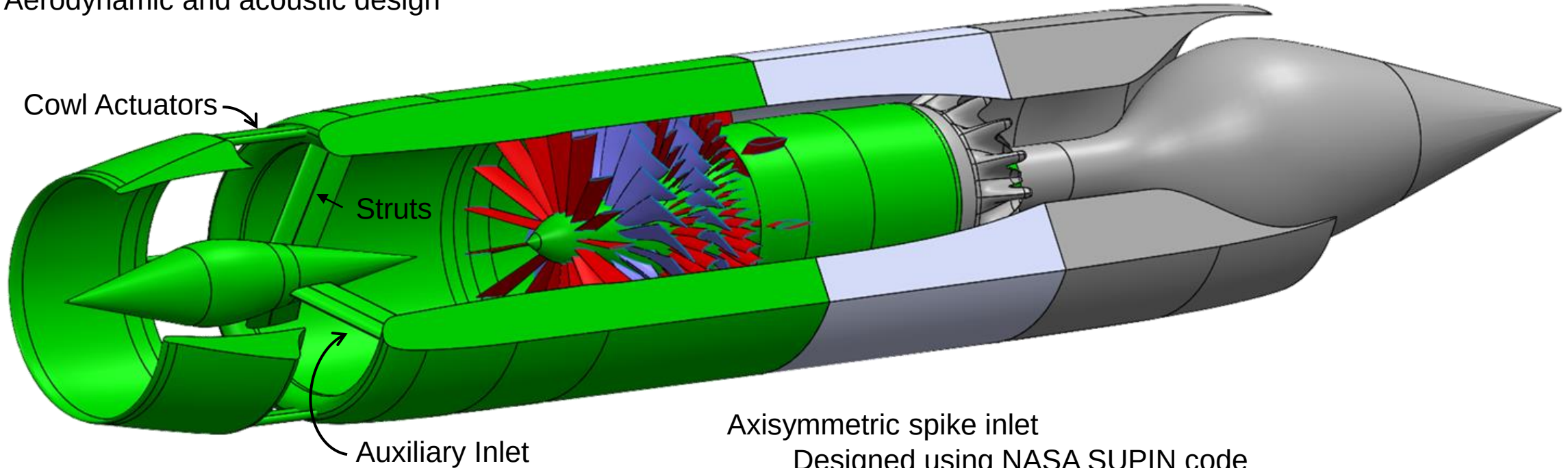
Supported by the NASA Commercial Supersonic Technology Project

Two-stage fan for commercial supersonic application



Fan system designed by GE Aviation under NASA contract

- Inlet guide vanes with two rotor/stator stages
- Aerodynamic and acoustic design



Auxiliary inlet required for off-design operation

- Mode switch around Mach 0.6
- Open for noise certification

Axisymmetric spike inlet

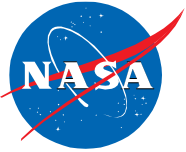
Designed using NASA SUPIN code

- (SUPersonic INlet design and analysis tool)

Aerodynamic cruise design augmented for subsonic operation:

- Upstream cowl split to create auxiliary inlet
- Struts to support center spike
- Actuators to support upstream cowl
- Gap between center spike and fan spinner

Fan stage and operating conditions



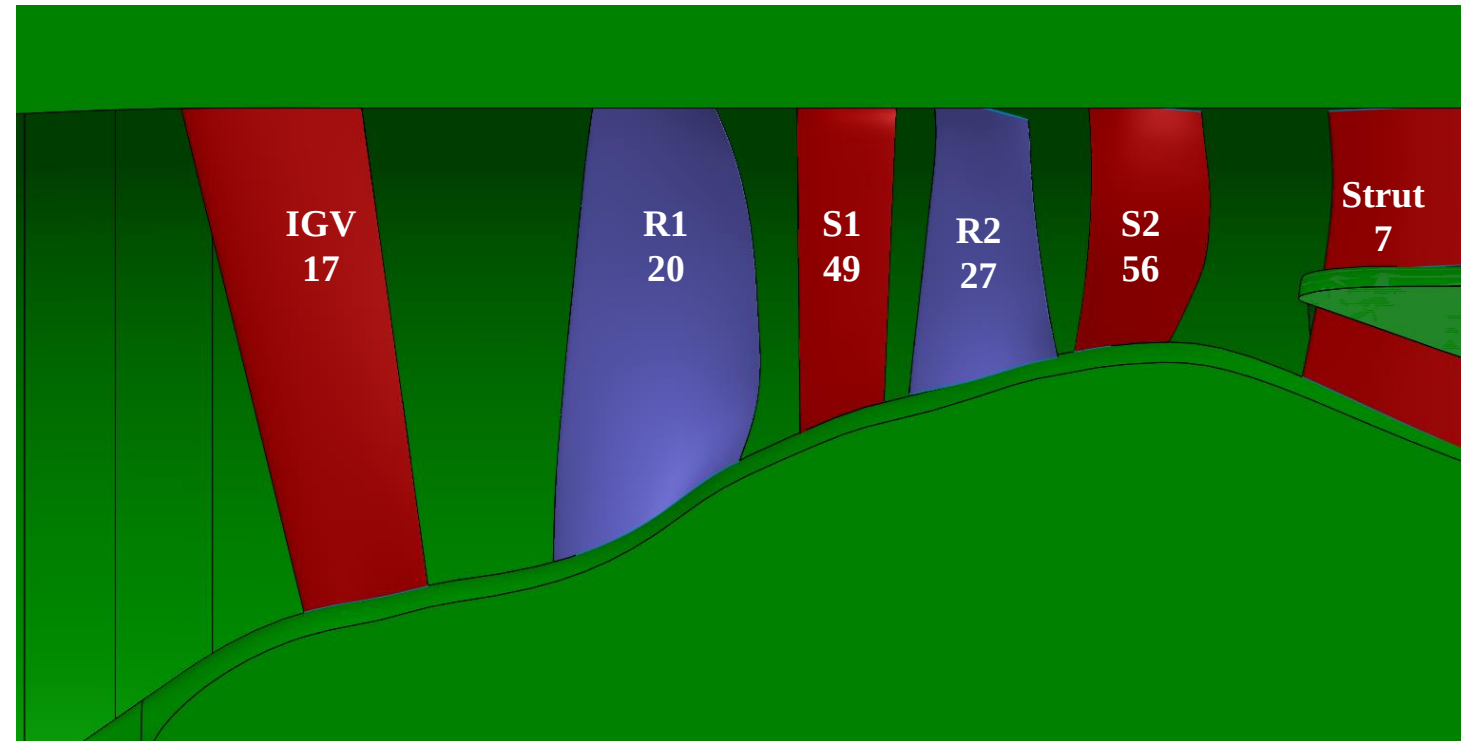
Contract delivery included fan design and main operating conditions

- Three noise rating points plus takeoff
- Fixed IGVs

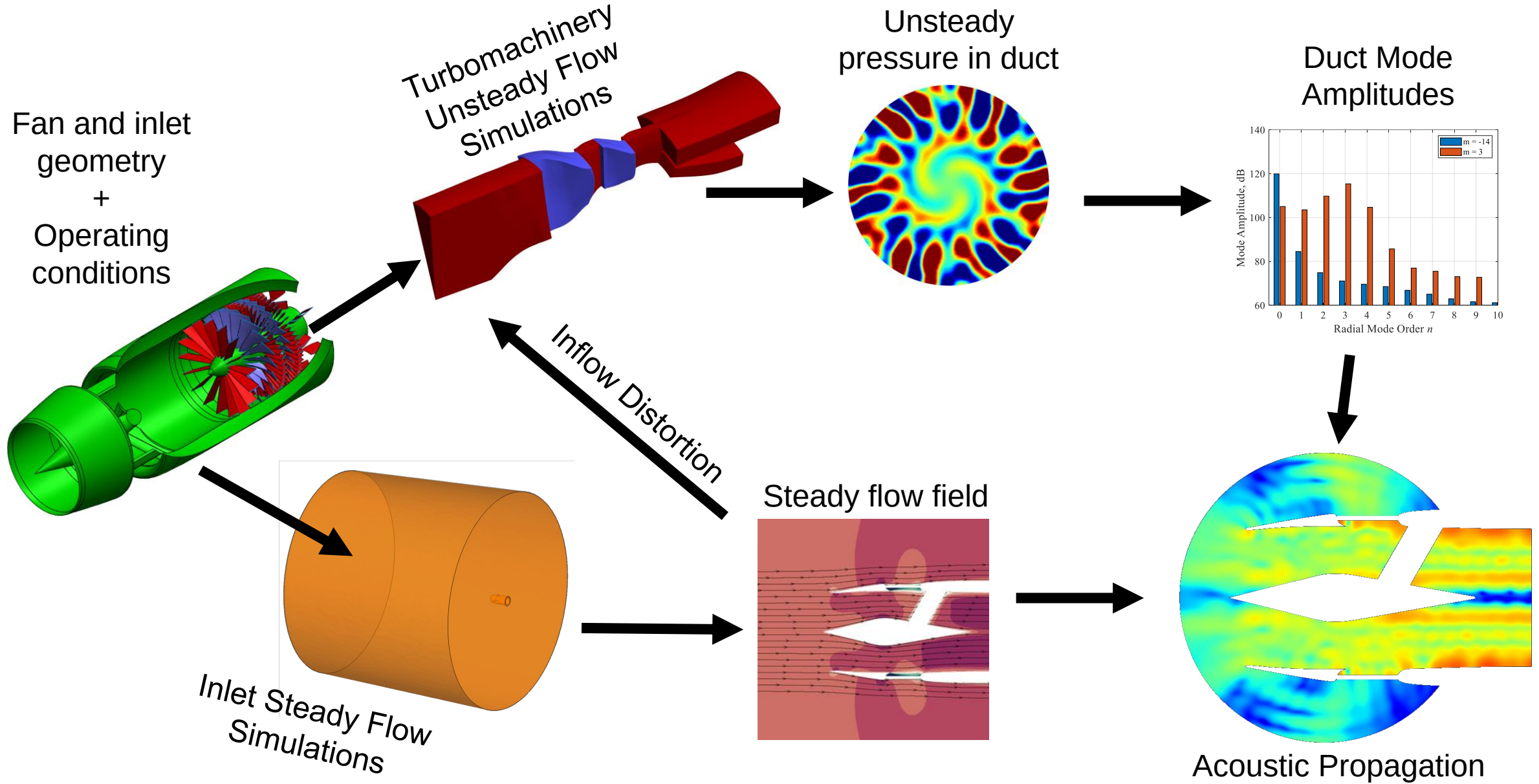
Jet noise varies considerably with operating condition

- Expected to be dominate at flyover and lateral
- Not considered in present report

	Approach	Flyover	Lateral	Takeoff
Flight Speed (m/s)	90	121	123	88
Fan Face Speed (m/s)	107	140	173	194
RPM	4533	5733	6672	7200
First Stage Fan BPF, Hz	1511	1911	2224	2400



Workflow from geometry to noise prediction

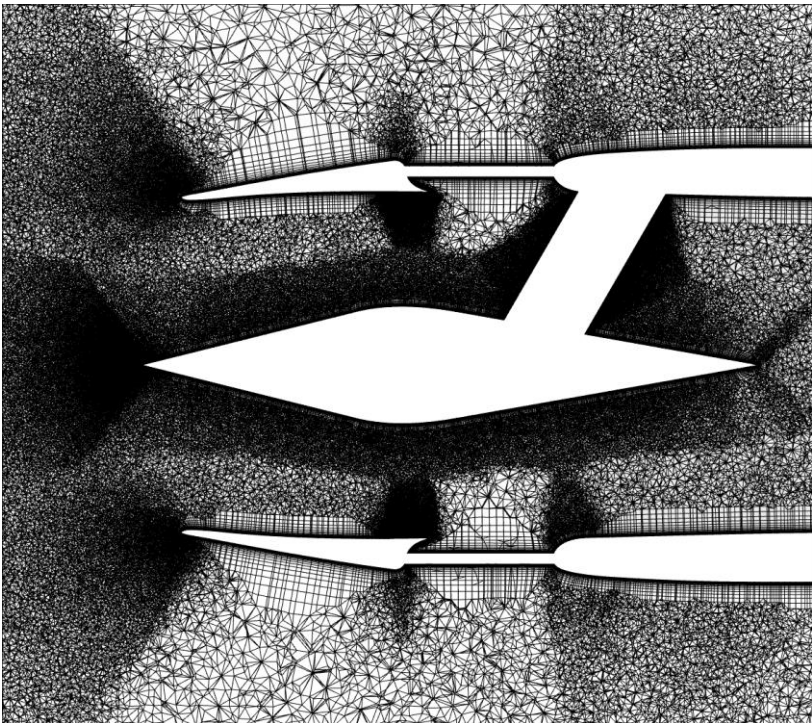
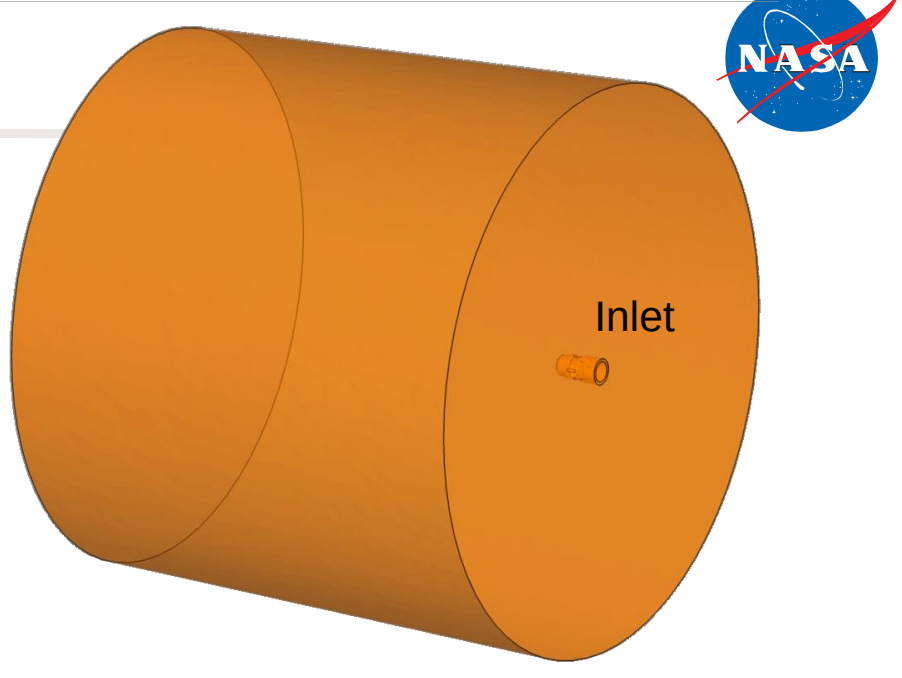


Flow Simulation

NASA code FUN3D used for inlet RANS

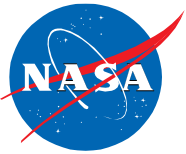
- Unstructured for complicated geometries
- Computationally efficient for many CPU cores
- 28.4 million nodes
- 20 hours on a 32 core workstation
- Menter SST two-equation

D. B. Stephens and A. Svetgoff, "Flow and Acoustics Simulations of a Supersonic Engine Inlet," AIAA/CEAS Aeroacoustics, Rome, Italy, 2024



<i>Run #</i>	<i>Condition</i>	<i>AoA (α), degrees</i>	<i>Flight Mach Number</i>	<i>Struts & Actuators</i>
1	Approach	5.20	0.261	Yes
2	Approach	0.00	0.261	Yes
3	Lateral	6.70	0.350	Yes
4	Lateral	0.00	0.350	Yes
5	Approach	0.00	0.261	No
6	Lateral	0.00	0.350	No
7	Flyover	6.94	0.360	Yes
8, 9, 10	Takeoff	0, 9, 12	0.250	Yes

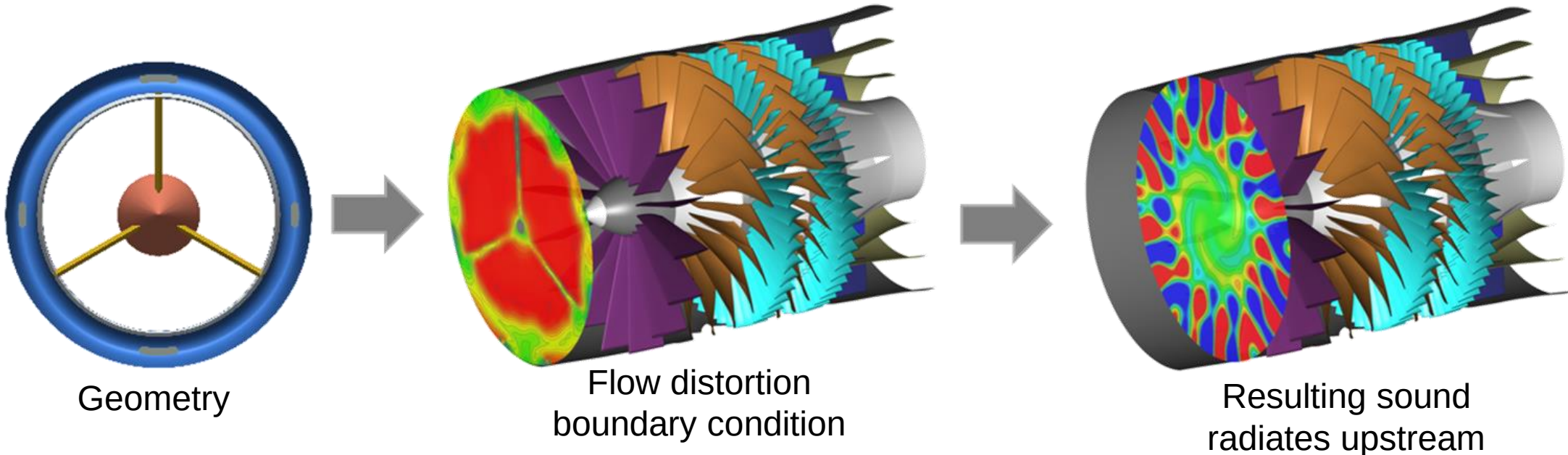
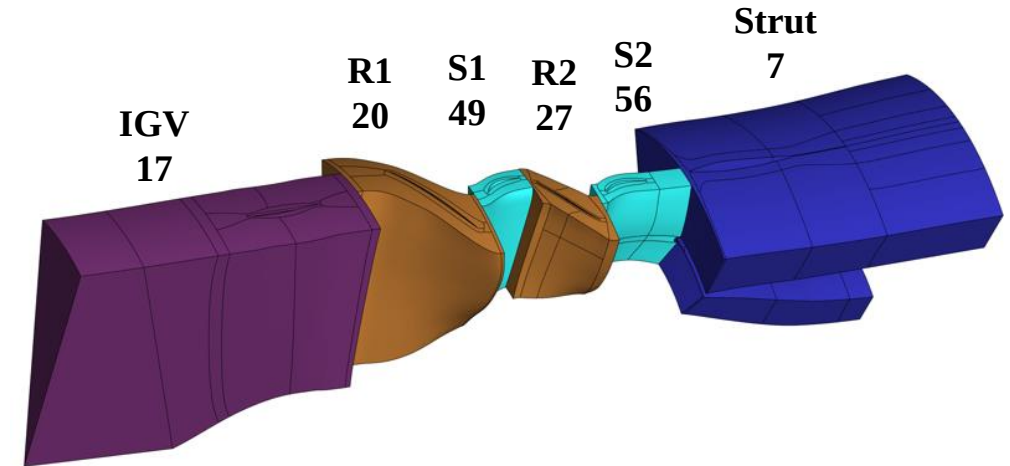
Turbomachinery Simulation



Commercial code FINE/Turbo

- Frequency domain URANS Non-linear Harmonic (NLH) method
 - Select blade passing frequency (BPF) and harmonics
- Simulate one passage per blade row, avoids cost of full wheel
 - 20 million vs 400+ million nodes
- Workstation class hardware rather than supercomputer
 - 32 cores, 76 hours for 4000 iterations

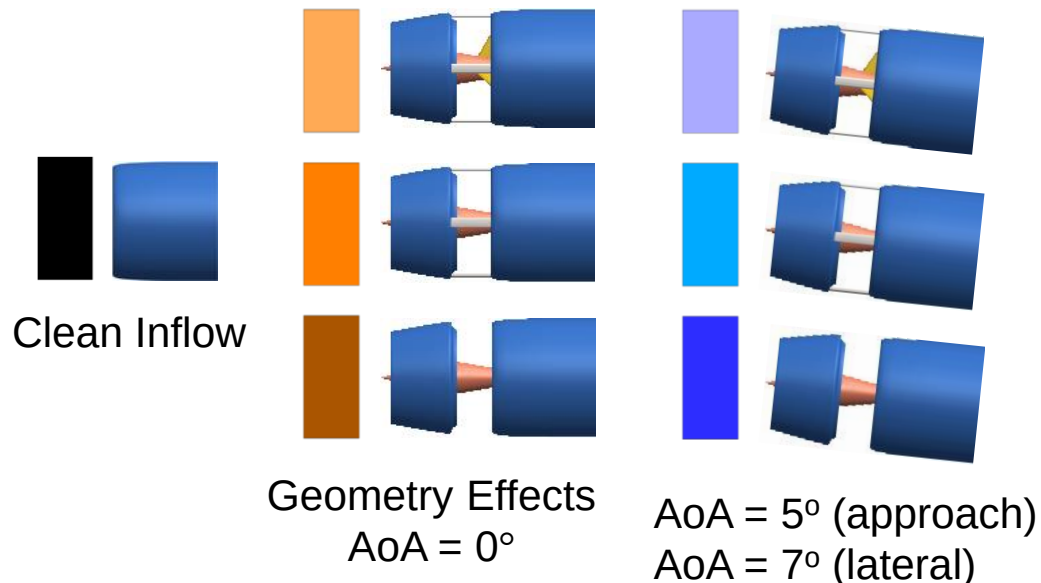
E. Envia, "Prediction of Inlet Tone Noise from Two-Stage Fans,"
AIAA/CEAS Aeroacoustics Conference, Rome, Italy, 2024.



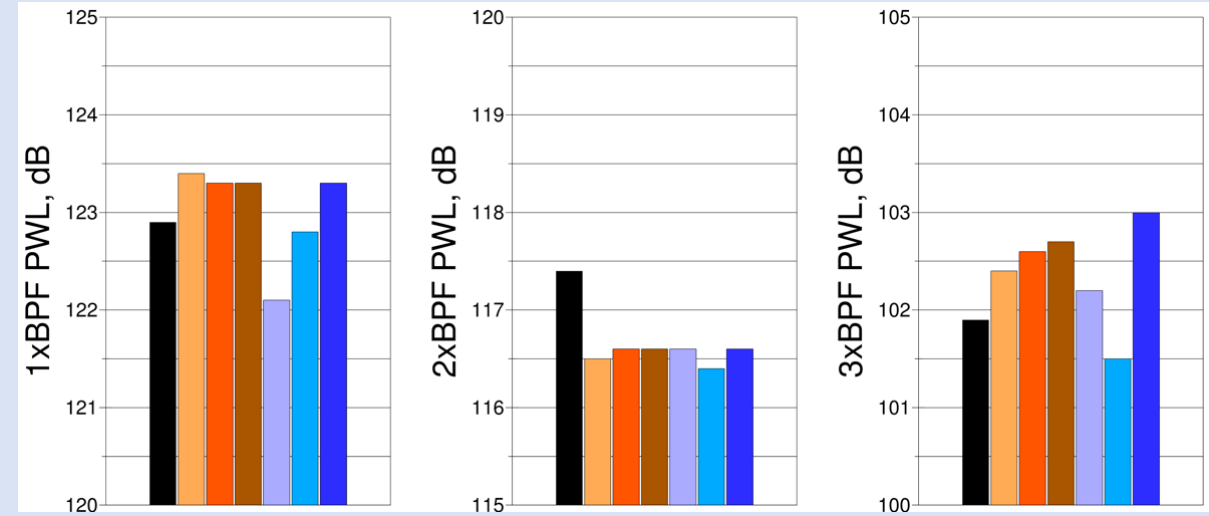
Turbomachinery Solution

Compare sound power for various inflow conditions

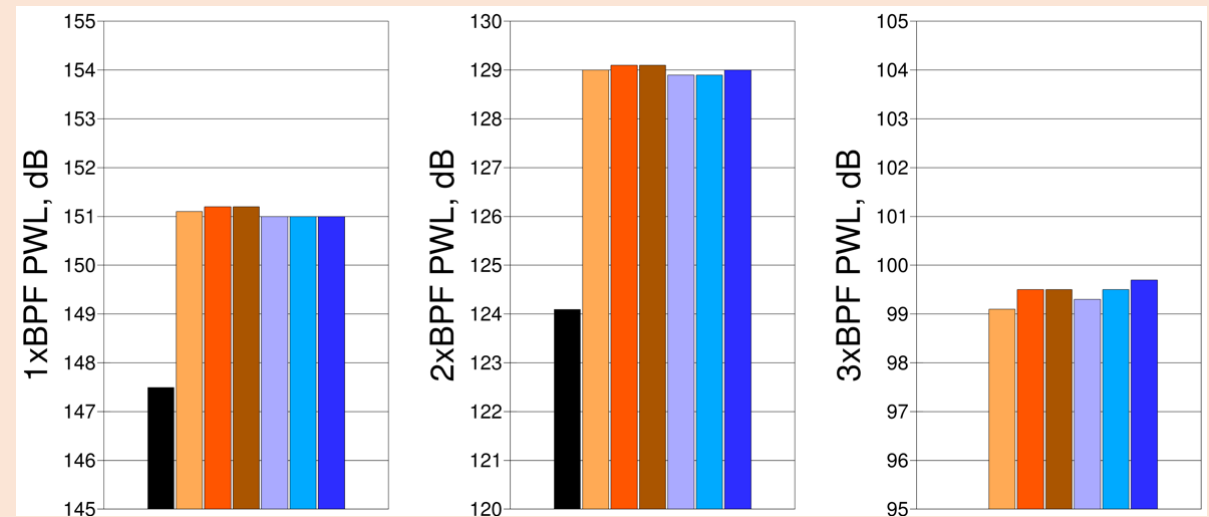
- Inlet geometry details
 - Auxiliary inlet causes 1-4 dB increase
 - Struts and actuators have smaller effect
- Angle of attack
 - Struts straighten flow
- Approach vs Lateral
 - Lateral 25 dB louder!
 - Jet noise expected to dominate



Approach



Lateral



Turbomachinery to Acoustic Simulation Interface

Tyler-Sofrin modes (circumferential & radial)

- Rotor/stator interaction (RSI) noise
- IGV wakes interacting with Rotor 1
- Potential field of Rotor 1 scattered by IGVs
 - Produces a sound field with spinning mode order m

$$m = n N_B - k N_V$$

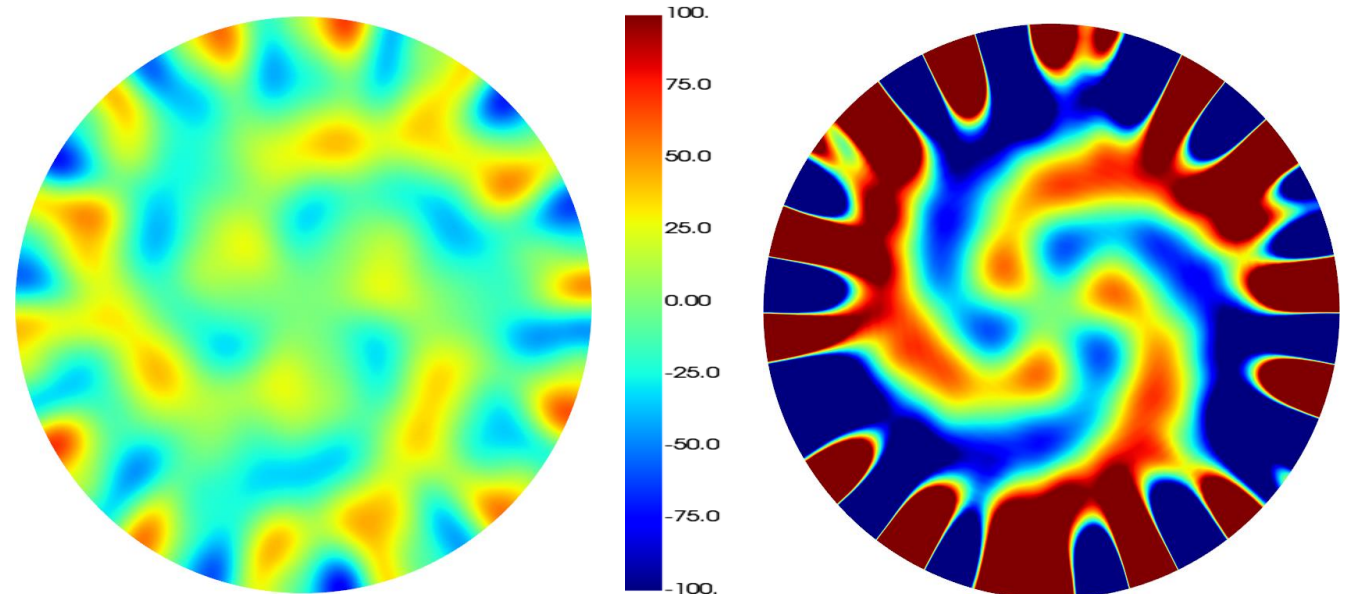
IGVs: $N_V=17$
Rotor 1: $N_B=20$

		Harmonic in static frame (n)		
		1xBPF	2xBPF	3xBPF
Harmonic in rotating frame (k)	k = 0	20	40	60
	k = 1	3	23	43
	k = 2	-14	6	26
	k = 3	-31	-11	9
	k = 4	-48	-28	-8

Approach

Pressure, Pa

Lateral



Acoustic Simulations in 2D

Commercial code Actran TM (turbomachinery)

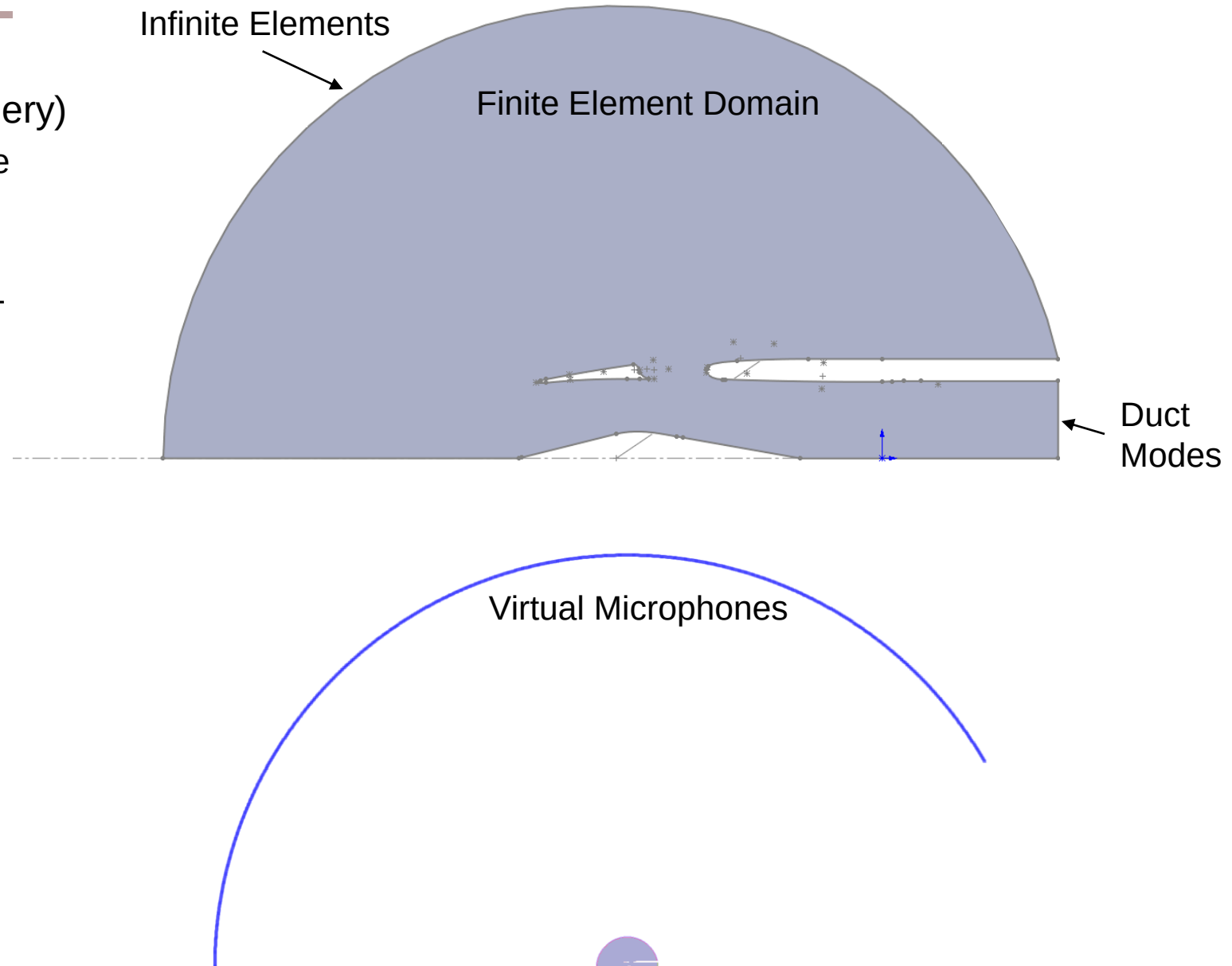
- Solves Möhring Analogy for convected wave equation
- Duct mode boundary condition for fan face
- Infinite elements for far field sound and non-reflecting boundary condition

2D Axisymmetric representation

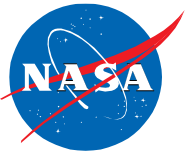
- Fast simulation time
- All relevant frequencies
- Allows spinning modes
 - Periodicity specified in advance

Assumptions

- Compressible potential flow
- Neglects spike struts
- Neglects cowl actuators
- Angle of attack



Results: Sound field examples

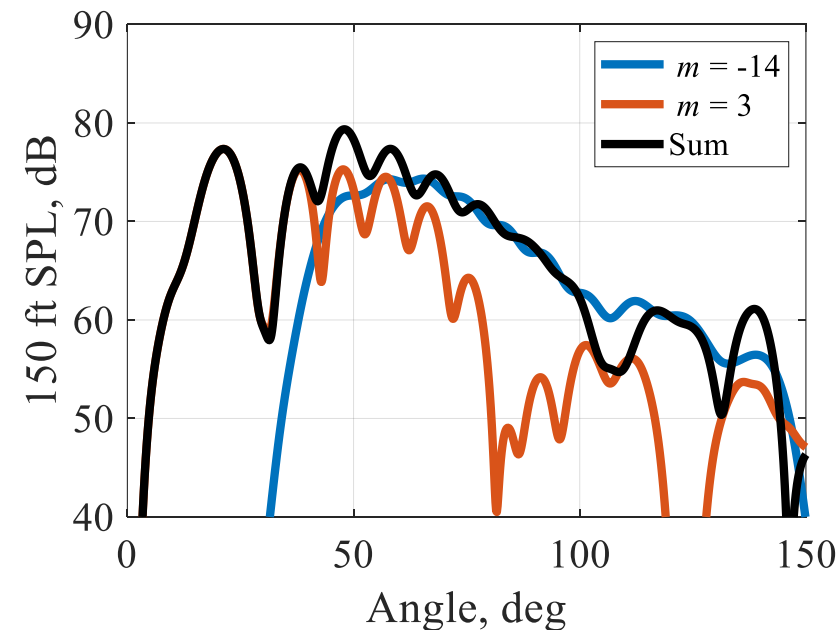
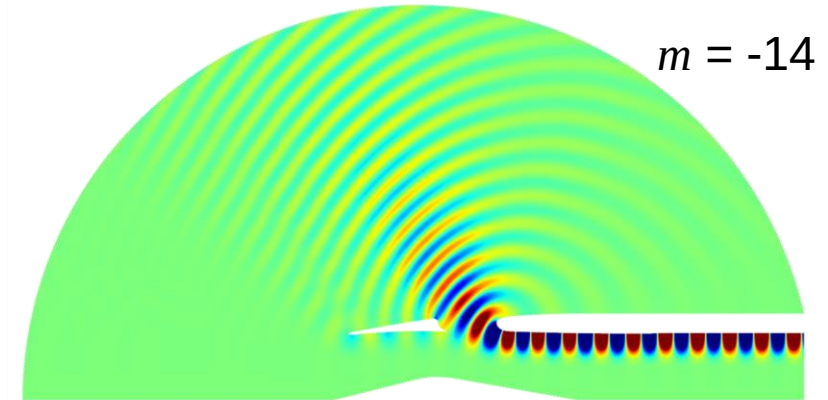
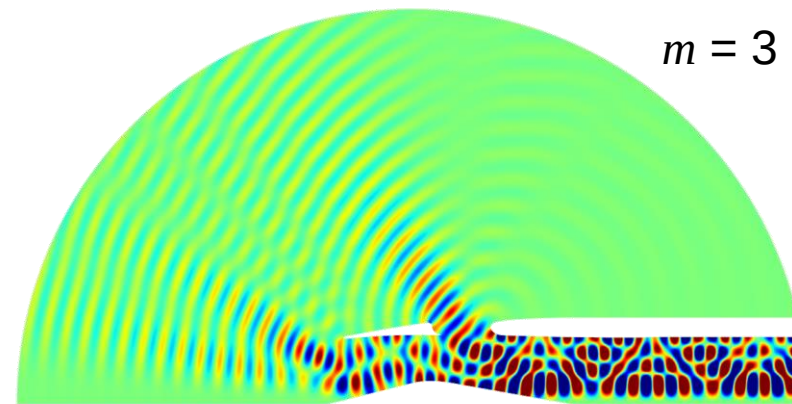


Approach conditions

- $m = -14$
 - One strong radial mode
 - High inclination
- $m = 3$
 - Five strong radial modes
 - Low inclination
- Radial modes injected with inter-mode phases preserved
- Cut-off modes are evanescent and decay

Solved separately in Actran TM

- Total sound field is the complex sum
- Mostly addition, some cancellation



Acoustic Simulations in 3D

Symmetric / antisymmetric solution method

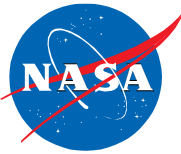
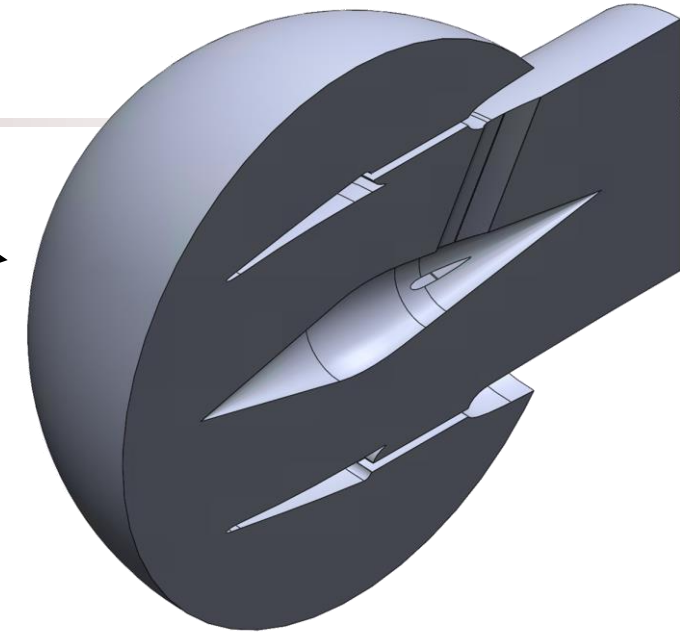
- Uses 1/2 domain geometry
- 1.22 m (48 inch) radius
- 2.9 million nodes
- 7 hours each on a 4x CPU, 500 GB RAM

Boundary conditions

- Flow field mapped from FUN3D
 - Infinite element boundary velocity
 - Fan face velocity
- Duct modes from FINE/Turbo
 - Table of complex amplitudes
 - $m = -14, m = 3$
 - Cut-off modes are evanescent and decay

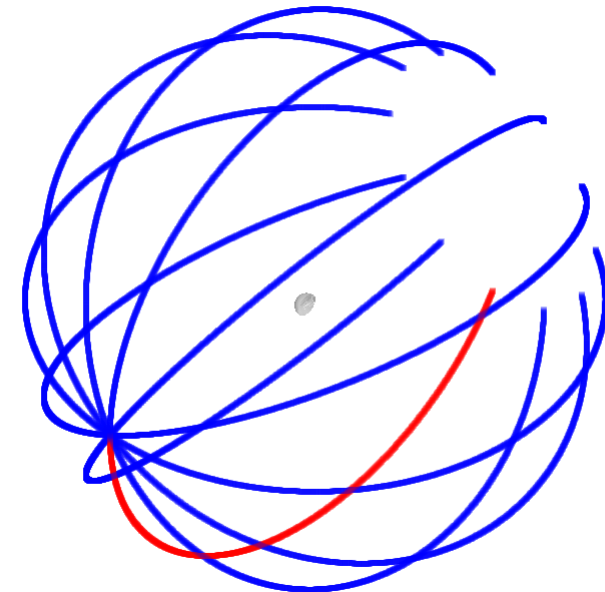
Far field sound collected on 12 arcs of field points

Infinite
Elements

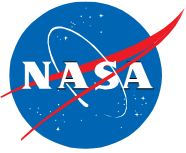


Duct
Modes

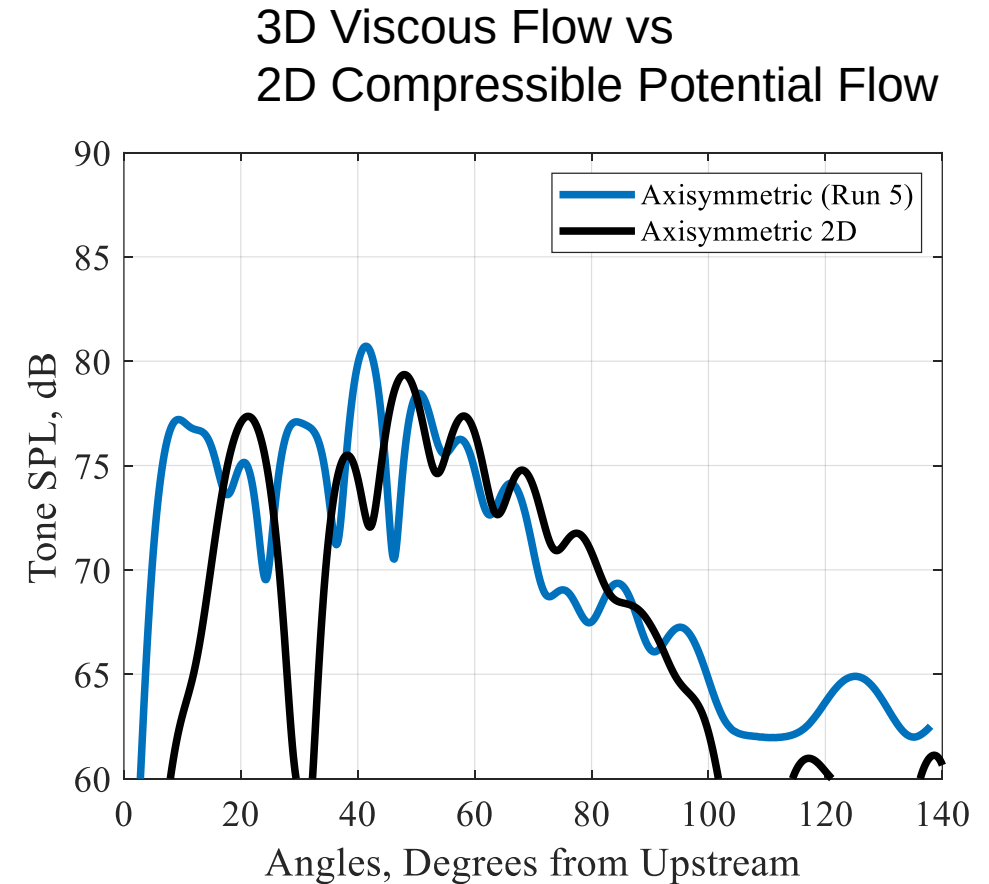
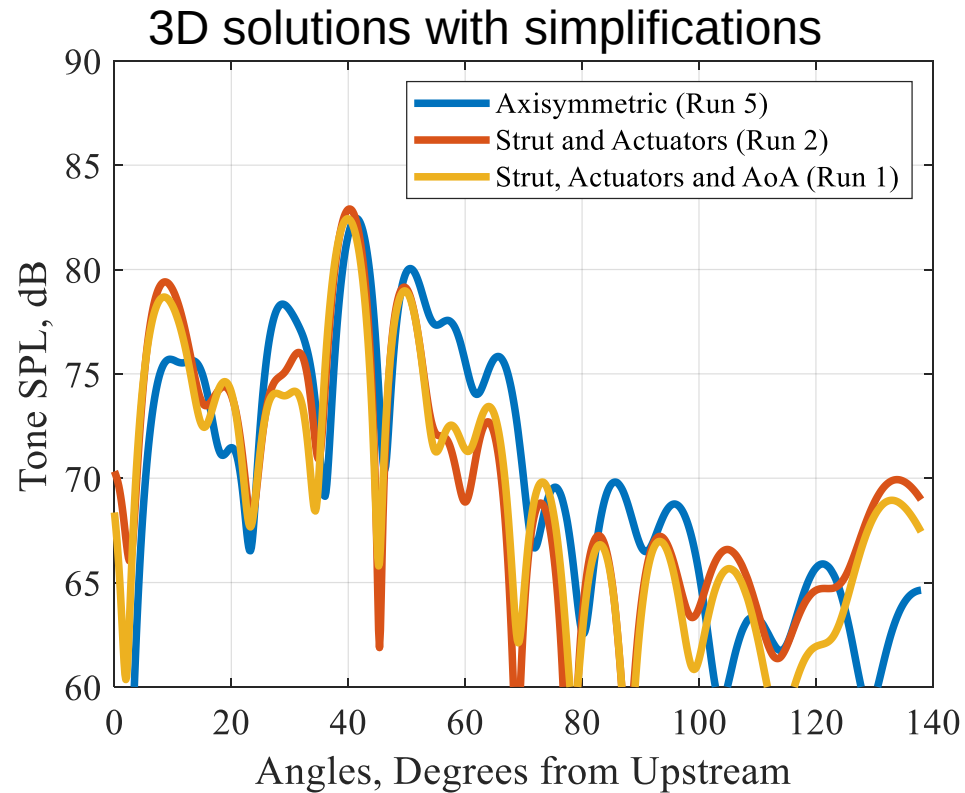
Virtual
Microphones



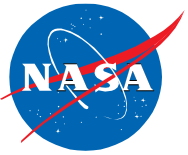
3D Far Field Results at Approach Conditions



Tone sound level projected to 46m (150') arc



Acoustic Inlet Liner



Long inlet allows considerable area for acoustic liner

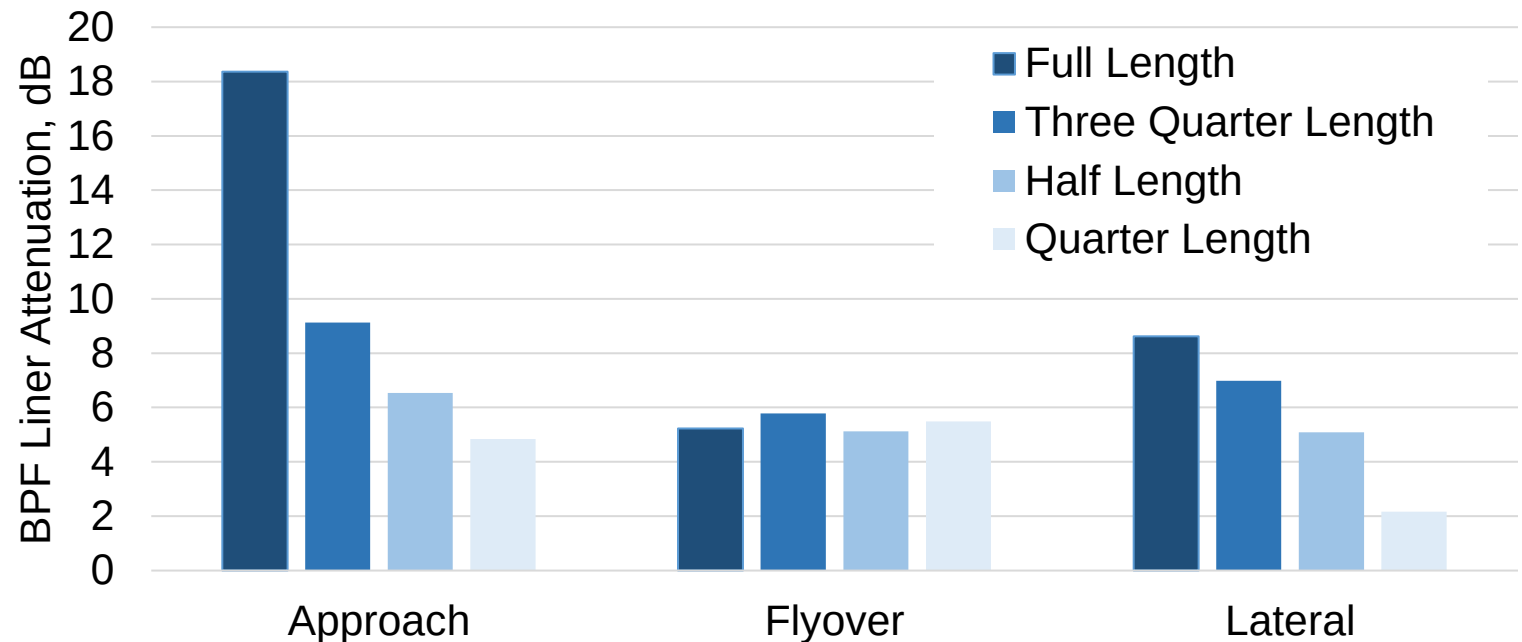
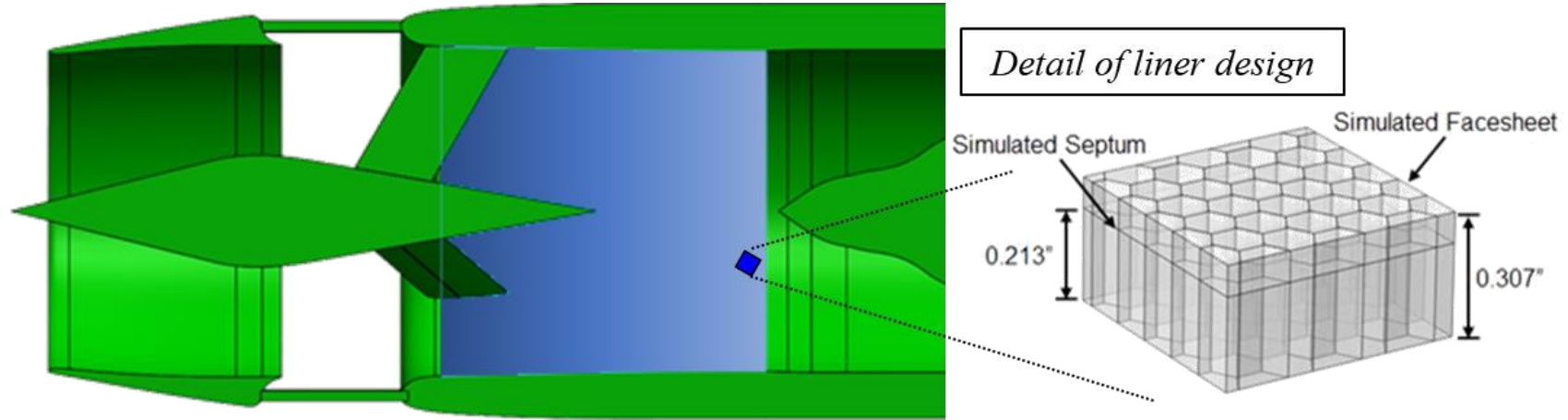
- L/D ~1 compared to 0.3-0.5 for modern subsonic inlets

Double degree of freedom liner

- Simulated in COMSOL to get complex impedance vs frequency
- Implemented in Actran TM

Non-monotonic response

- Longer length helps attenuate $m=3$
- Even a short liner reduces $m=-14$



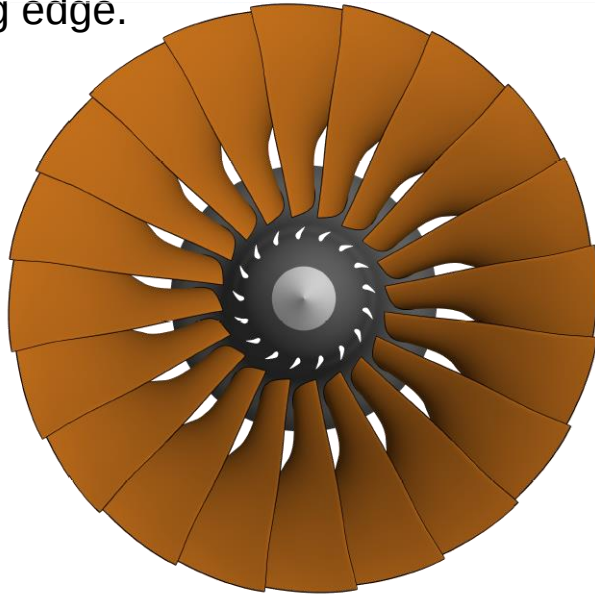
Engine Length Spacing Effect

More compact engine reduces weight

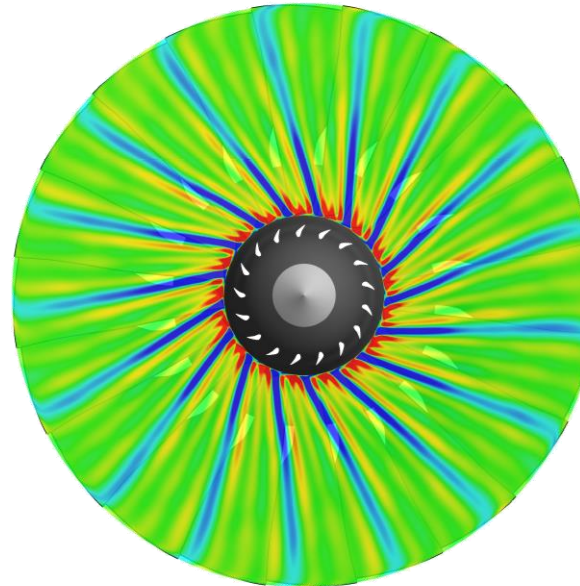
Want to quantify effect on noise for varied IGV-R1 spacing

Use URANS simulations to compute acoustic power levels at multiple LTO conditions for each spacing.

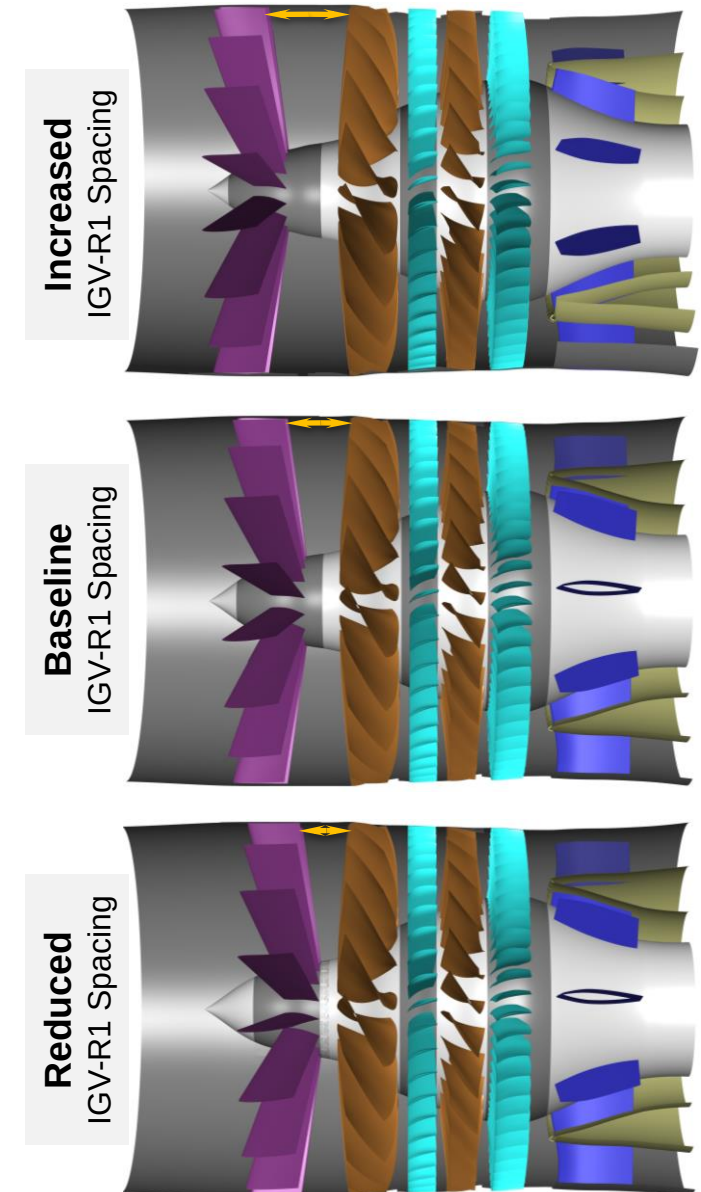
- Negligible changes in the aerodynamic performance of the fan were observed
- Baseline spacing has the minimum noise levels. Small spacing leads to the largest increases in the noise levels.
- The cause is traced to the behavior of the rotor upwash phase along the rotor leading edge.



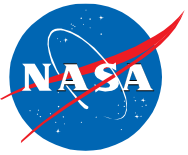
Rotor 1



IGV Wake Trace
(1x BPF Axial Velocity Perturbations at Rotor 1 LE)



Knowledge Gaps Identified and Conclusions

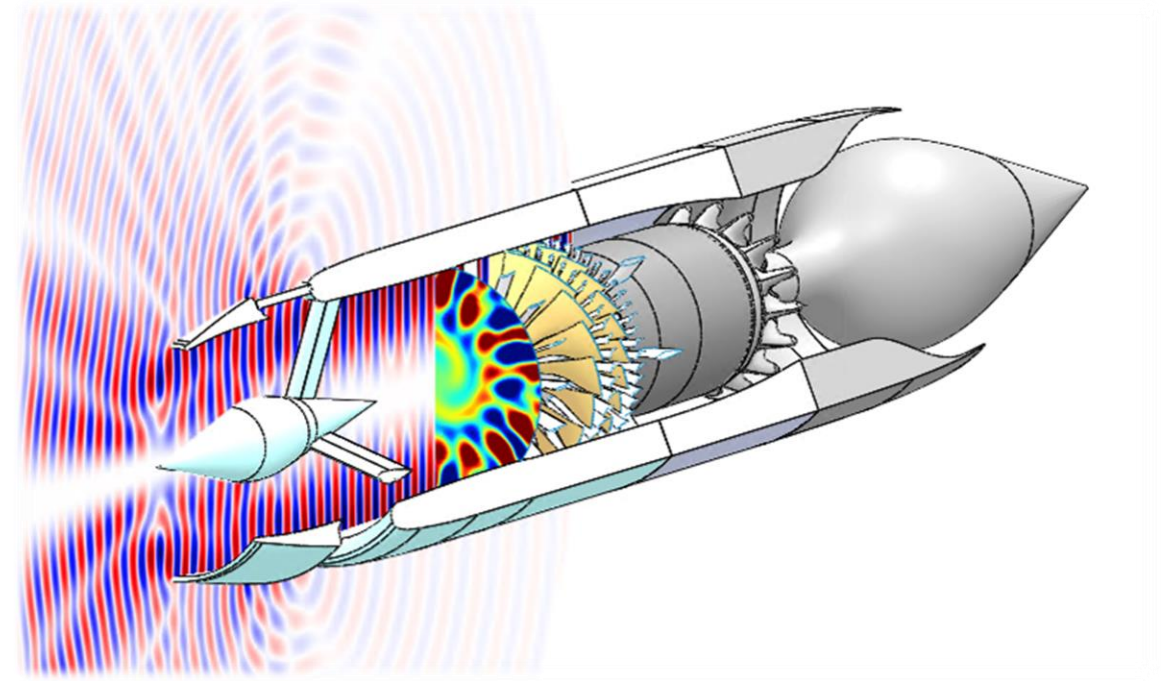


Areas for further investigation

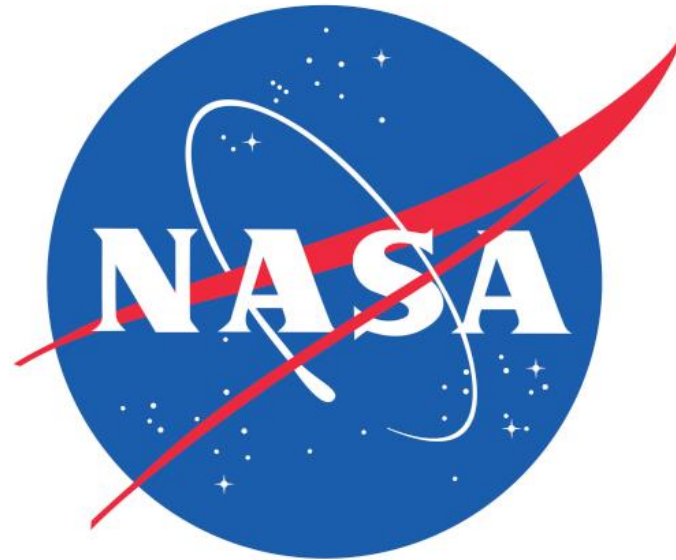
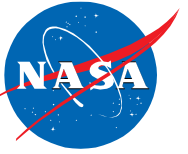
- Aft fan noise
- Broadband fan noise
- Noise shielding
- Acoustic liners in hot, high-speed flows

Conclusions

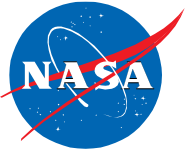
- Two-stage fan noise investigated using physics-based simulation
- Absolute levels predicted and trends identified
 - Long inlet mitigates effect of angle of attack
 - Noise due to IGV-R1 interaction dominates
 - R2 fan noise much weaker
 - Spacing and liners investigated
 - Findings incorporated into tools for system noise
 - See companion paper



Questions?



Abstract



NASA created, validated, and applied a high-fidelity simulation toolchain for noise prediction of a fan system for a near-term civilian supersonic aircraft engine. A high fidelity inlet and multistage fan design were acquired as the basis for physics-based computational studies. The overall tone noise was computed, which was used to help improve empirical models of fan inlet noise for system analysis purposes. Additional insights were gained during the study of the fan installation details and these are shared in this paper. Both overall amplitudes and variations due to design details should be of interest to engineers tasked with designing quiet fan systems for supersonic commercial aircraft. The outlook for high-fidelity simulations of aft fan noise and installation effects will also be discussed.