Computational AeroAcoustics for Fan Noise Prediction

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NASA Glenn Research Center

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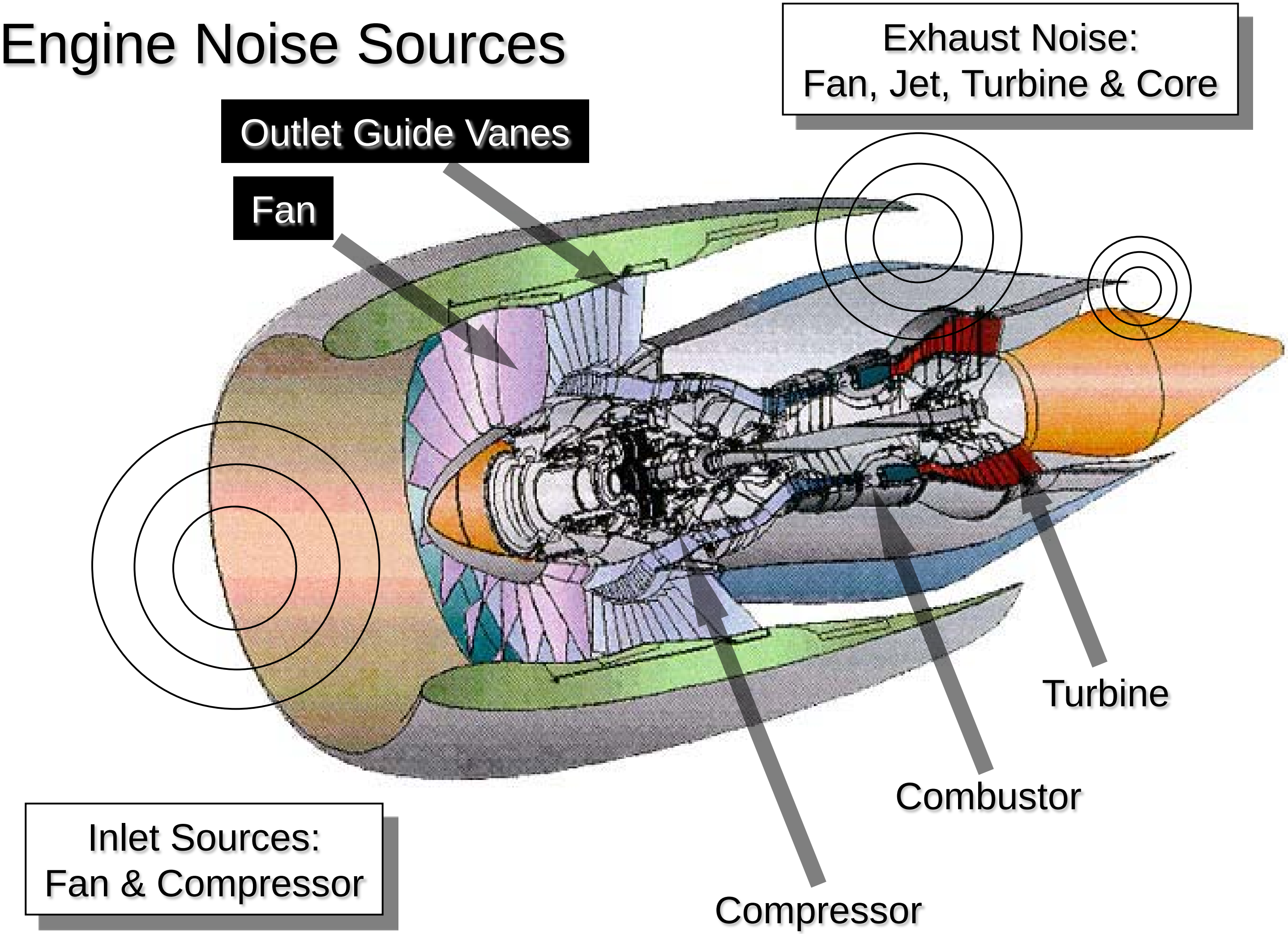
Indianapolis, IN
May 21st, 2002

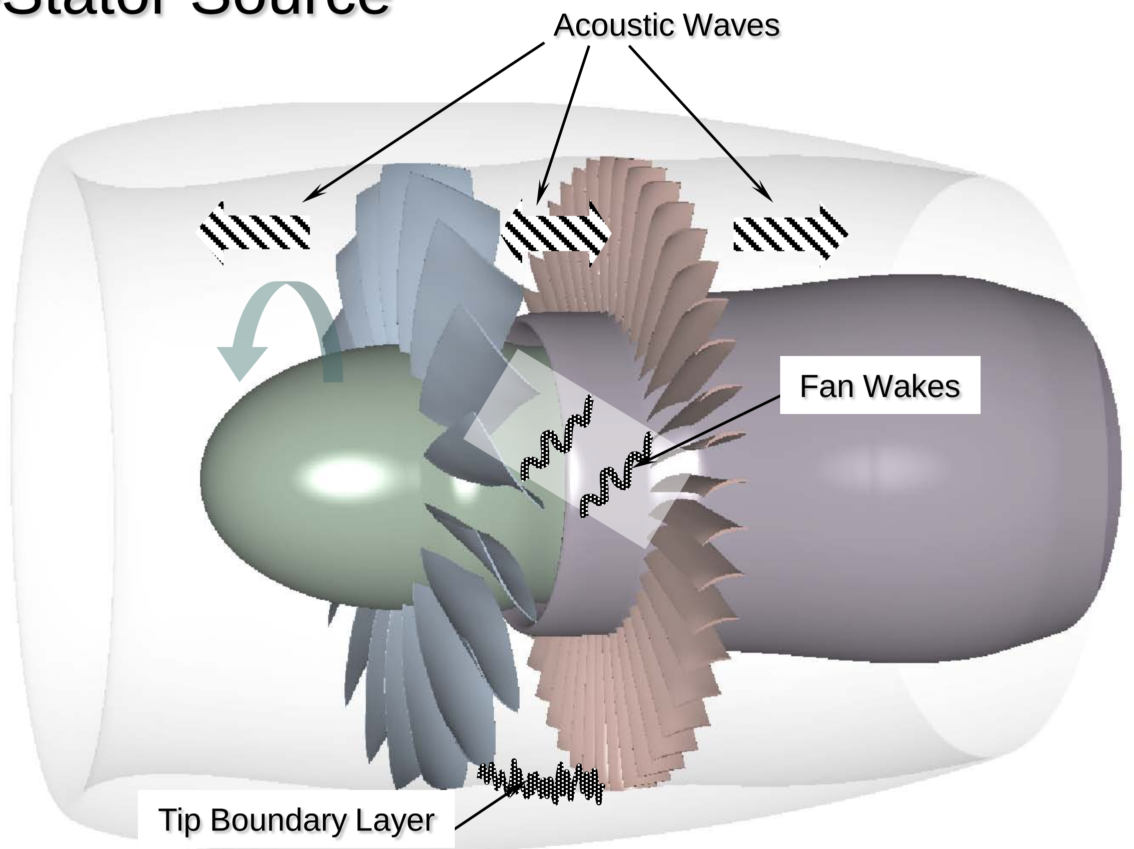
Application of
3D Linearized Euler Analysis
to Fan Noise Prediction

Ed Envia

❑ Engine Noise Sources

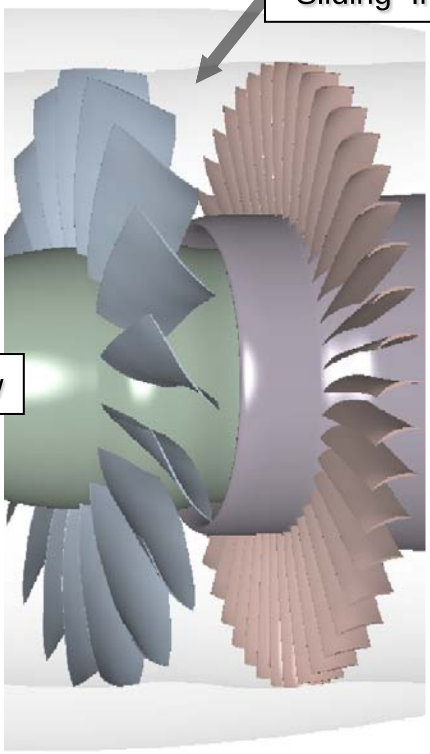


❑ Rotor-Stator Source

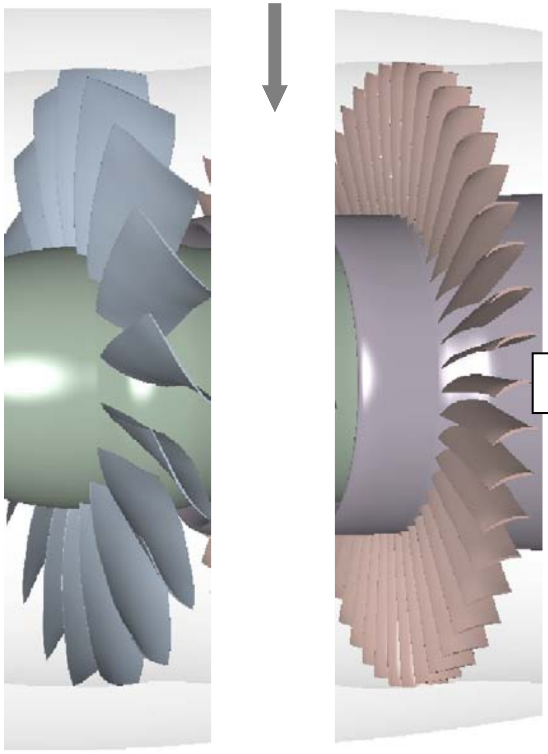


Rotor-Stator Interaction Noise
Tonal & Broadband

❑ Modeling Strategies



Coupled Blade-Row Computation



Isolated Blade-Row Computations

❑ Some of the Technical Issues

❖ Coupled Blade Row Strategy (Navier-Stokes)

- Blade/Vane Ratio Problem (Multiple-Passage Domains)
- Information Transfer Across the Sliding Interface
- Turbulence Modeling
- Grid Issues (Structured v. Unstructured, Topology, Resolution)
- Time Accuracy
- …

❖ Single Blade Row Strategy (N-S for Rotor, Euler for Stator)

- Swirling Inflow/Outflow Type Non-Reflecting Boundary Conditions
- Iterative Blade-Row Coupling ?
- Grid Issues
- Time Accuracy / Frequency Resolution
- …

❖ Stringent Computational Accuracy

- Acoustic Perturbations ~0.2% of Background Flow (140 dB = 0.03 psi)

❑ LINFLUX Tone Noise Prediction Results

- ❖ Wind Tunnel Test Data
  - ➢ Realistic Configurations
  - ➢ Flow and Acoustic Data

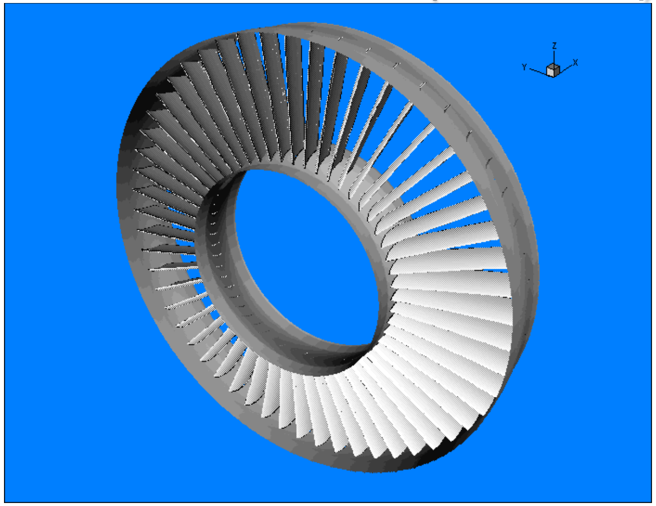
SDT Fan

ADP Fan 1

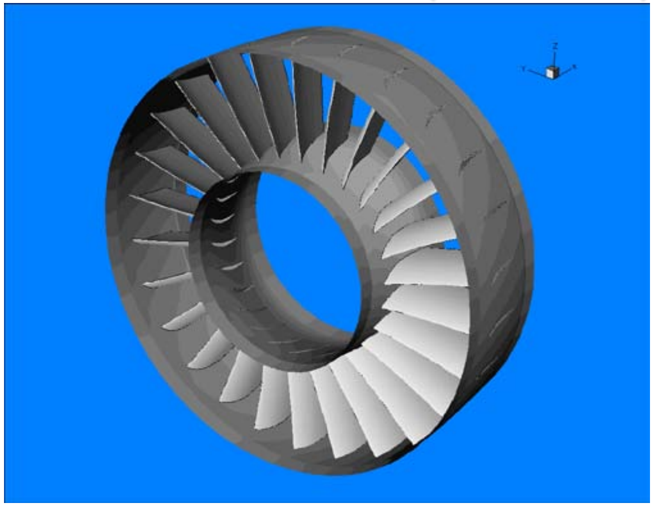
Data-Theory Comparisons
SDT Fan OGVs (3)

Tip Speed: 7808 rpm (Approach)
Frequency: 1xBPF & 2xBPF

SDT Cut-Off Stator (54-Vanes)



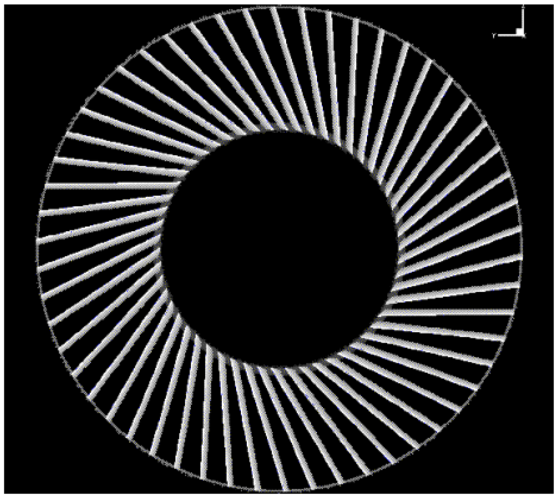
SDT Cut-On Stator (26-Vanes)

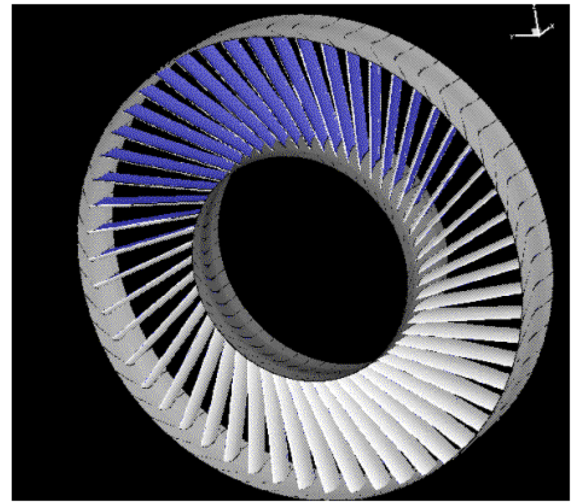


AFT Tone Power Levels: Predictions (Black), Data (Red)

Cut-Off Stator (2xBPF)			Cut-On Stator (1xBPF)		
Mode: (m,n)	PWL (dB)		Mode: (m,n)	PWL (dB)	
(-10,0)	113	114	(-4,0)	124	127
(-10,1)	100	100	(-4,1)	120	123
(-10,2)	101	106			
(-10,3)	102	101			
Total	114	115	Total	125	128

54-Vane Configuration: Leaned OGV (Straight)





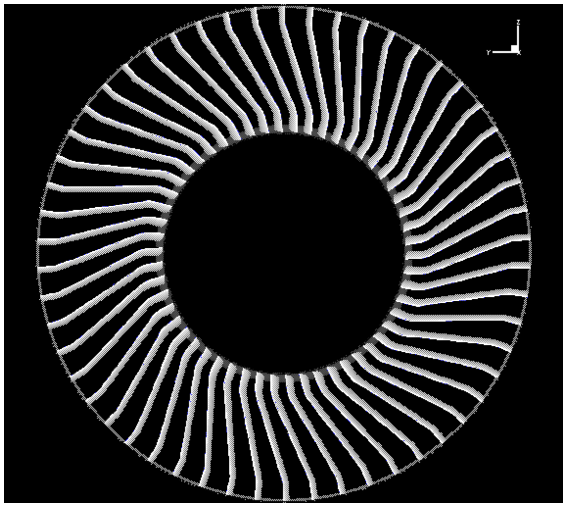
❑ Synopsis

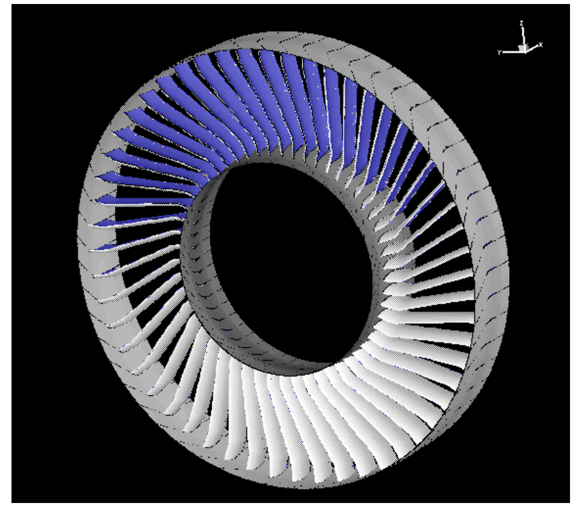
- Converged TURBO and LINFLUX Solutions (Poor Quality Meanflow, “Separated” at the Hub)
- Mixed Noise Reduction Benefits Predicted at 2xBPF (w.r.t. Radial SPLs & PWLs)

m,n	***SPL***		***PWL***	
(-10,0)	***118***	***111***	***112***	***105***
(-10,1)	***106***	***116***	***100***	***109***
Total	***118***	***117***	***112***	***111***

Black: Radial OGV (Theory).
Blue: Straight Lean OGV (Theory)

54-Vane Configuration: Leaned OGV (Composite)





- Synopsis
  - Converged TURBO and LINFLUX Solutions (Meanflow Solution Could be Improved Further)
  - Sizable Noise Reduction Benefits Predicted at 2xBPF (w.r.t. Radial SPLs & PWLs)

m,n	*SPL*	*PWL*
(-10,0)	*118 111*	*112 105*
(-10,1)	*106 105*	*100 98*
Total	*118 112*	*112 106*

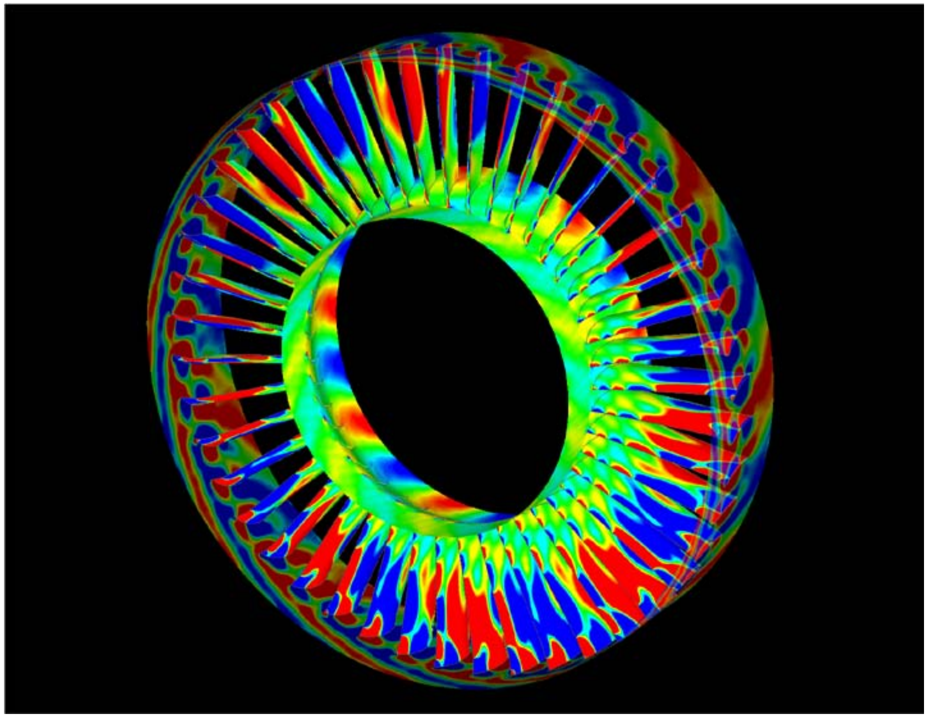
Black: Radial OGV (Theory)
Blue: Composite Lean (Theory)

Data-Theory Comparisons
ADP Fan 1 OGV

Tip Speed: 8750 rpm (Takeoff)
Frequency: 2xBPF

❑ Mode Power Levels

- Highly Converged TURBO and LINFLUX Solutions
- Excellent Data-Theory Comparisons

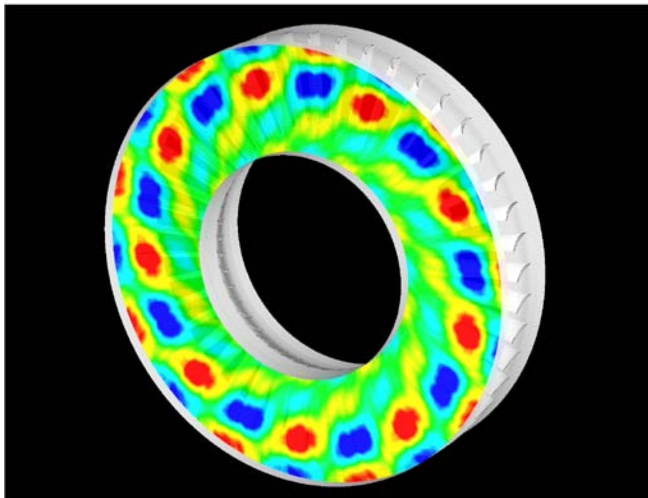


Predictions (Black), Data (Red)

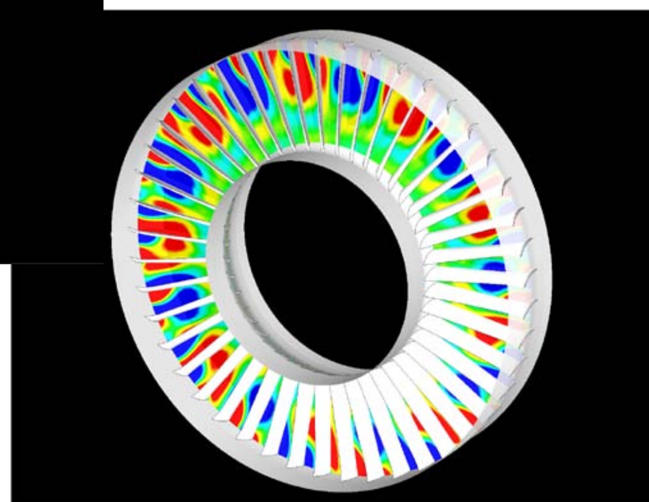
Cut-Off Stator (2xBPF)		
Mode: (m,n)	***PWL (dB)***	
(-9,0)	*122*	*122*
(-9,1)	*121*	*121*
(-9,2)	*119*	*119*
(-9,3)	*111*	*110*
Total	*126*	*126*

❑ Mode r.m.s. Pressure Levels

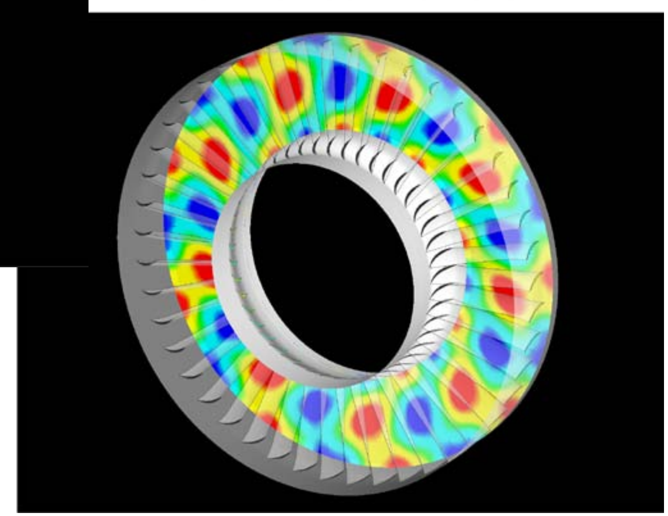
Upstream of OGV



Mid-Chord



Downstream of OGV



Conclusions & Issues

- Need a robust mean flow solution for reliable LINFLUX results.
- Inviscid mean flow calculations are problematic for unconventional geometries.
- Do linearized Navier-Stokes methods offer any advantages?
- If so, can one do “selective” linearization?

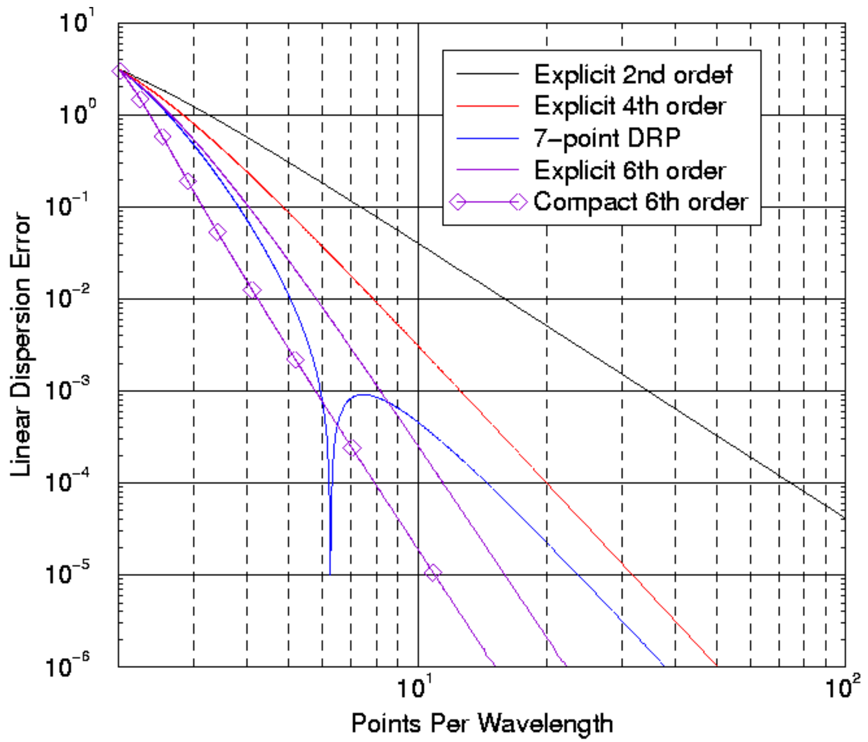
Development of a High-Accuracy Finite-Difference, Time-Domain Fan Noise Prediction Code

Ray Hixon
R.M. Nallasamy
Scott D. Sawyer
Rodger W. Dyson
Danielle Koch

NASA GRC – May 21st, 2002

Why High-Order Differencing?

- In an unsteady problem, waves of various types must be propagated.
- The errors in the numerical spatial derivatives affect the wave propagation speed.
- High-order schemes allow fewer points per wavelength to be used.



Governing Equations

- The code is designed to solve the non-linear Euler or Navier-Stokes equations in 2D or 3D.
- In Navier-Stokes mode, the code is designed to be either a DNS solver (no turbulence model), a LES solver (constant-coefficient Smagorinsky subgrid model), or an unsteady RANS solver (with a k-ε turbulence model).

Code Structure

- The code solves the flow equations in chain rule curvilinear form (non-conservative).
- The code is written in Fortran 90 with MPI message passing for computational efficiency, and is designed to be fully portable between computer architectures and operating systems (testing is currently performed on SGI, Linux, and Mac OSX).
- The code uses structured multi-block grids.

Solution Procedure

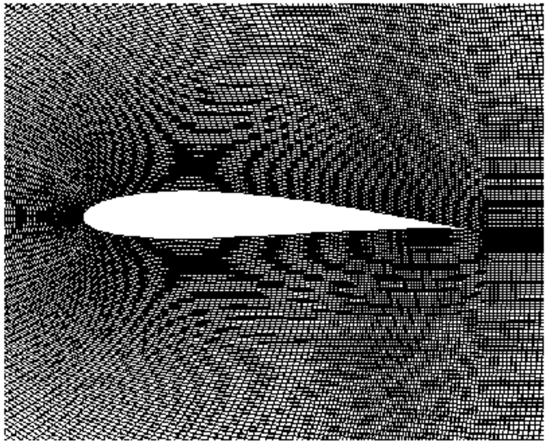
- The code uses finite-differences to obtain the spatial derivatives (explicit 2nd order, explicit 6th order, 7-point DRP, or compact 6th order derivatives are implemented).
- The code marches explicitly in time, using an optimized Runge-Kutta scheme. In future, a fourth-order Adams-Bashforth scheme will be implemented.
- The code currently uses constant-coefficient 10th order artificial dissipation.

Assessment

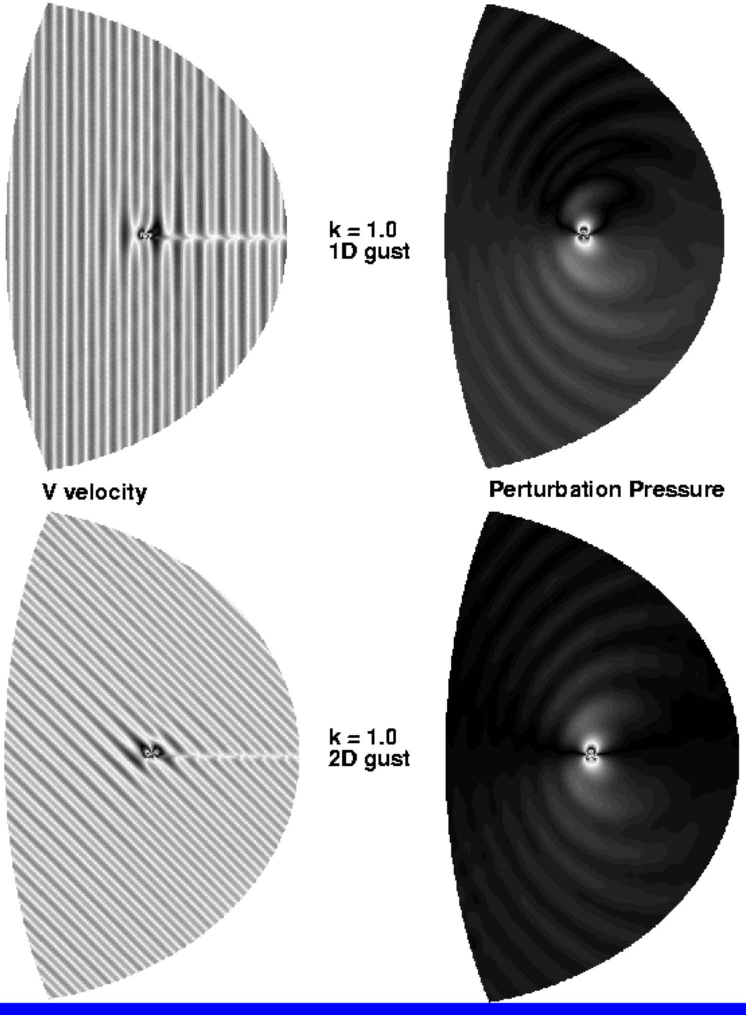
- In previous work with an earlier version of this code, the benchmark problem of the gust response of a Joukowski airfoil was solved.
- This test case evaluated the ability of the code to capture the effects of changing the airfoil geometry, the gust geometry, and the gust reduced frequency.

Curvilinear Grid Performance Test: Gust Response of a Joukowski Airfoil

Closeup of Cambered Airfoil Grid



In this benchmark CAA problem, the effects of wall geometry, gust geometry, curvilinear grids, and farfield boundary conditions are tested.

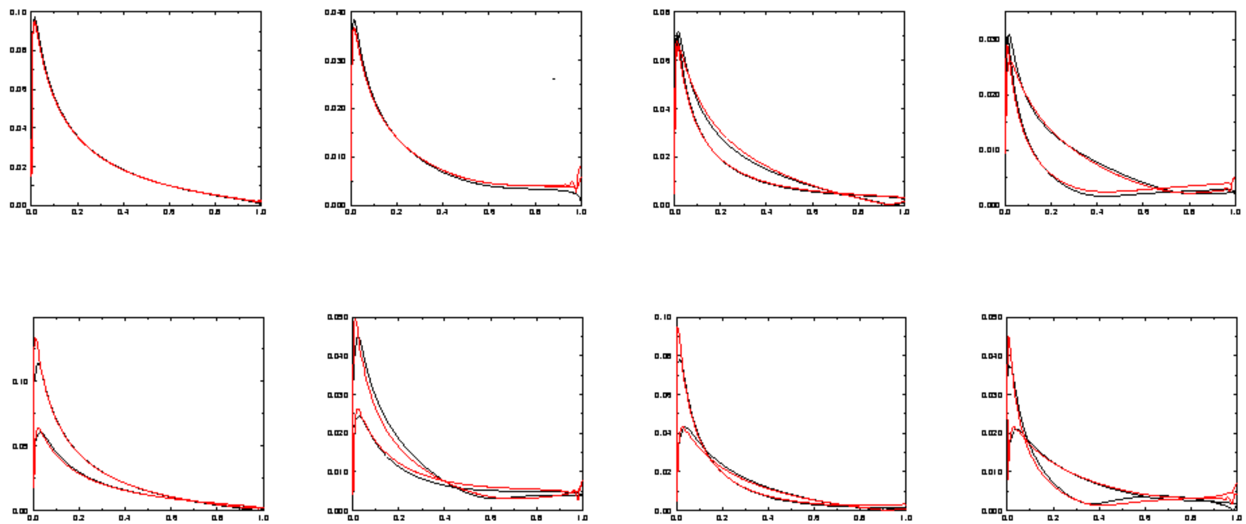


Airfoil Surface RMS Pressure Disturbance for Joukowski Airfoil in a Vortical Gust

1–D Gust, k = 0.1 | 1–D Gust, k = 1.0 | 2–D Gust, k = 0.1 | 2–D Gust, k = 1.0

Symmetric Airfoil

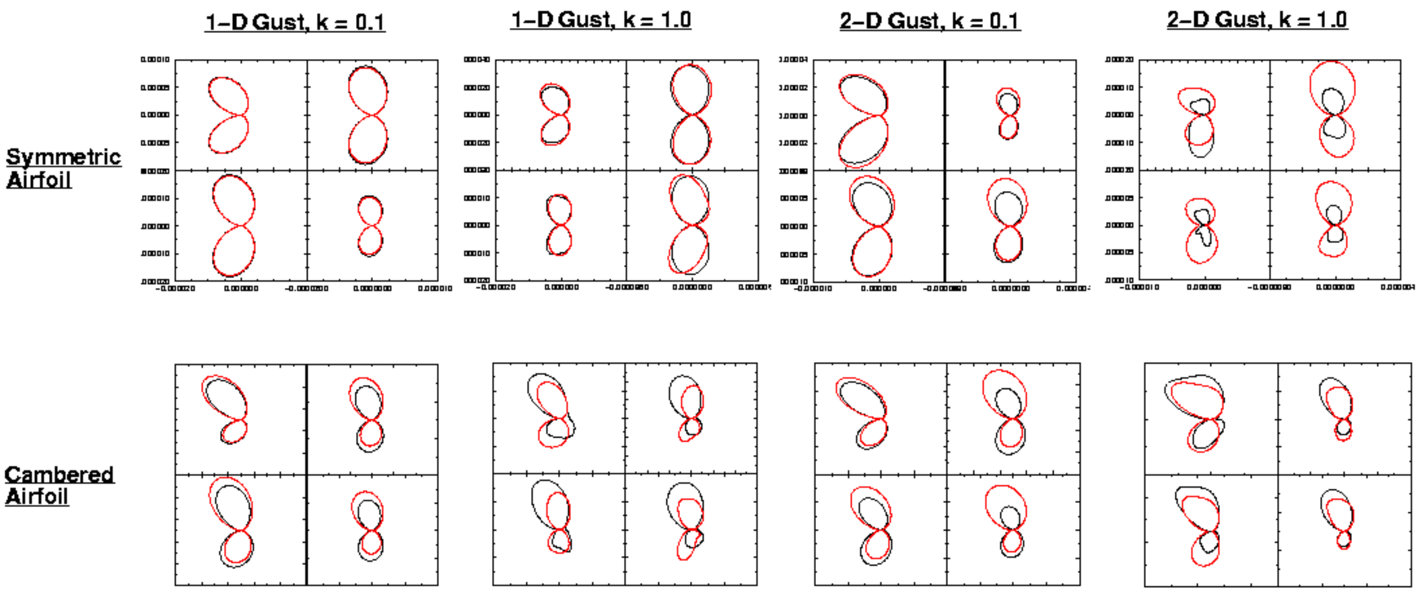
Cambered Airfoil

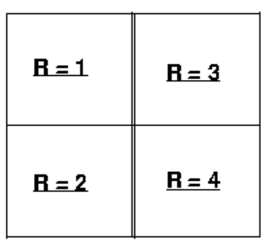


GUST3D Results

Computed Results

Far Field Noise Radiation Results for Joukowski Airfoil in a Vortical Gust



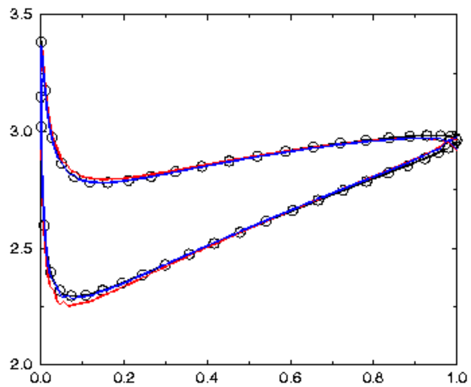


GUST3D Results

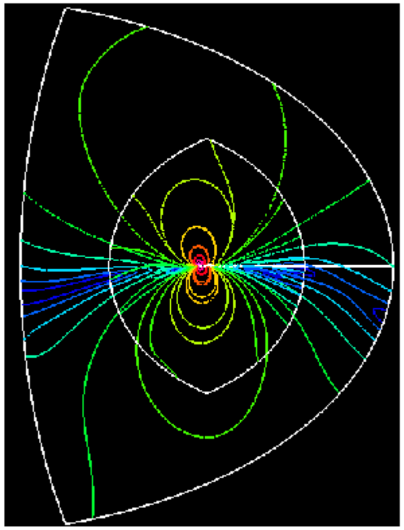
Computed Results

Boundary Distance Study for Joukowski Airfoil Problem (Cambered, k=0.1, 2D gust)

Mean Pressure on Airfoil



Log Pressure Perturbation Contours

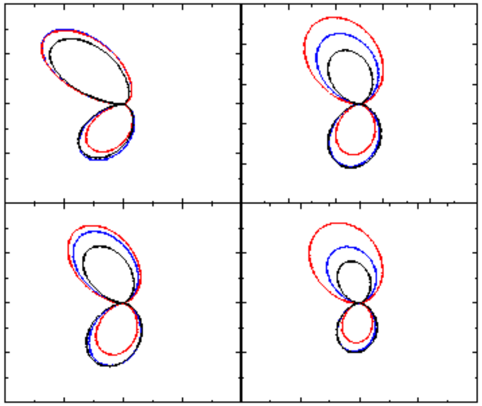


GUST3D Results

Computed Results (Coarse Grid = 433 x 125 = 54,125 points)

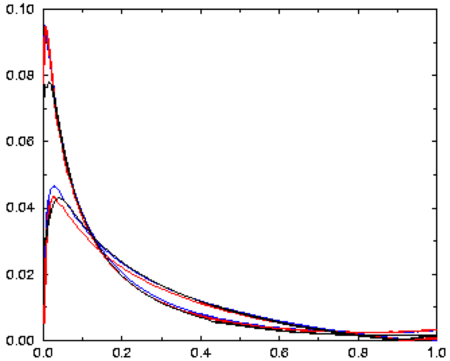
Computed Results (Large Grid = 605 x 240 = 145,200 points)

Pressure Perturbation in Far Field



R = 1	R = 3
R = 2	R = 4

RMS Pressure Perturbation on Airfoil



Future Directions

- The code is currently being parallelized.
- New boundary conditions are being added to the code.
- Plan to include improved artificial dissipation models, time stepping methods, and parallelization techniques.

2D Cascade Benchmark Test

Alternative High-Order Approaches

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Cascade Benchmark Problem

- Gust – Cascade Interaction Problem
- Periodicity Requires 27 Passages (22B / 54V)
- Gust has a Multi-Frequencies Character
  - 1x, 2x & 3xBPF
  - Amplitudes ~ 9%, 0.9% & 0.2% of the Mean Velocity
  - Minimum Wavelength is on order of 3/11 of the Chord
- Accuracy Requirement: ~1% Error at 3xBPF

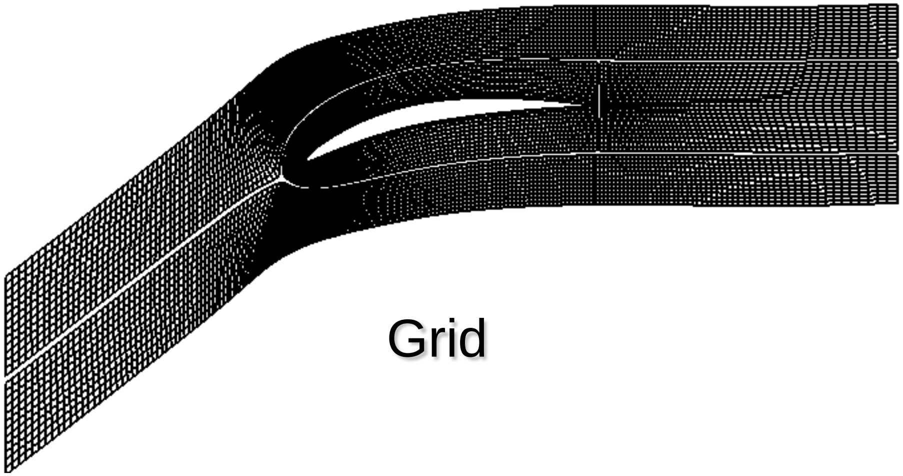
Need 6th Order Accuracy in Space & Time

Team Effort

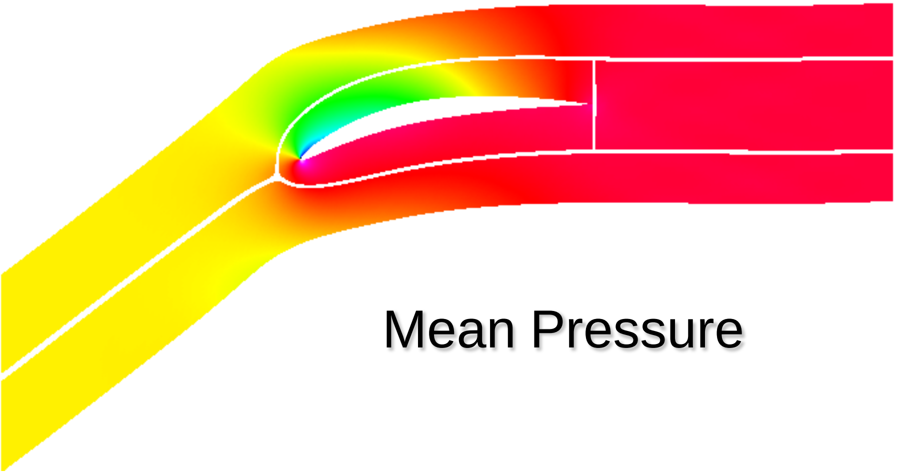
- Dr. R. Hixon, Principal Code Designer
- Dr. R. Nallasamy, Boundary Conditions
- Dr. S. Sawyer, Boundary Conditions
- Ms. D. Koch, PE, Grid Generation
- Dr. R. Dyson, Team Coordinator
- Dr. E. Envia, Turbomachinery

Preliminary Cascade Results

- The grid used by the code for this case has a 6-way grid singularity upstream of the leading edge.
- Initial results are promising for this case.



Grid



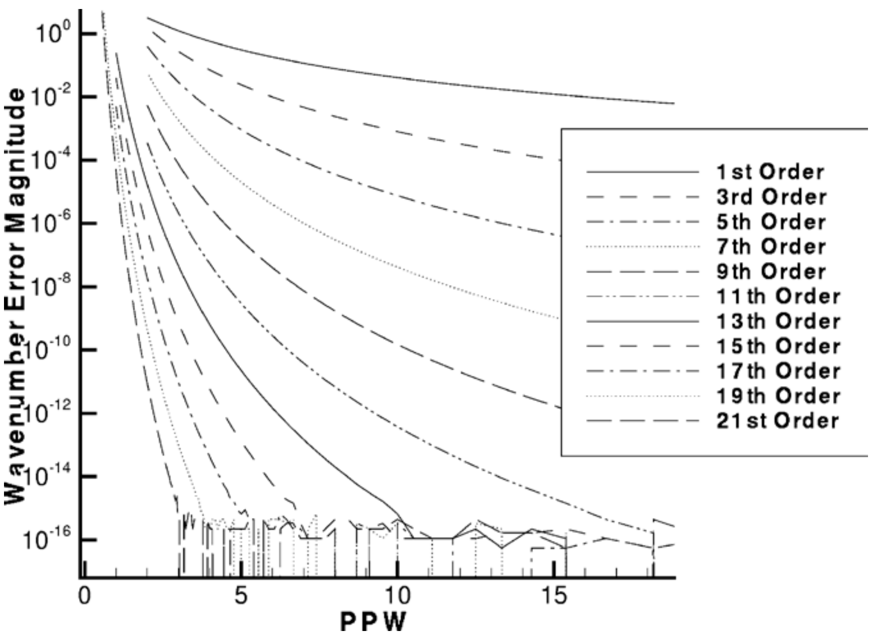
Mean Pressure

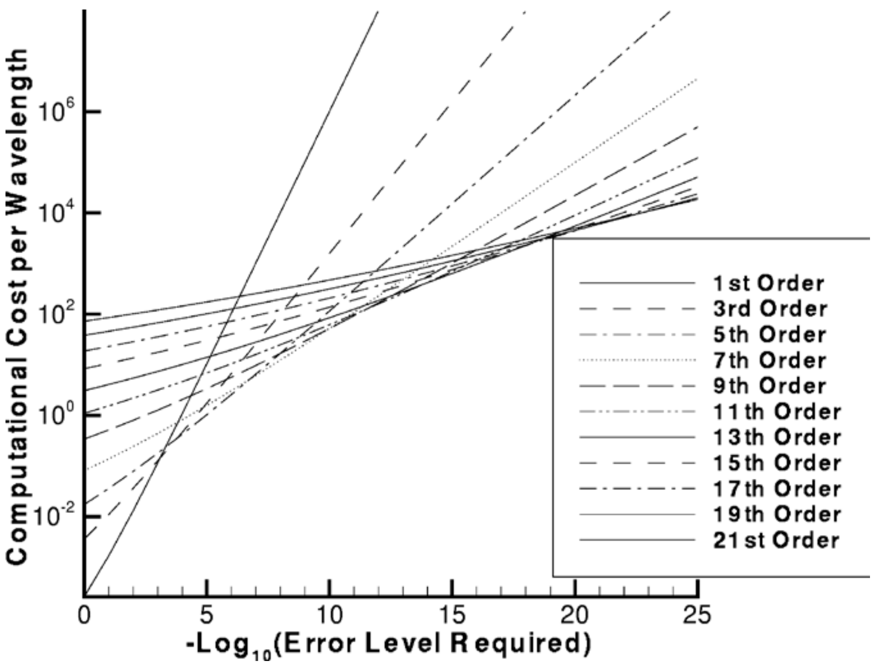
Arbitrary High-Order Methods

- Motivation:
  - High Resolution and Efficiency

- Challenges:
  - Need High Accuracy in Space and Time
  - Consistent Boundary Conditions (Surface & Farfield)
  - Complex Geometry (Cartesian vs. Curvilinear)

Why Arbitrarily High-Order?





Consistent Boundary Conditions

- Propagating waves accurately in time:

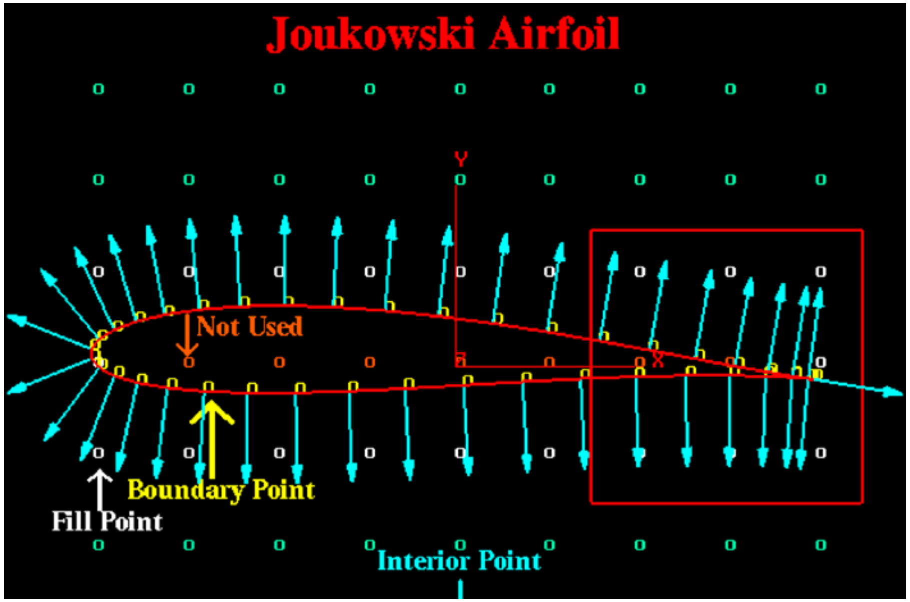
$$p(x,y,t+\Delta t) = p(x,y,t) + \frac{\partial p(x,y,t)}{\partial t}\Delta t + \frac{\partial^2 p(x,y,t)}{\partial t^2}\frac{\Delta t^2}{2!} + \dots$$

- Requires high order time derivatives
- Otherwise will get dispersion/dissipation

$$\frac{\partial p}{\partial t} = -\left(u\frac{\partial p}{\partial x} + v\frac{\partial p}{\partial y} + \gamma p\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right)\right)$$

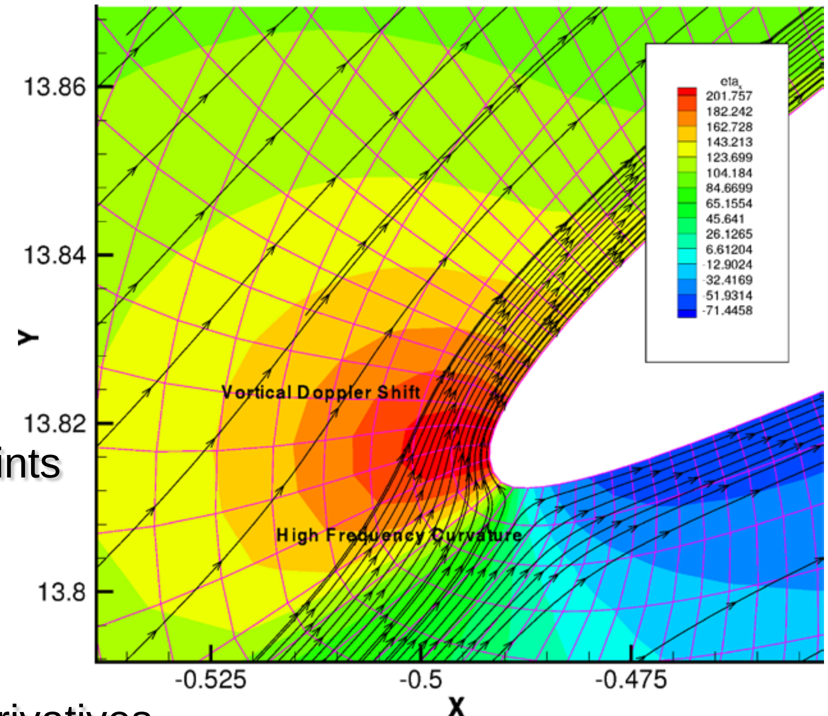
$$\boxed{\text{Errors in Time = Errors in Space}}$$

Complex Geometry – Cartesian Grid



- Advantages
  - No metrics
  - No singularities
  - Easy grid generation
  - Efficiency (few boundary pts)
- Challenges
  - Surface interpolation algorithm
  - Resolving curvature
  - Adaptive resolution with h and p refinement

Complex Geometry – Curvilinear Grid



- Advantages
  - Easy interpolation
  - Curvature more easily resolved
  - Centered boundary stencils with ghost points

- Challenges
  - Computing very high-order metric derivatives
  - 1st order grid singularities
  - High order boundary conditions are more complex

Future Work

- Validate Current compact 6th Order Code
  - 2D benchmark problem
- Incorporate New Technology as Needed
  - High order boundary conditions
  - Higher order time advancement everywhere
- Validate Full 3D-Stator
  - Assess the overall efficiency/usefulness

Computational AeroAcoustics for Fan Noise Prediction

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An overview of the current state-of-the-art in computational aeroacoustics as applied to fan noise prediction at NASA Glenn is presented. Results from recent modeling efforts using three-dimensional inviscid formulations in both frequency and time domains are summarized. In particular, the application of a frequency-domain method, called LINFLUX, to the computation of rotor-stator interaction tone noise is reviewed and the influence of the background inviscid flow on the acoustic results is analyzed. It has been shown that the noise levels are very sensitive to the gradients of the mean flow near the surface and that the correct computation of these gradients for highly loaded airfoils is especially problematic using an inviscid formulation. The ongoing development of a finite-difference time-marching code that is based on a 6th-order compact scheme is also reviewed. Preliminary results from the nonlinear computation of a gust-airfoil interaction model problem demonstrate the fidelity and accuracy of this approach. Spatial and temporal features of the code as well as its multi-block nature are discussed. Finally, latest results from an ongoing effort in the area of arbitrarily high-order methods are reviewed and technical challenges associated with implementing correct high-order boundary conditions are discussed and possible strategies for addressing these challenges are outlined.