OVERVIEW OF AIRCRAFT NOISE PREDICTION TOOLS ASSESSMENT

Milo D. Dahl

Presentation for the NASA Supersonic and Subsonic Fixed Wing Technical Working Group Meeting

December 4-5, 2007

Abstract:
The acoustic assessment task for both the Subsonic Fixed Wing and the Supersonic projects under NASA's Fundamental Aeronautics Program was designed to assess the current state-of-the-art in noise prediction capability and to establish baselines for gauging future progress. The documentation of our current capabilities included quantifying the differences between predictions of noise from computer codes and measurements of noise from experimental tests. Quantifying the accuracy of both the computed and experimental results further enhanced the credibility of the assessment. This presentation gives sample results from codes representative of NASA's capabilities in aircraft noise prediction at the system level and at the component level. These include semi-empirical, statistical, analytical, and numerical codes. An example of system level results is shown for an aircraft. Component level results are shown for airframe flaps and landing gear, for jet noise from a variety of nozzles, and for broadband fan noise. Additional results are shown for modeling of the acoustic behavior of duct acoustic lining and the attenuation of sound in lined ducts with flow.

Overview of Aircraft Noise Prediction Tools Assessment

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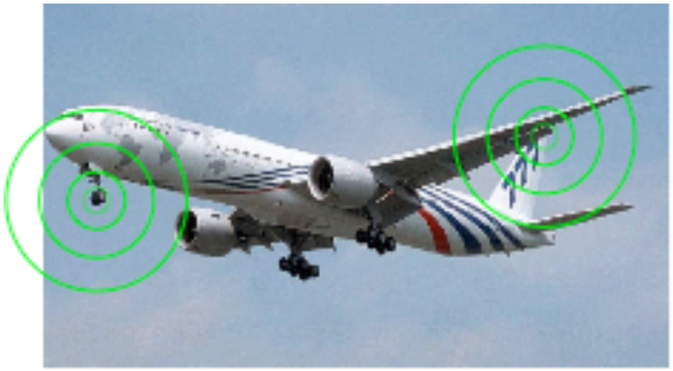
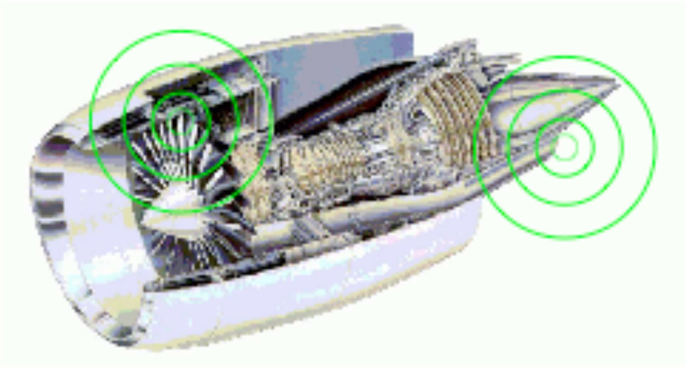
Technical Working Group Meeting

December 4-5, 2007



Airframe Noise



Engine Noise

Outline

- Background
- Process of Assessment
- Topic Areas and Codes
- Sample Results
  - Systems Level
    - Aircraft (example)
    - Engine (summary)
  - Component Level
    - Airframe Noise
    - Jet Noise
    - Fan Noise
    - Liner and Duct Acoustics
- Concluding Remarks

Fundamental Aeronautics Program Plan

Motivation: "*NASA needs robust, highly accurate tools and methods for performance prediction*…"

Paradigm: Predict → Test → Validate

Goal: Physics-based multi-disciplinary analysis and optimization (MDAO) tools with quantified levels of uncertainty.

Fundamental Aeronautics Program Plan
Current NASA Capability

Specific milestones in:
Subsonic Fixed Wing and Supersonic
Require assessment of noise prediction capability

- Document current capabilities for noise prediction versus validated data bases

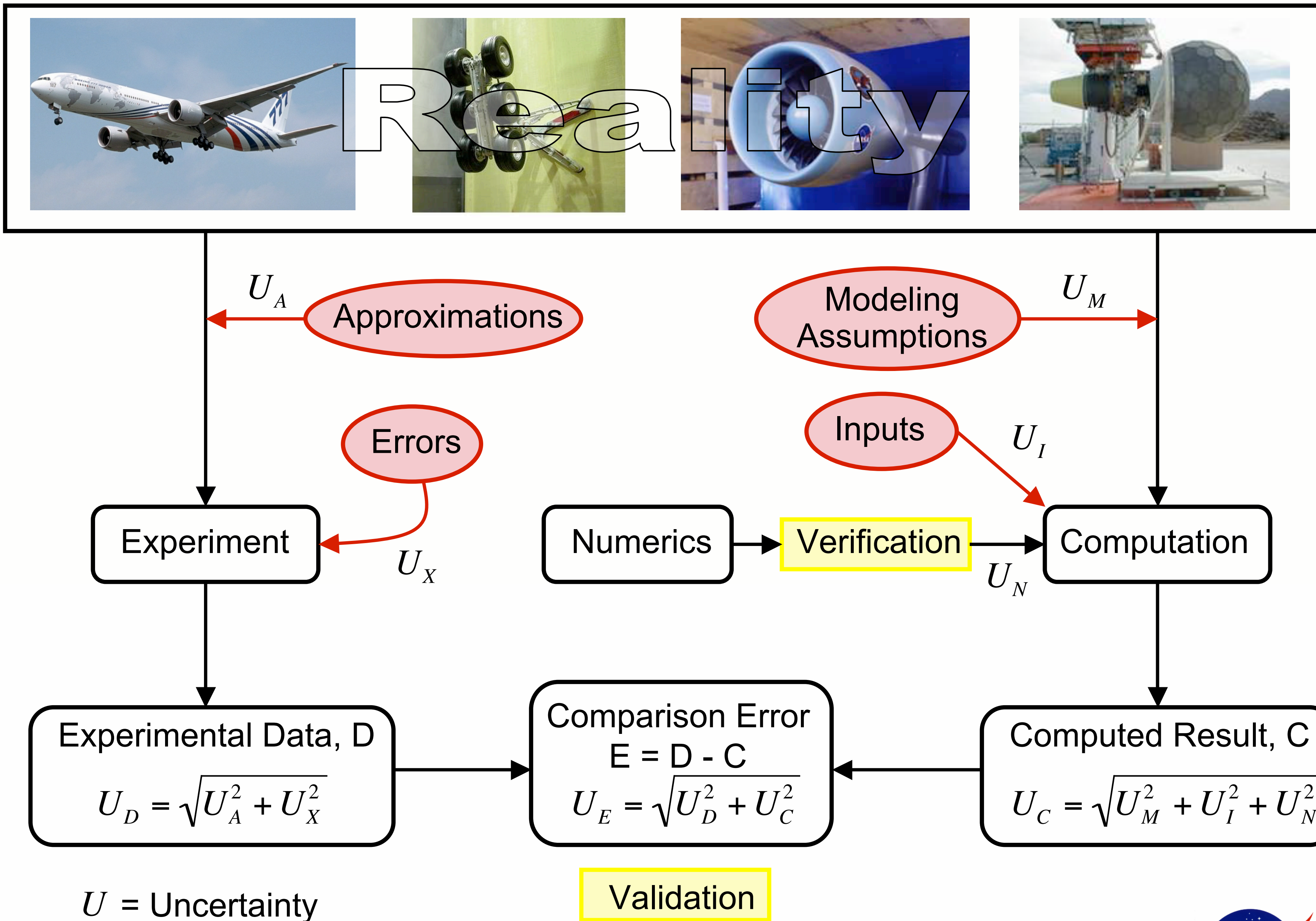
Assess state-of-the-art capability to predict noise

- Quantify our 'error bars' or *levels of uncertainty*

Establish Baselines

- Identify where to improve our tools (predictive and diagnostic)
- Identify needed experimental data

Verification and Validation Diagram



Definition of Assessment

Assessment: Act of documenting the degree to which computer models and codes meet the specified requirements following a verification and validation process.

- Assessment is part of the V & V process

  Quantified data available:
  - Verification that the code is right
  - Validation comparing predictions to measurements

- Necessary condition for credible assessment:
  - Quantitative assessment of accuracy
  - State our ‘error bars’ or *levels of uncertainty*

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Topics
Systems and Components Assessed

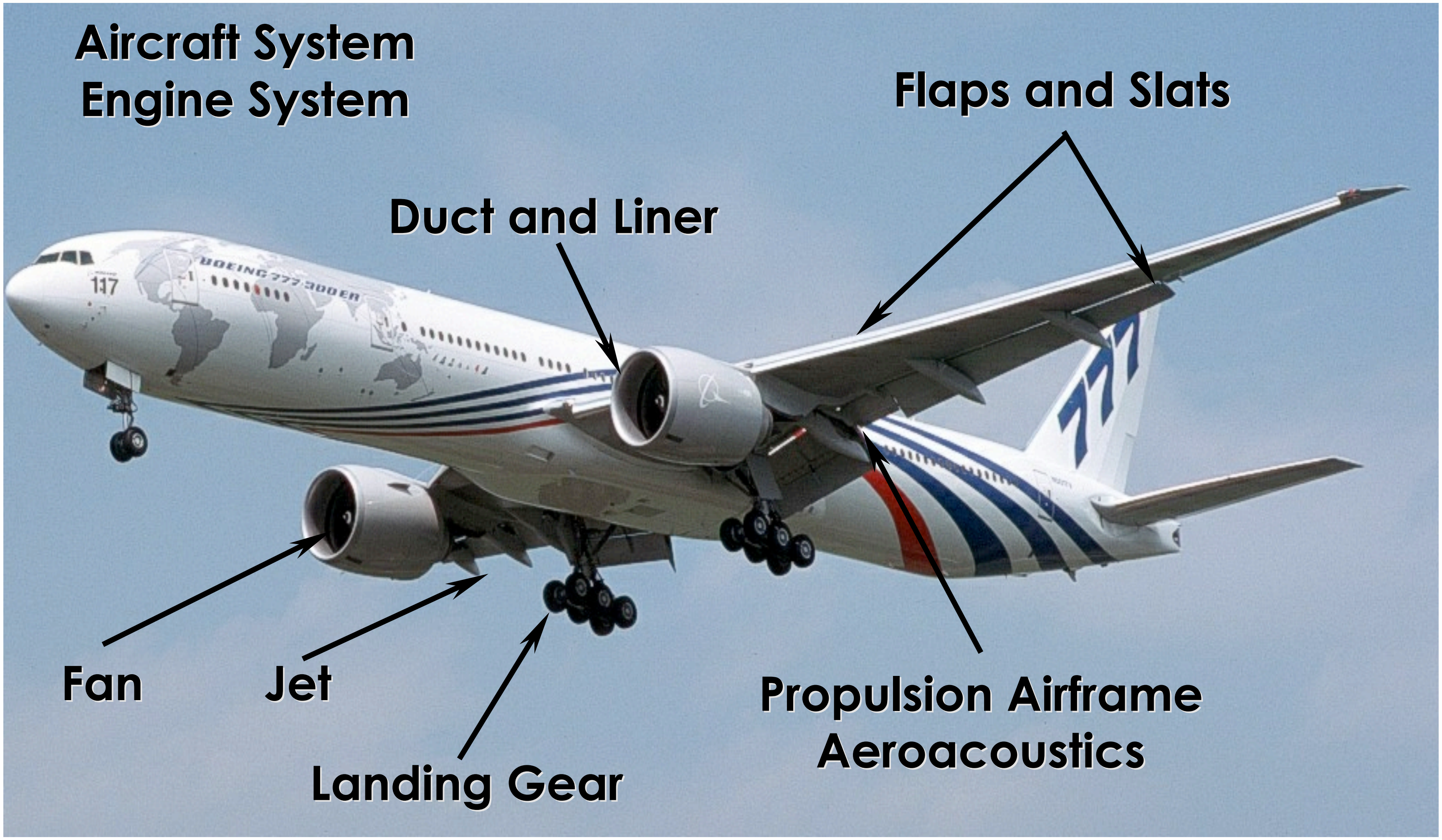


Table of Codes

Topic	Codes					
Airframe						
Flaps	ANOPP-L25					
Slats	ANOPP-L25	CFL3D				
Landing Gear	ANOPP-L25	CFL3D				
Propulsion Airframe Aeroacoustics	JET3D					
Aircraft System	ANOPP-L25					
Engine System	ANOPP-L25					
Fan	ANOPP-L25	RSI	V072	Linflux		
Jet	ANOPP-L25	JeNo	JET3D			
Liner Physics	Two-Parameter	Crandall Full Solution	Composite Empirical	Fluid Mechanical		
Duct Acoustics	CH3DPA	LEE2DDS	CH2DDS	CH3DDS	LEE2DIS	LEE3DIS

	Semi-Empirical
	Statistical + CFD
	Analytical + CFD
	Numerical/CAA

Why These Codes?

- Publicly available, will be available, or available to qualified users
- Representative of state-of-the-art or current capability at NASA
- Developed for or applied to the prediction of aircraft related noise
- Limited resources

Sample Results for System Level Predictions

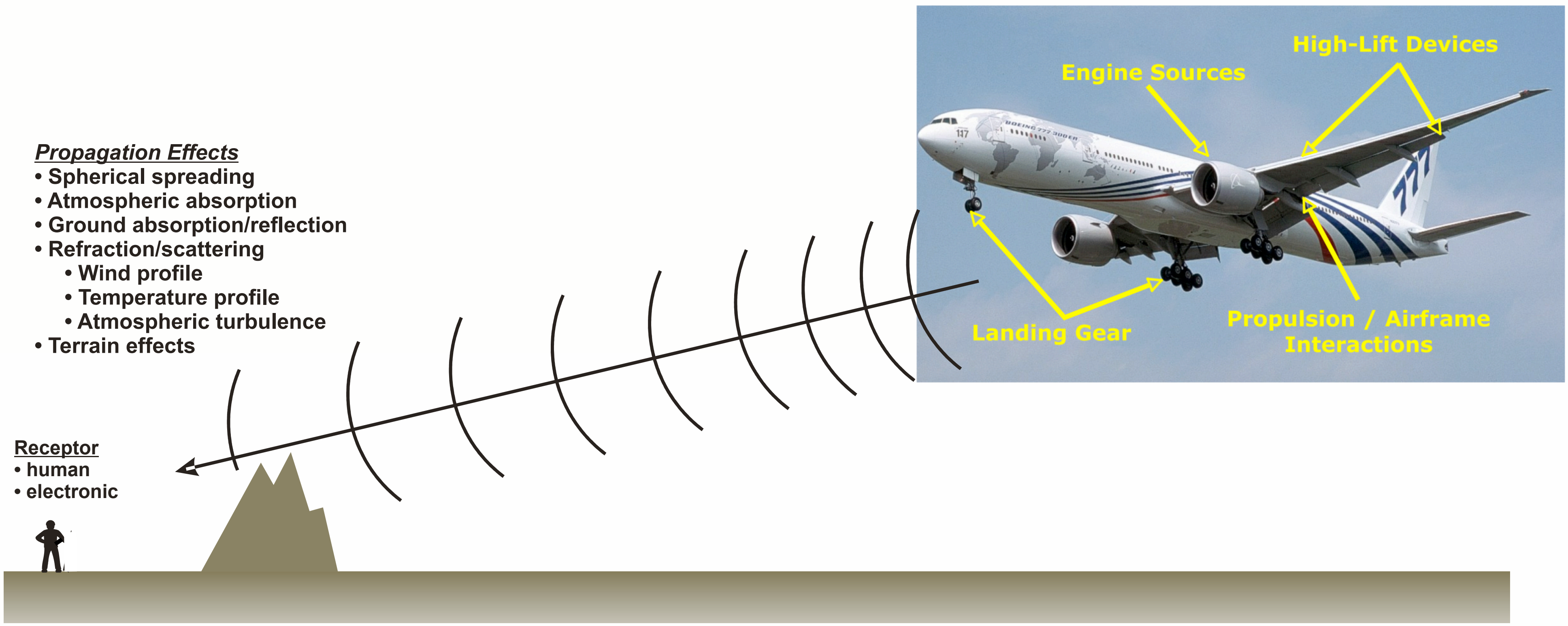
Topic	Codes					
Airframe						
Flaps	ANOPP-L25					
Slats	ANOPP-L25	CFL3D				
Landing Gear	ANOPP-L25	CFL3D				
Propulsion Airframe Aeroacoustics	JET3D					
Aircraft System	ANOPP-L25					
Engine System	ANOPP-L25					
Fan	ANOPP-L25	RSI	VO72	Linflux		
Jet	ANOPP-L25	JeNo	JET3D			
Liner Physics	Two-Parameter	Crandall Full Solution	Composite Empirical	Fluid Mechanical		
Duct Acoustics	CH3DPA	LEE2DDS	CH2DDS	CH3DDS	LEE2DIS	LEE3DIS

(yellow)	Semi-Empirical
(green)	Statistical + CFD
(cyan)	Analytical + CFD
(purple)	Numerical/CAA

Aircraft System Noise Prediction

• NASA's **A**ircraft **NO**ise **P**rediction **P**rogram (**ANOPP**) was designed to predict the total aircraft noise signature from propulsion and airframe noise sources and to propagate the total noise to arbitrary ground observers.

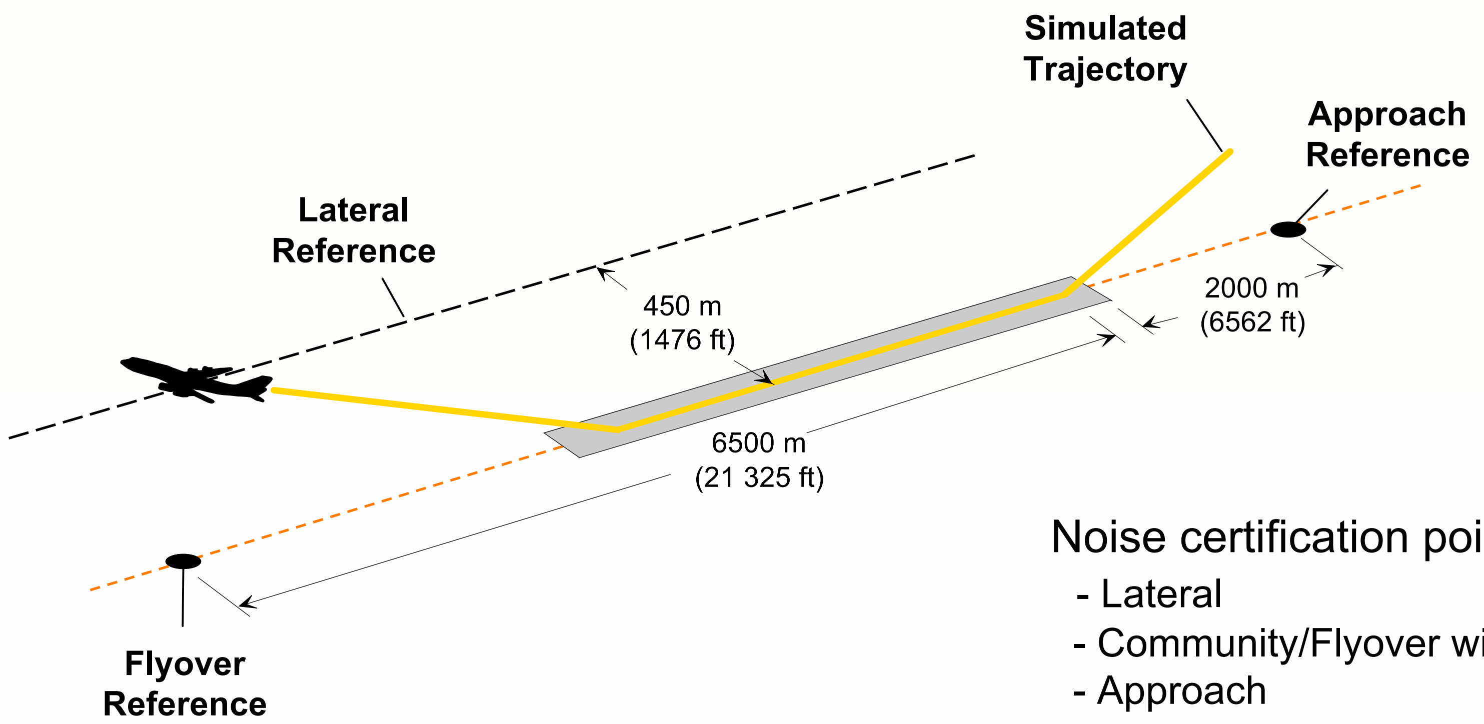
• Since inception (1970's), NASA has continued to extend and improve capabilities. Current version: ANOPP-Level-25



Receiver ← Propagation ← Source

Noise Analysis for B737-800 with CFM56-7B Engines

- Noise predictions performed using ANOPP Level 25
- Predictions compared to levels obtained at certification points

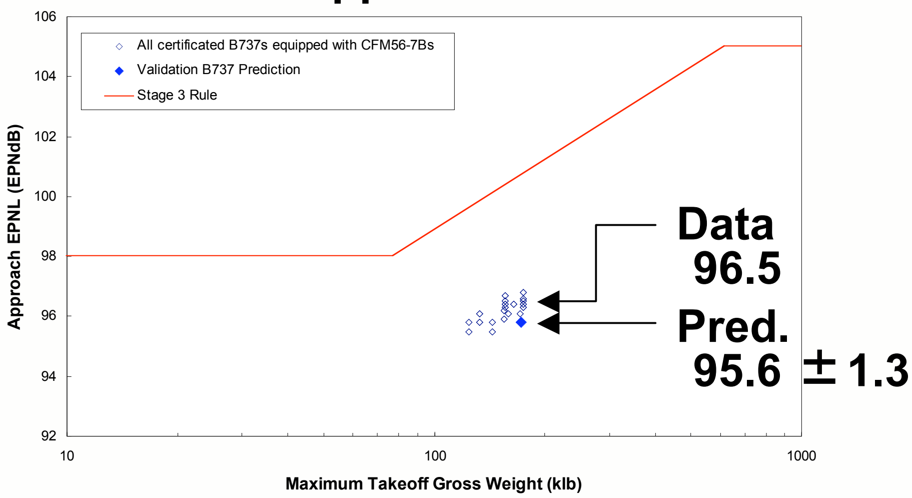


Noise certification points:
- Lateral
- Community/Flyover with cutback
- Approach

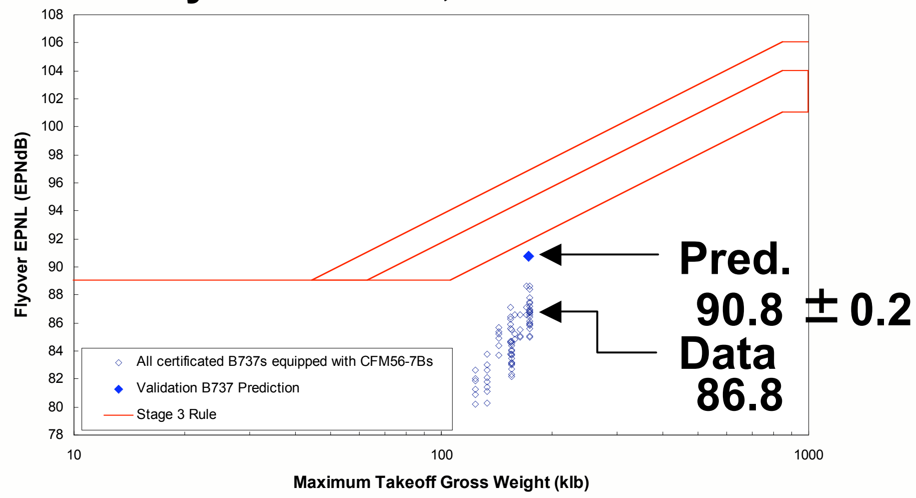
Comparison of ANOPP Predictions and Certification Noise Data

Total of 73 Certificated B737s equipped with CFM56-7B engines

Approach EPNL



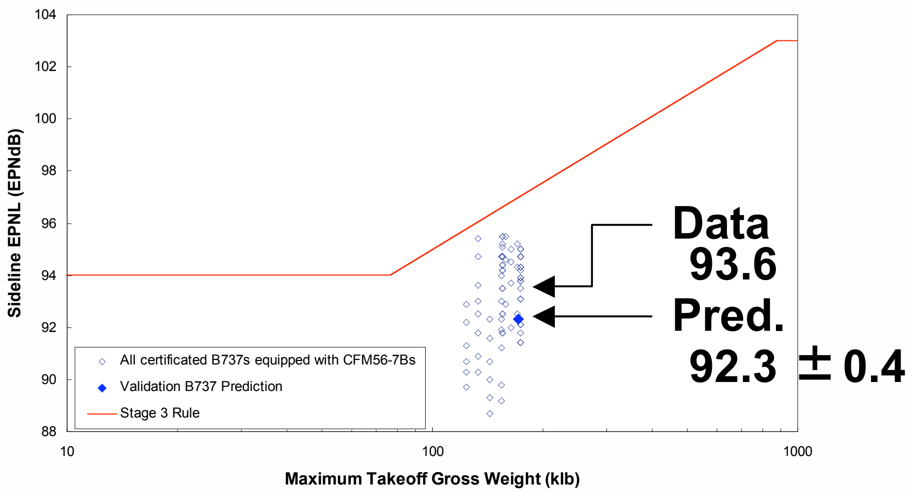
Flyover EPNL, with cutback



Lateral EPNL

Uncertainty based on 21 simulations to get 95% confidence intervals

Data from multiple aircraft



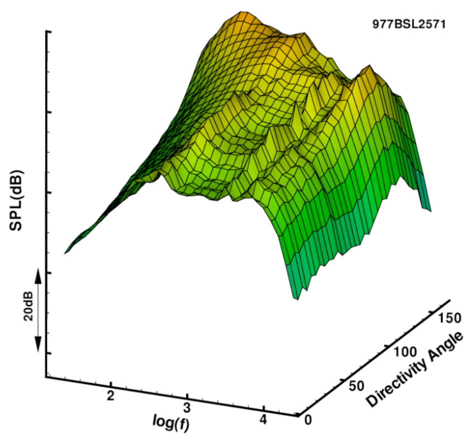
Remarks on Noise Analysis Comparison

- Some causes of discrepancies:
  - Fan noise predictions too high at cutback power?
  - Liner suppression predictions
  - Cycle & aeromechanical modeling
  - Trajectory & throttle setting assumptions
  - Cancelling errors
- EPNL is a complex, high-level, multidisciplinary metric with many independent variables affecting its outcome. Not the best data to be used in validation of prediction methods.
- Full aircraft noise data appropriate for validation purposes is very limited to non-existent (requires engine cycle definition, aircraft geometry details, noise directivity and at a minimum spectra.
  - proprietary nature of "**detailed"** engine cycle data, geometry and noise measurements limit access
  - Flight tests are expensive and measurements are highly dependent on configuration

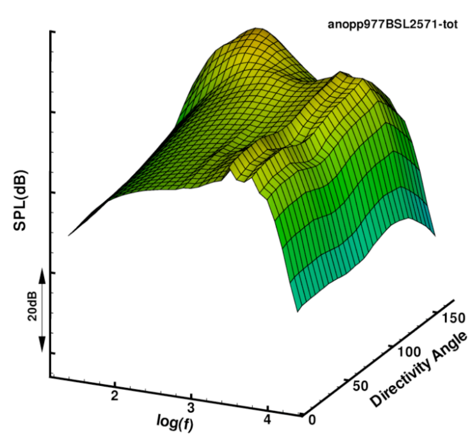
Engine Systems Assessment

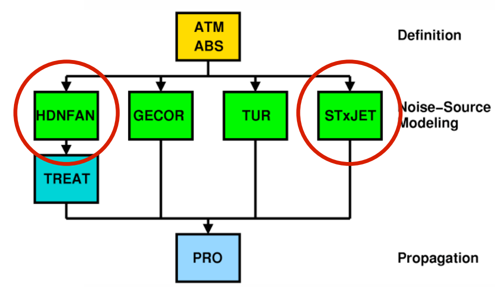
- ANOPP L25v3 predictions (NASA GRC)
- Existing (new) NASA/Honeywell EVNERT static engine test data
- Total engine noise (fan+combustor+turbine+jet) fan and jet models updated - current dominant sources
- Details given in separate presentation

TECH977 ENGINE TEST



ANOPP L25v3 PREDICTION





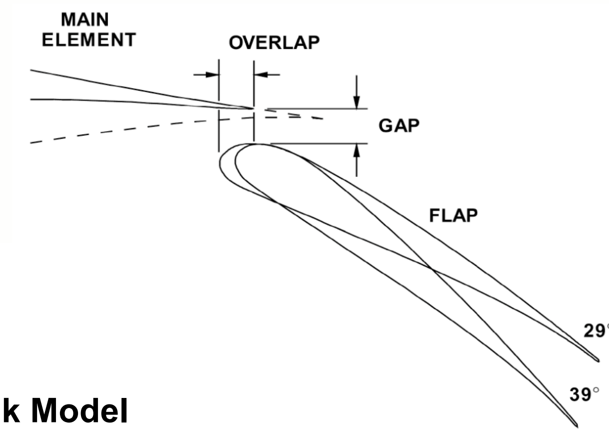
Airframe Noise Prediction

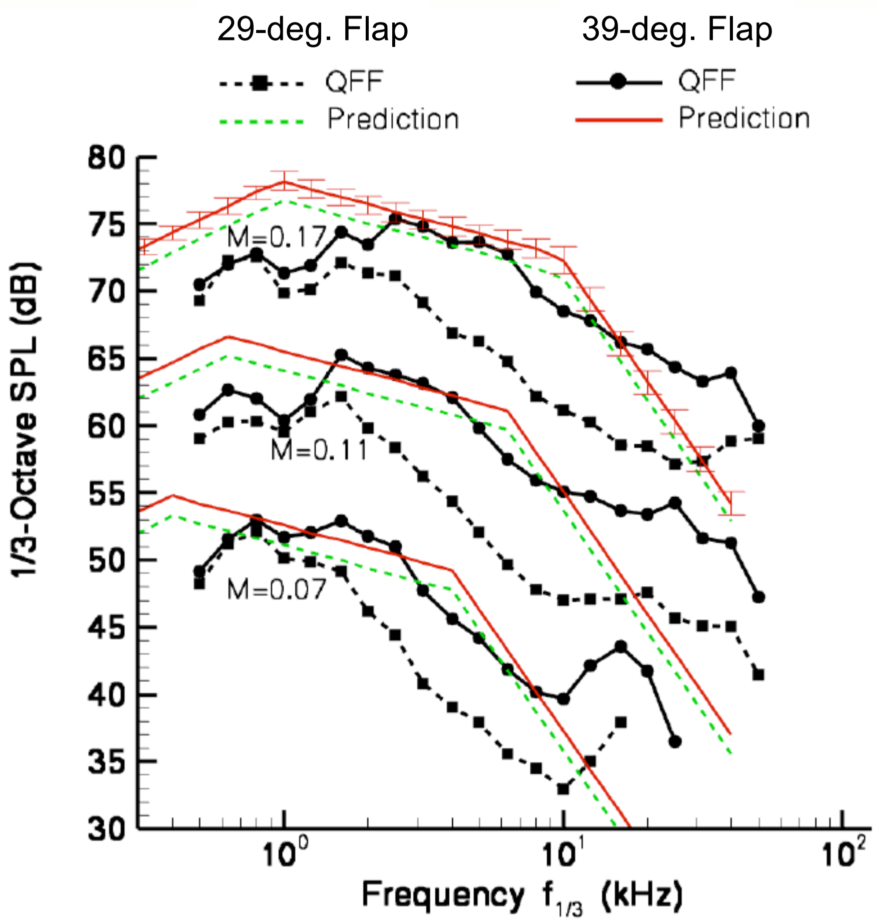
		Trailing-Edge Flap		Leading-Edge Slat		Landing Gear	
Test Cases		DATA	PREDICTION	DATA	PREDICTION	DATA	PREDICTION
Model Tests	NACA 63-215 & Flap	Acoustic	ANOPP				
	6.3% B-777 High Fidelity					Acoustic	ANOPP
	10% "B-757" Simplified					Acoustic	CFL3D/FWH
	30P/30N Model			Aero	CFL3D		
	Tandem Cylinders					Aero & Acoustic	CFL3D/FWH
Flight Tests	VC–10	Acoustic	ANOPP	Acoustic	ANOPP		
	DC–9–31			Acoustic	ANOPP		
	G–550	Acoustic	ANOPP			Acoustic	ANOPP

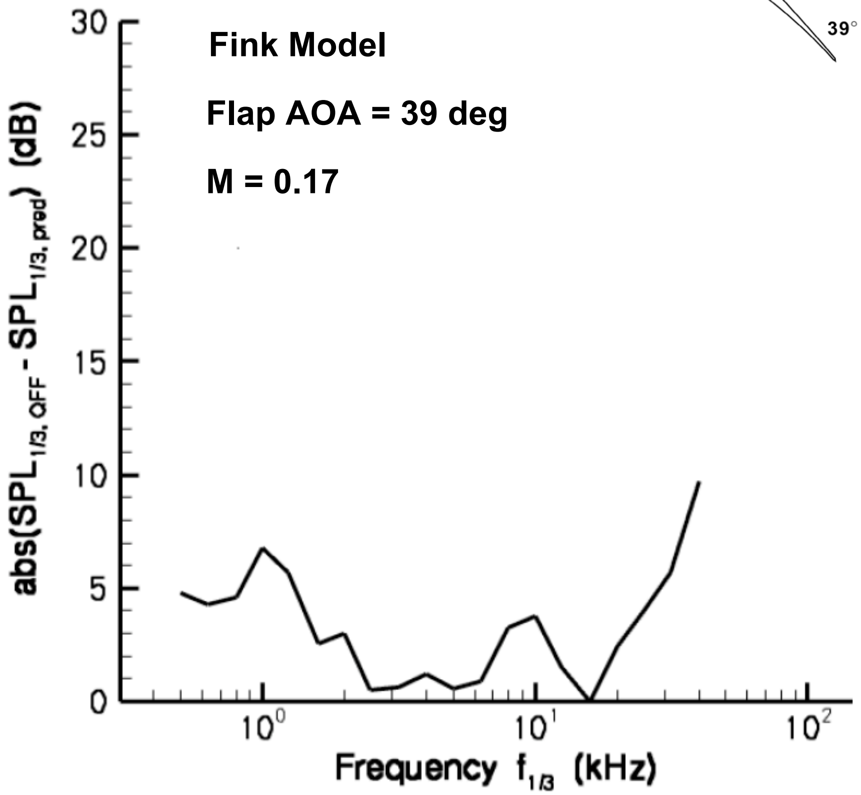
- ANOPP – Semi-empirical, Fink & Boeing models
- CFL3D – CFD based prediction

Flap-Edge Noise Measurement and Prediction

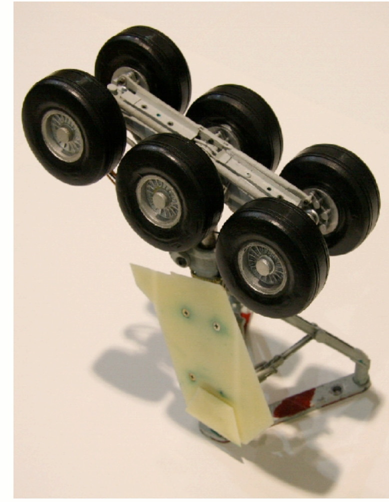
- Measurements in QFF, s.d. ≤ ±0.19 dB
- ANOPP Fink Model, uncertainty ≤ ±1 dB





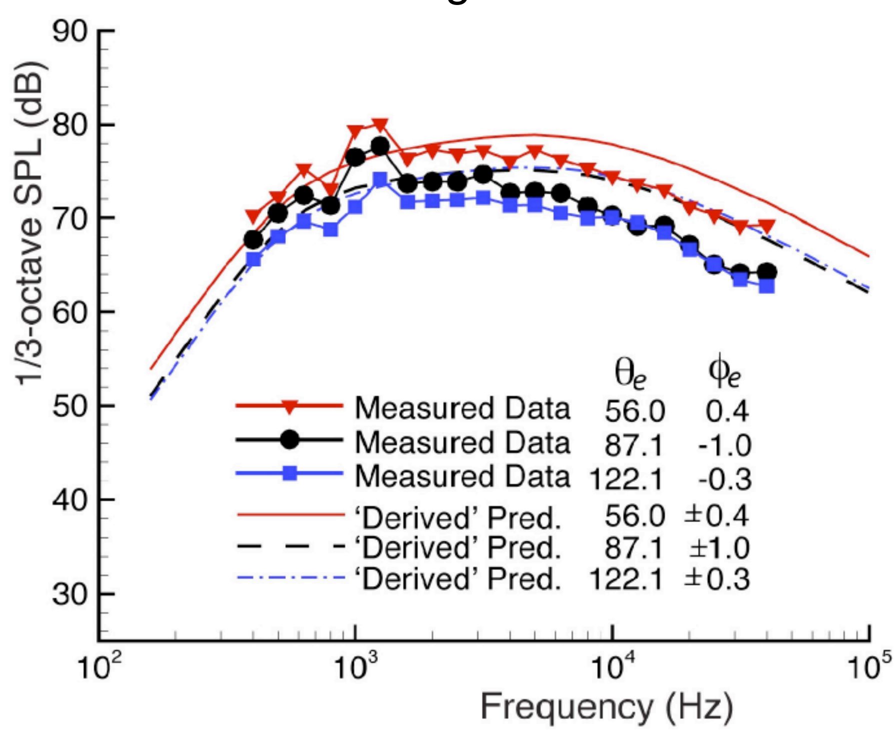


Aeroacoustic Measurement and Prediction Boeing - 777 Landing Gear Model

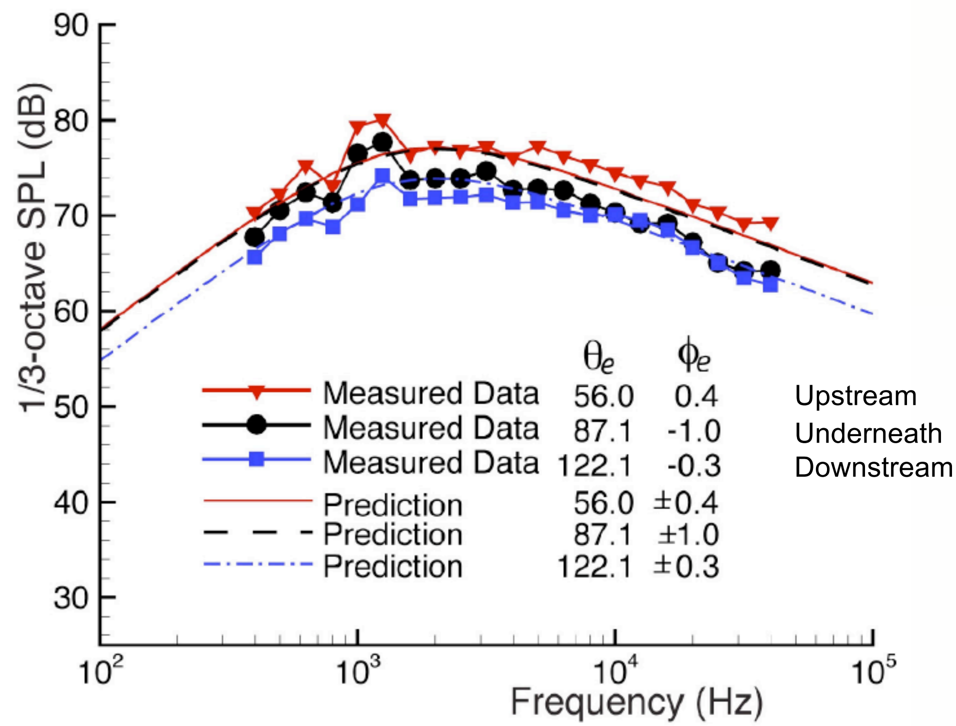


- 6.3%-scale model measured in QFF, s.d.≤ ±0.19 dB
- Uncertainty of predictions ≤ ±0.45 dB
- Flow condition, M = 0.17

ANOPP Boeing-Guo derived model



ANOPP Fink model

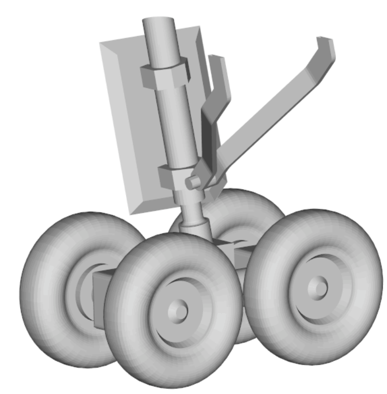


Computational Fluid Dynamics Coupled to Acoustic Analogy

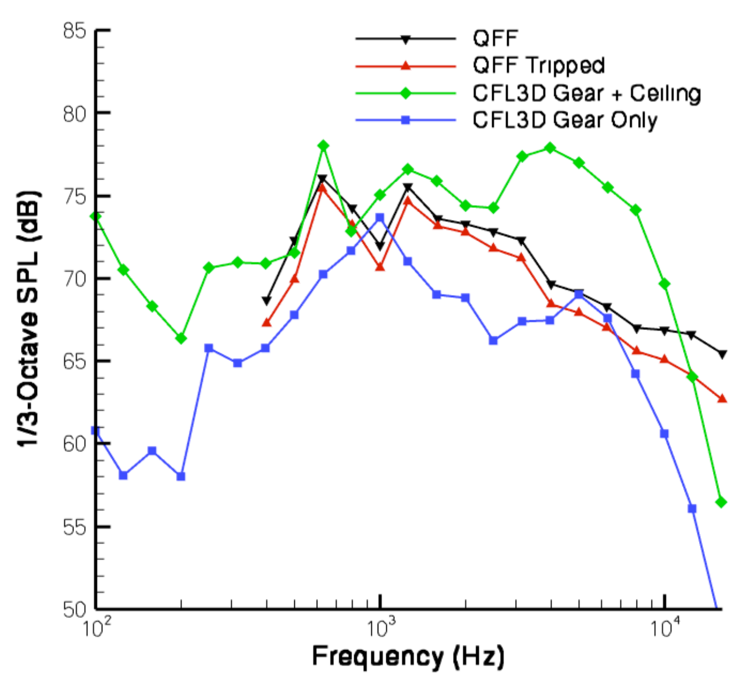
- **CFL3D**
  - Unsteady simulations of noise sources using a 2nd-order CFD code
    - Unsteady, hybrid RANS/LES calculations
  - Coupled with a Ffowcs Williams-Hawkings solver at a bounding surface to predict the far-field noise
- **Measurements**
  - NASA Basic Aerodynamic Research Tunnel (BART)
  - NASA Quiet Flow Facility (QFF)
- **Examples**
  - Simplified Landing Gear
  - Tandem Cylinders

Simplified Landing Gear Model

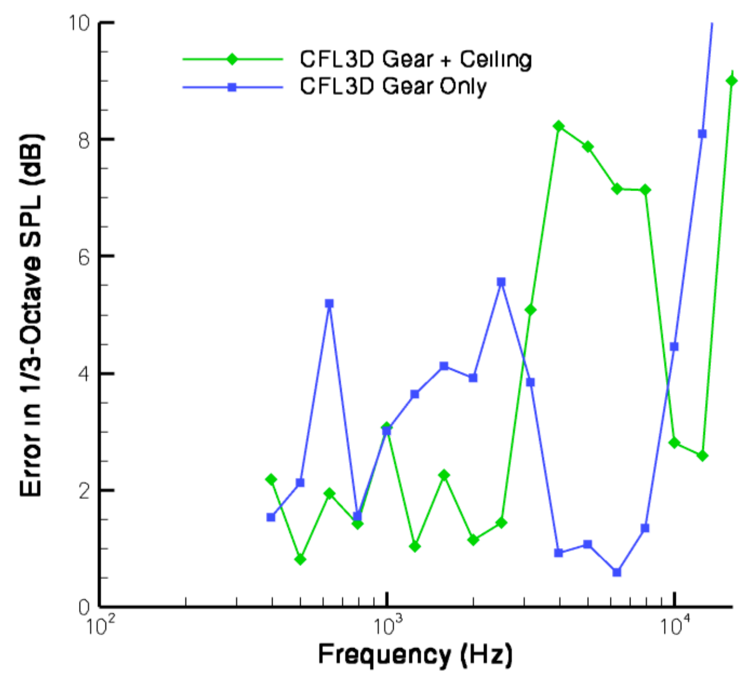
- Measurements in QFF
- CFL3D, 13.3 million grid points
- Flow condition, M = 0.17



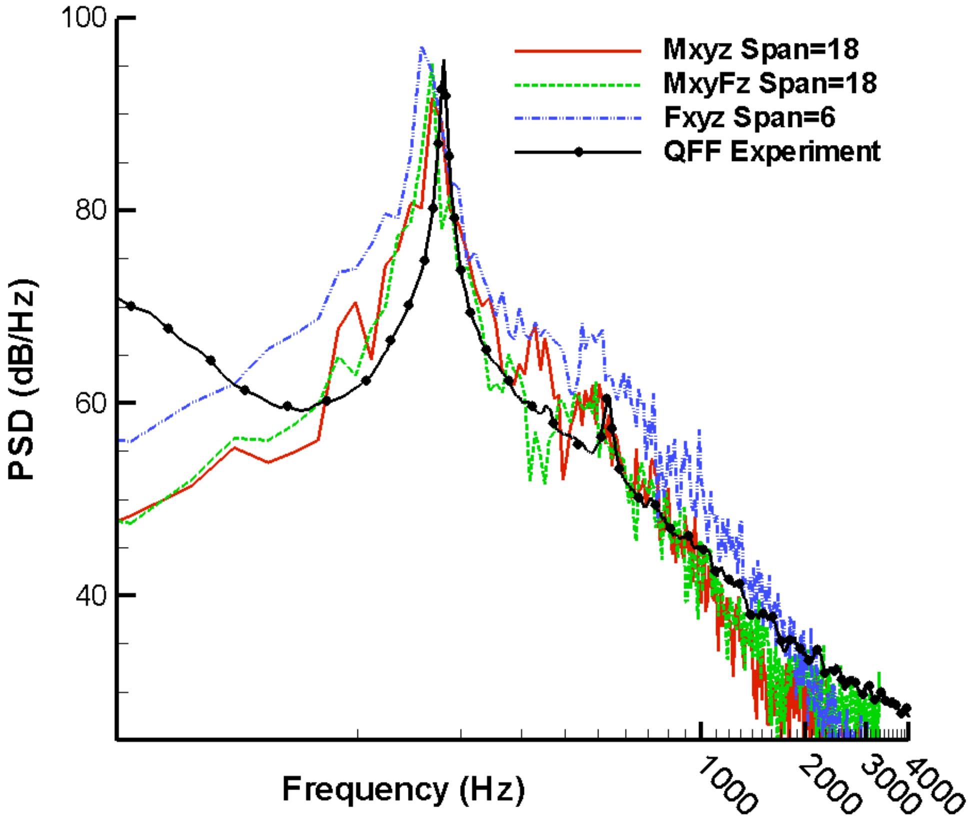
Overhead Comparison
Measured and Predicted Spectra

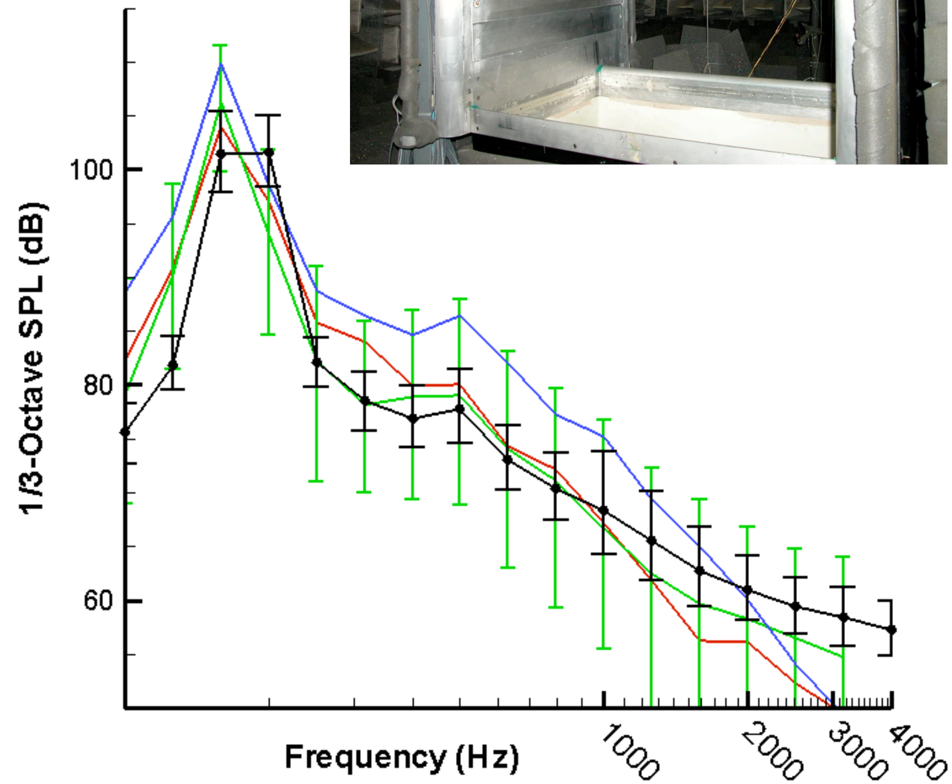


Overhead Comparison
Error in Prediction



Tandem Cylinder Prototype for Landing Gear Interactions





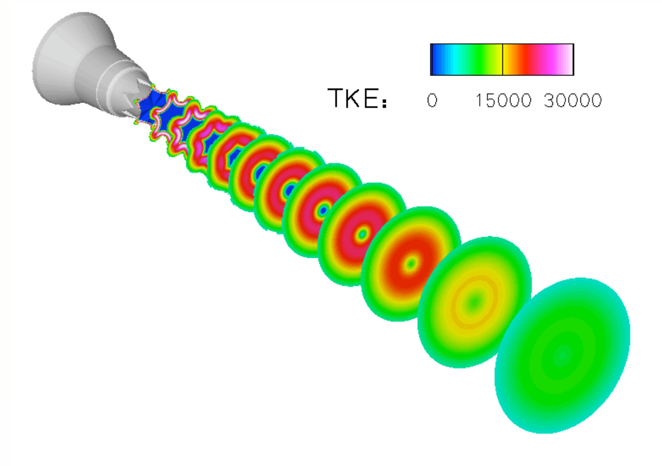
- Main features captured by prediction
- CFL3D has long run times → low number of cases → higher uncertainty and less ability to determine range of applicability

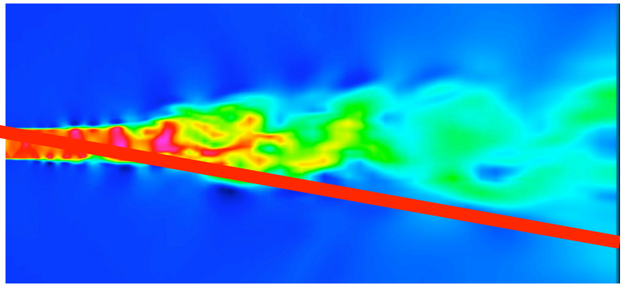
Airframe Noise Prediction

- Semi-Empirical methods
  - Very efficient (minutes to hours)
  - Reasonable predictions of spectral content
  - Amplitudes sometimes have large errors
    - Extrapolation outside of experimental database
    - Impossible to capture the unique features of every aircraft
- CFD methods
  - Very inefficient (months)
  - Reasonable predictions of spectral content and amplitudes
    - High-frequency content often lost because of grid resolution
  - Possible to capture the unique features of an aircraft
- A compromise between fidelity and efficiency is needed

Assessment of Jet Noise Prediction

- Types of Codes available
  - Semi-Empirical
    - Input: Vjet, Tjet, Ambient, Axisymmetric Nozzle Geometry
    - Output: SPL (freq, observer location)
    - Basis: Scaled Equivalent Sources
    - E.g. ST2Jet module in ANOPP
  - Statistical
    - Input: RANS CFD of jet plume
    - Output: SPL (freq, observer location)
    - Basis: Acoustic Analogy
    - E.g. Jet3D, JeNo
  - Time-resolved
    - Input: Nozzle geometry/plume grid
    - Output: Time records very near, very far from jet
    - Basis: Filtered Navier-Stokes Eq'ns
    - E.g. Unnamed individual research codes





Example of CFD Coupled to Acoustic Analogy for Jet Type Flows

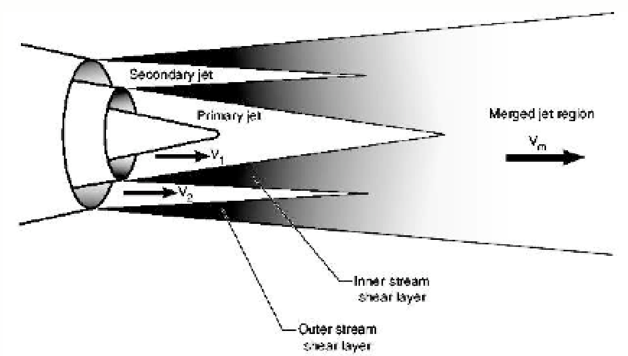
- **PAB3D - CFD**: Structured grid, Reynolds-averaged Navier-Stokes solver with nonlinear algebraic Reynolds stress turbulence models.

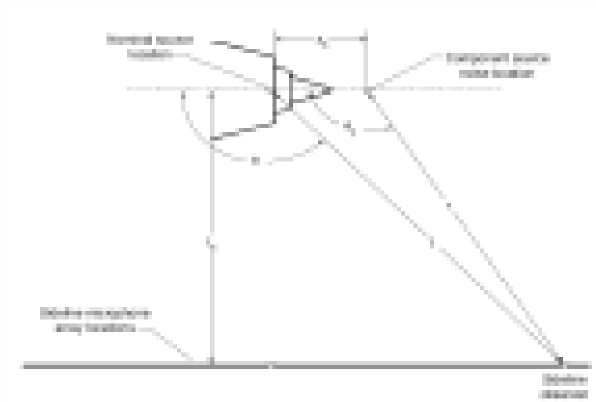
  Focused on propulsion/aerodynamic applications over the last 20 years - afterbody separation, jet mixing, thrust vectoring, nozzle internal performance, etc.

- **Jet3D – Jet Noise Prediction**: Modern implementation of Lighthill's Acoustic Analogy, able to handle complex 3D turbulent flows and installed jet configurations.
- Jet3D uses mean flow and anisotropic turbulence computed by PAB3D to model two-point space-time correlations and construct the Lighthill stress tensor.

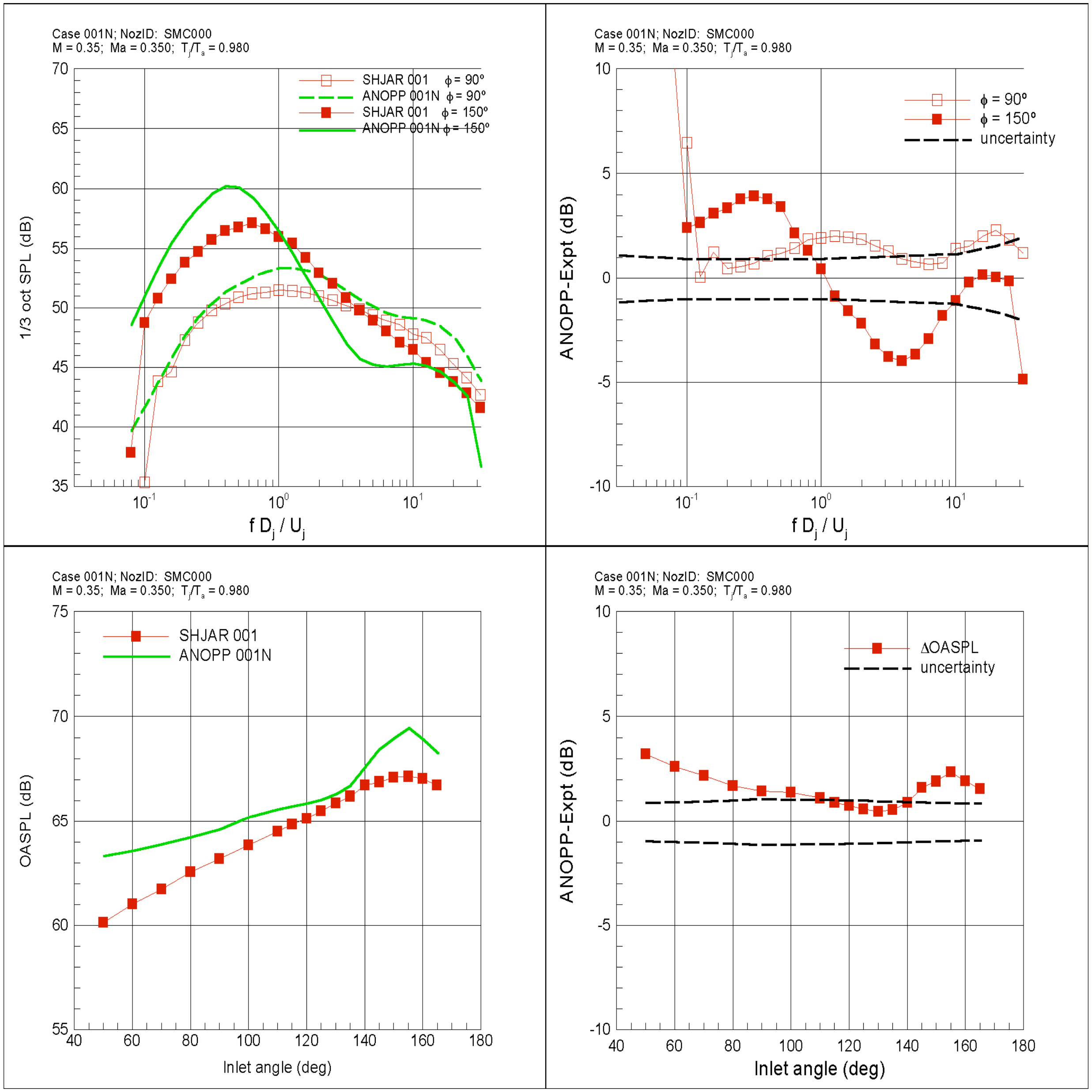
Assessment Parameter Space

- 266 cases considered, covering broad range of parameters:
  - BPR (0 — 14)
  - Mach (0.35 — 2.0)
  - Acoustic Mach (0.3 — 2.4)
  - Temperature Ratio (0.8 — 3)
  - Axial geometry (internal/external mixer, C-D)
  - Azimuthal geometry (axisymmetric, chevrons, lobed mixer)





Assessment Figure Format



1/3 octave spectra
φ = 90°, 150°
predicted vs
experiment

Spectral difference
φ= 90°, 150°
with uncertainty
band

OASPL
predicted vs
experiment

OASPL difference,
with uncertainty
band

‘Typical’ results of different codes

Semi-Empirical

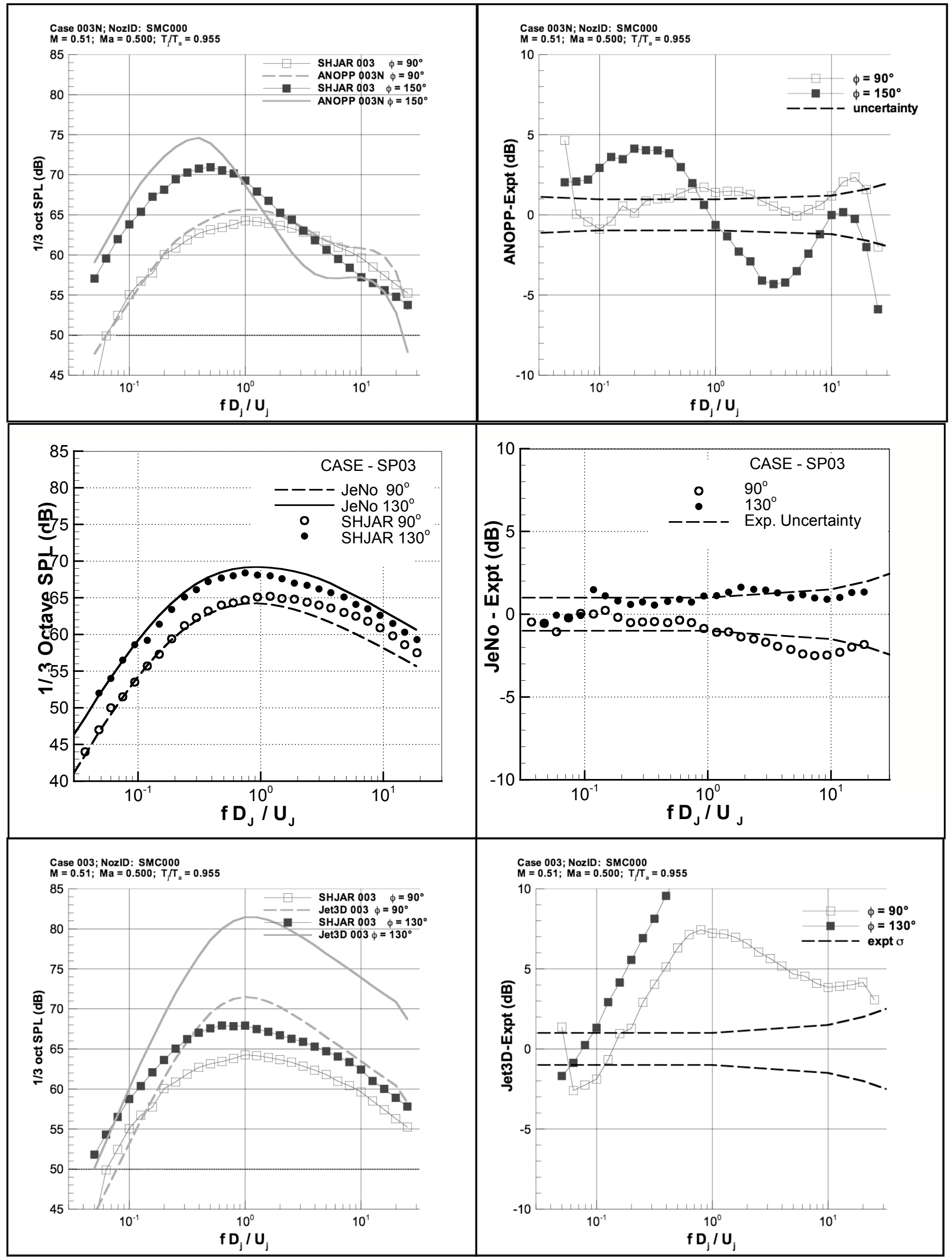
ANOPP vs Expt

Statistical

JeNo vs Expt

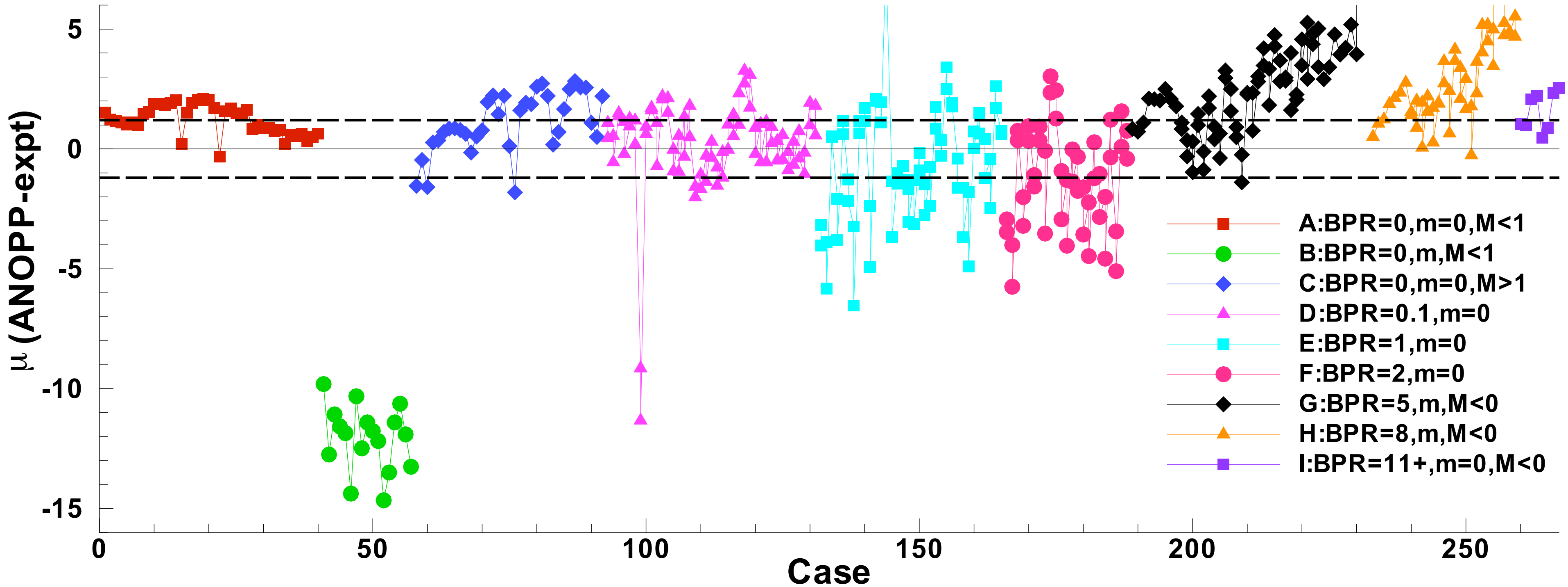
Statistical

Jet3D vs Expt



Average Error in Jet Noise OASPL
All ANOPP Assessment Cases

ANOPP ST2Jet model



- BPR - Bypass Ratio
- M - Mach number
- m - Azimuthal Geometry (ex. Chevrons)

- Percent within uncertainty:
  - 51% m = 0
  - 21% m > 0 (B,G,H)

Jet Noise Prediction Assessment Summary

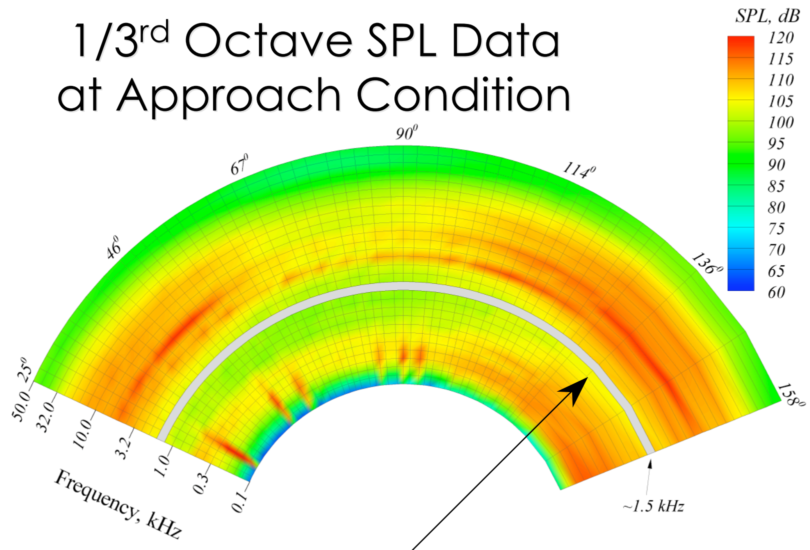
- Overall findings
  - No empirical nor statistical model predicts noise of *all* subsonic axisymmetric nozzle flows within experimental uncertainty.
  - The ANOPP code predicts spectral directivity *to within 2dB* for axisymmetric nozzles over a broad range of conditions.
  - The statistical code JeNo v1.0 predicts spectral directivity to within experimental uncertainty for subsonic *cold* jets, but deviates when either jet speed or temperature is elevated.
  - The spectral code Jet3D does not predict any of the jets very well, missing both the directivity and the peak frequency.
- Recommendations
  - Use ANOPP for round jets, minding the 2dB error bar.
  - Add temperature-related sources to JeNo. Enhance source model to better describe noncompactness.
  - Investigate shortcomings of Jet3D for basic jets.

Fan Noise Prediction Assessment Highlights

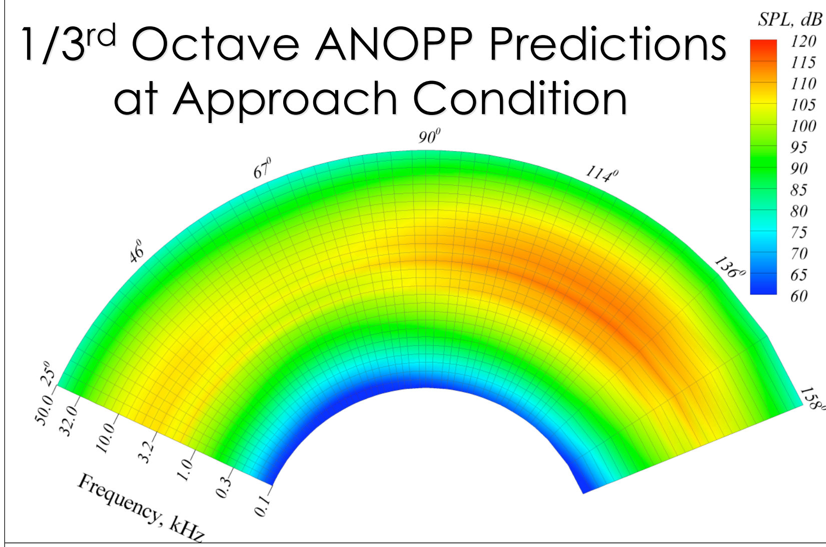
- **Goal:** Assess current fan noise prediction capability
- **Approach:** Compare predictions from representative codes to benchmark datasets
- **Codes:** Representative codes include:
  - Empirical: HDFAN module in ANOPP L25/V3
  - Analytical: V072 & RSI codes
  - Computational (i.e., CAA): LINFLUX code
- **Benchmarks:** Measured data from three 22-inch scale model fans covering the following bypass ratios:
  - ADP: Ultra high bypass ratio
  - SDT: High bypass ratio
  - QHSF: Low bypass ratio

ANOPP Representative Results (ADP Fan)

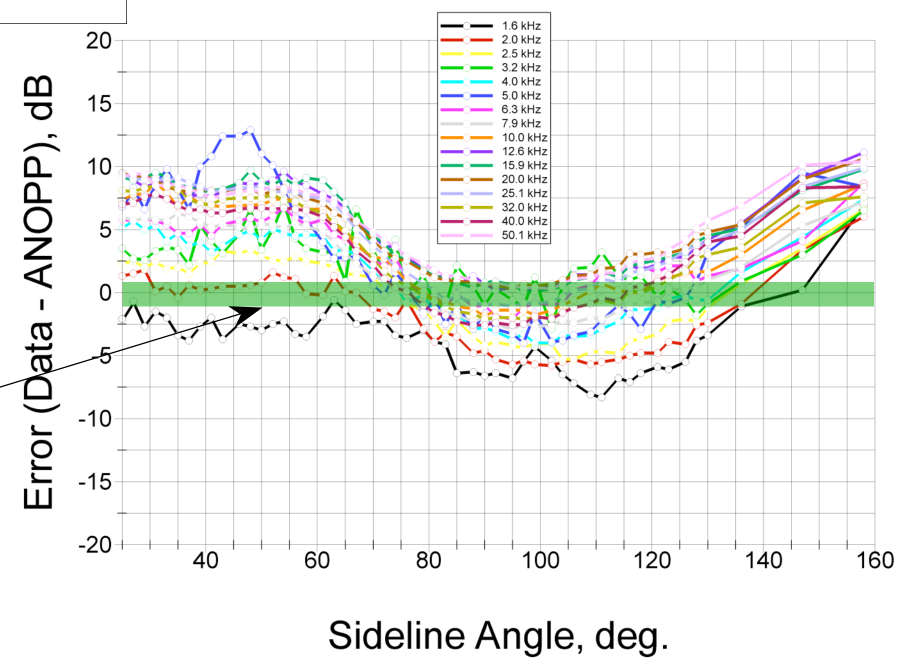
1/3rd Octave SPL Data at Approach Condition



1/3rd Octave ANOPP Predictions at Approach Condition



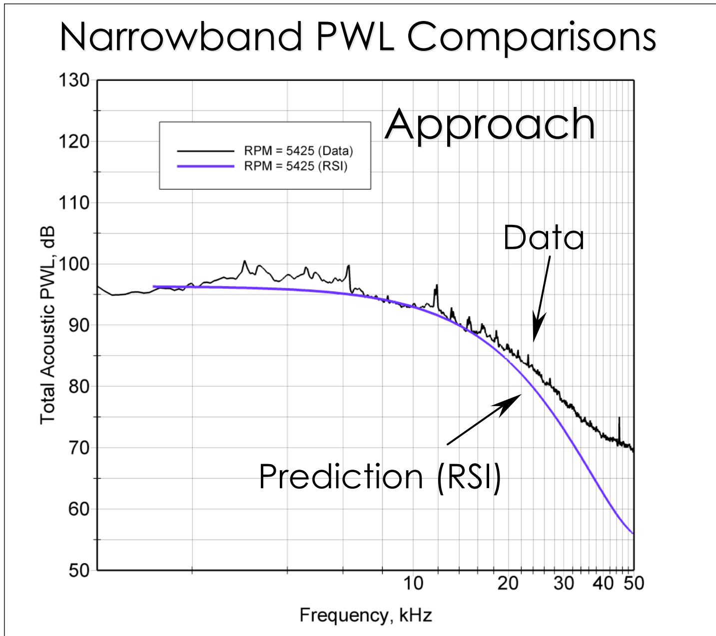
Data/Theory Comparisons

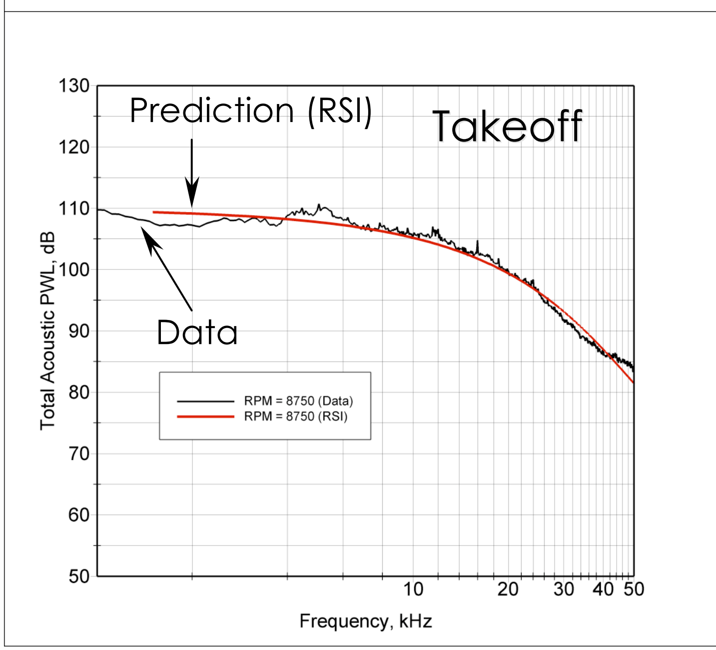


Measured fan noise data contaminated with drive rig noise below about 1.5 kHz.

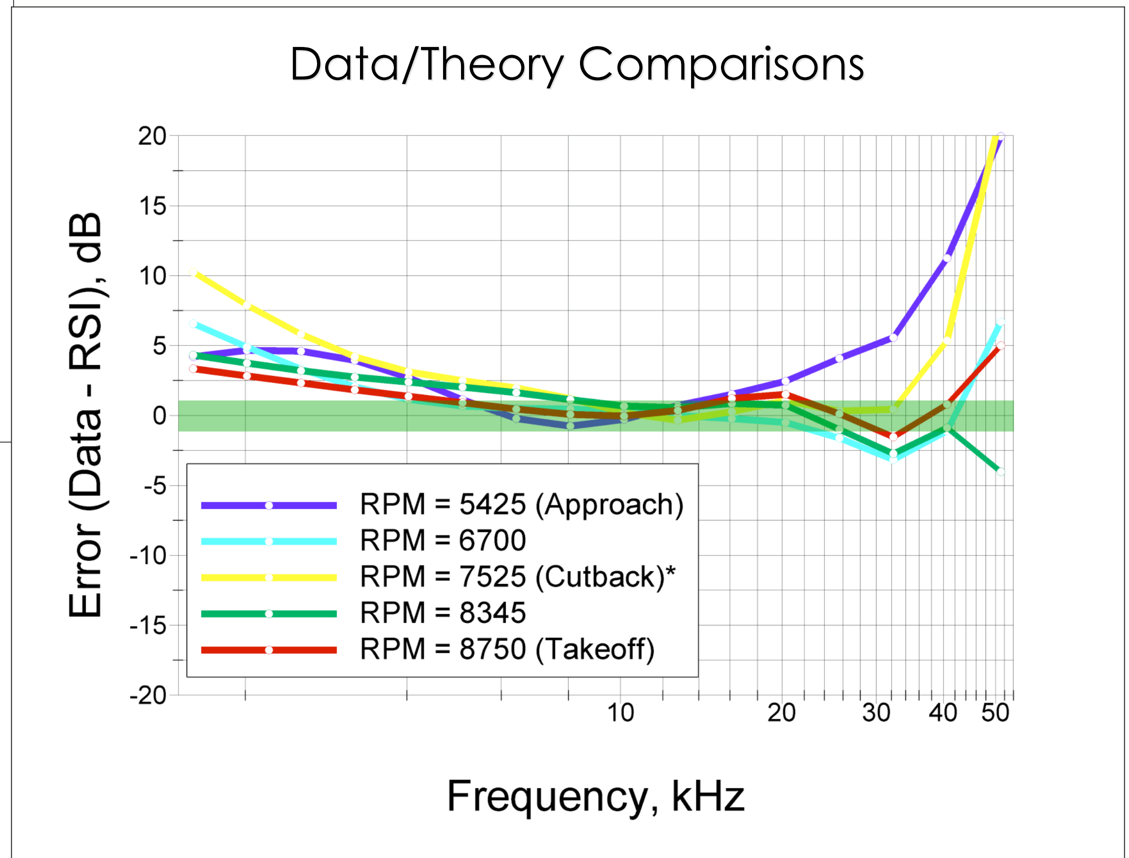
Green band (±1 dB) represents the measurement uncertainty.

RSI Representative Results (ADP Fan)





Green band (±1 dB) represents the measurement uncertainty.



*** Measured data for the cutback condition are suspect due to the presence of extraneous tone content that are inconsistent with the design of the fan, but have been included in the analysis for the sake of completeness.**

Fan Noise Summary

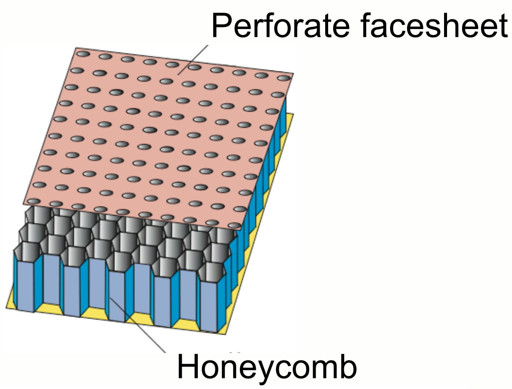
- **ANOPP:**
  - Predictions are within ±5 dB of measured sideline sound pressure levels with some exceptions below 2 kHz, and for angles larger than 135°, where the error is larger.
  - Data/theory discrepancy trends are more consistent above 10 kHz.
  - ADP was not part of the database of fans from which the existing HDFAN module of ANOPP was created.
  - All ANOPP calculations have been completed and the results analyzed.
- **RSI:**
  - The code predicts the measured acoustic power levels to within 5 dB or less below 4 kHz and to within 2.5 dB or less in the range of 4 kHz to 30 kHz. Above 30 kHz the discrepancies can be larger depending on the fan tip speed.
  - The code, for the most part, tends to underpredict the measured levels.
  - The predictions for the SDT and QHSF are being generated and analyzed.
- **V072 & LINFLUX:**
  - The predictions are being generated for up to the first three harmonics of the blade passing frequency.

Sample Results for Liner and Duct Acoustics

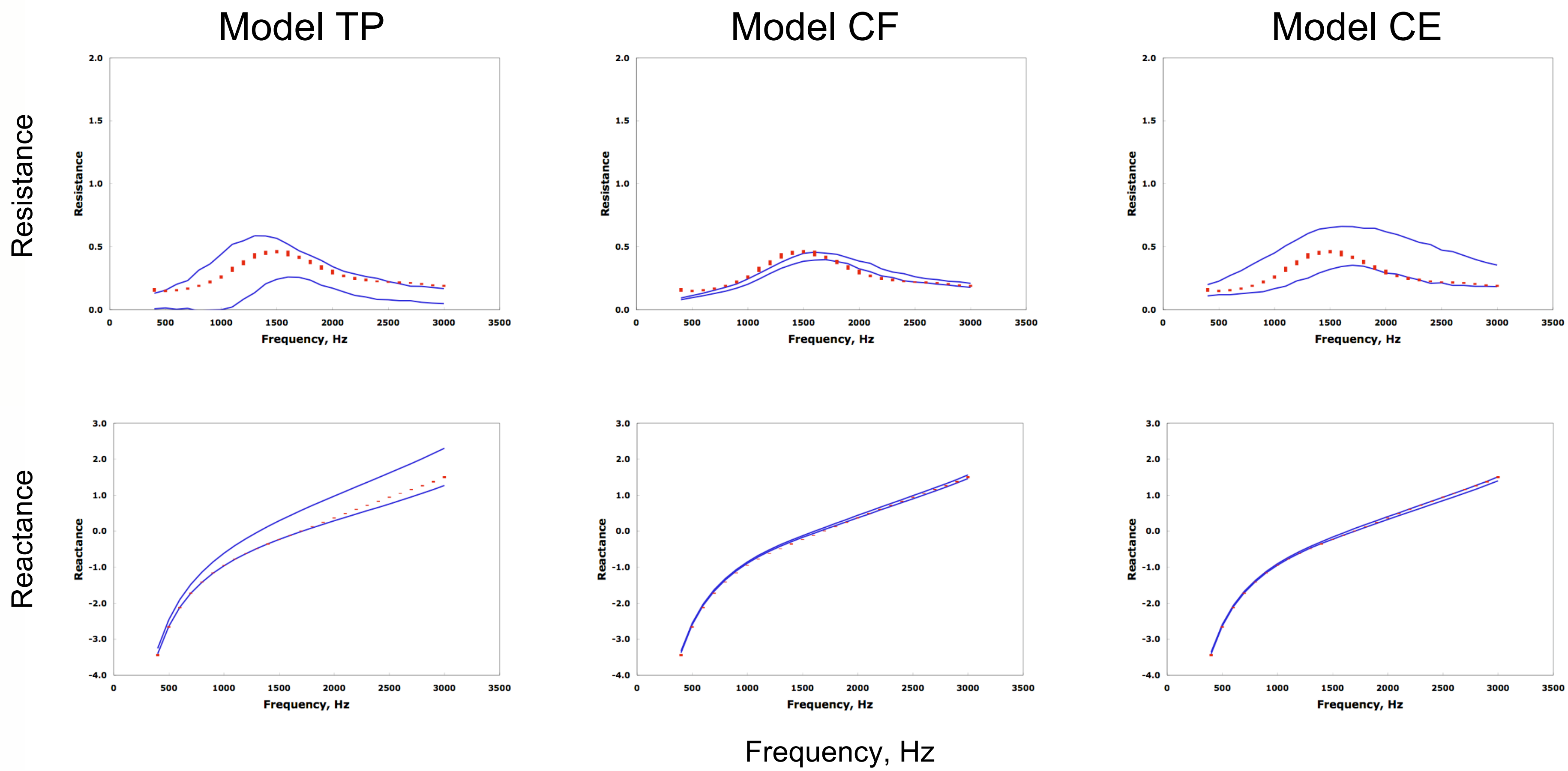
Topic	Codes					
Airframe						
Flaps	ANOPP-L25					
Slats	ANOPP-L25	CFL3D				
Landing Gear	ANOPP-L25	CFL3D				
Propulsion Airframe Aeroacoustics	JET3D					
Aircraft System	ANOPP-L25					
Engine System	ANOPP-L25					
Fan	ANOPP-L25	RSI	V072	Linflux		
Jet	ANOPP-L25	JeNo	JET3D			
Liner Physics	Two-Parameter	Crandall Full Solution	Composite Empirical	Fluid Mechanical		
Duct Acoustics	CH3DPA	LEE2DDS	CH2DDS	CH3DDS	LEE2DIS	LEE3DIS

Yellow	Semi-Empirical
Green	Statistical + CFD
Cyan	Analytical + CFD
Purple	Numerical/CAA

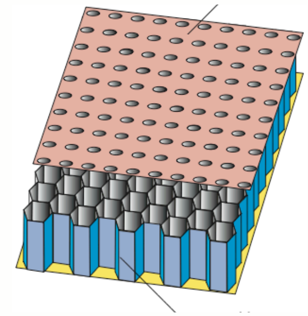
Impedance Comparisons



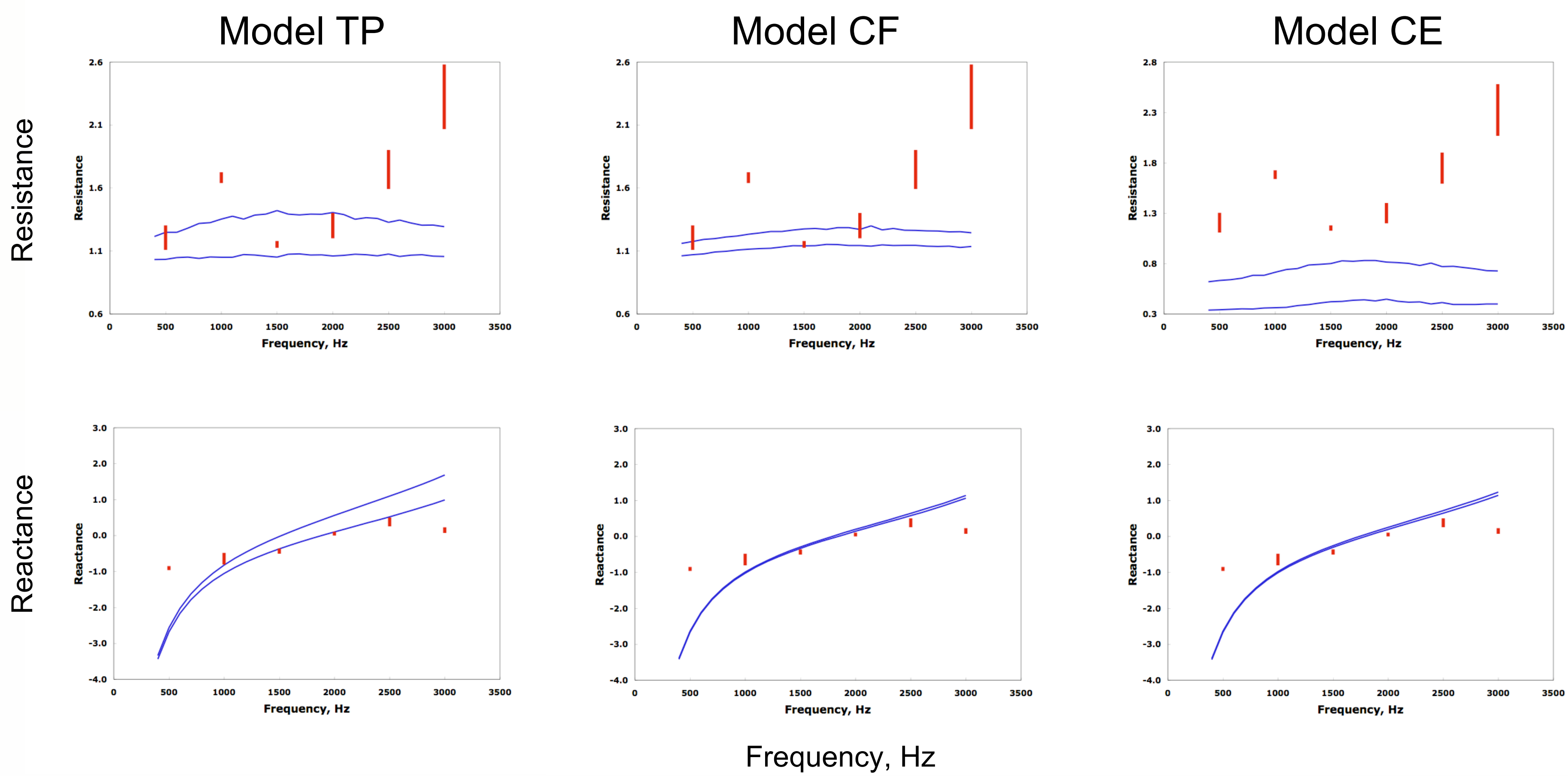
- 14 NIT Measurements (Red), 31 Simulations (Blue)
- 95% Confidence Intervals Shown
- No Flow, Source: 140 dB SPL



Impedance Comparisons with Flow

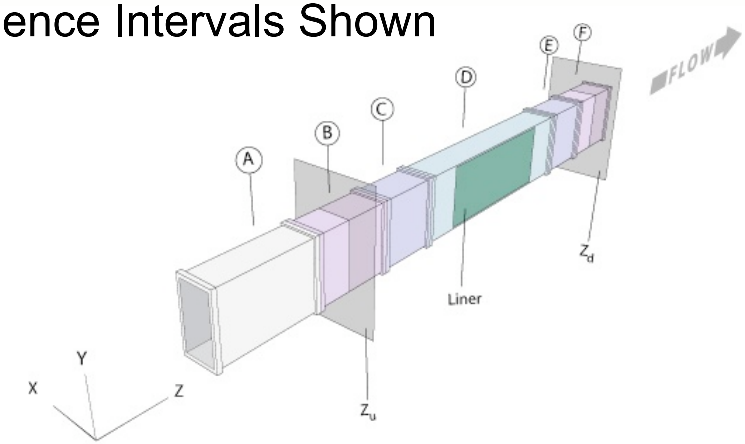


- 10 GIT Measurements (Red), 31 Simulations (Blue)
- 95% Confidence Intervals Shown
- Flow condition: M = 0.4, Source: 140 dB SPL



Acoustic Attenuation in a Flow Duct
Example Result Format

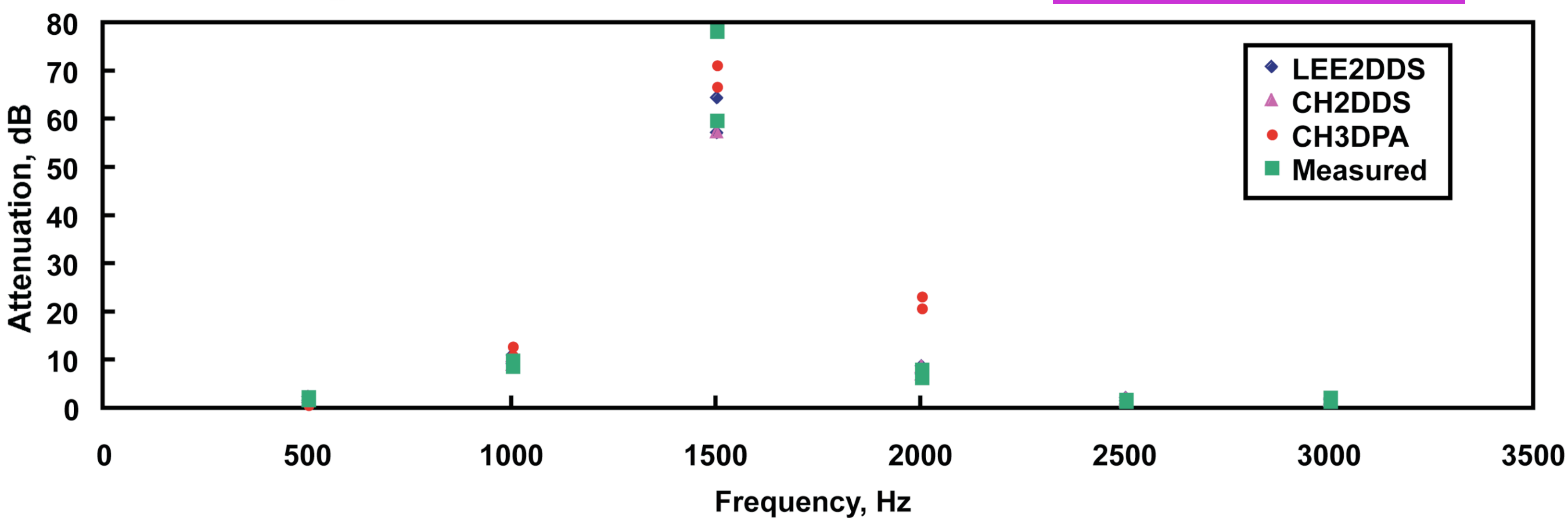
- 8 GIT Measurements, 31 Simulations for each code
- 95% Confidence Intervals Shown
- No flow



$$\phi(z) = \int_0^b \int_0^a I(x,y,z)\,dxdy$$

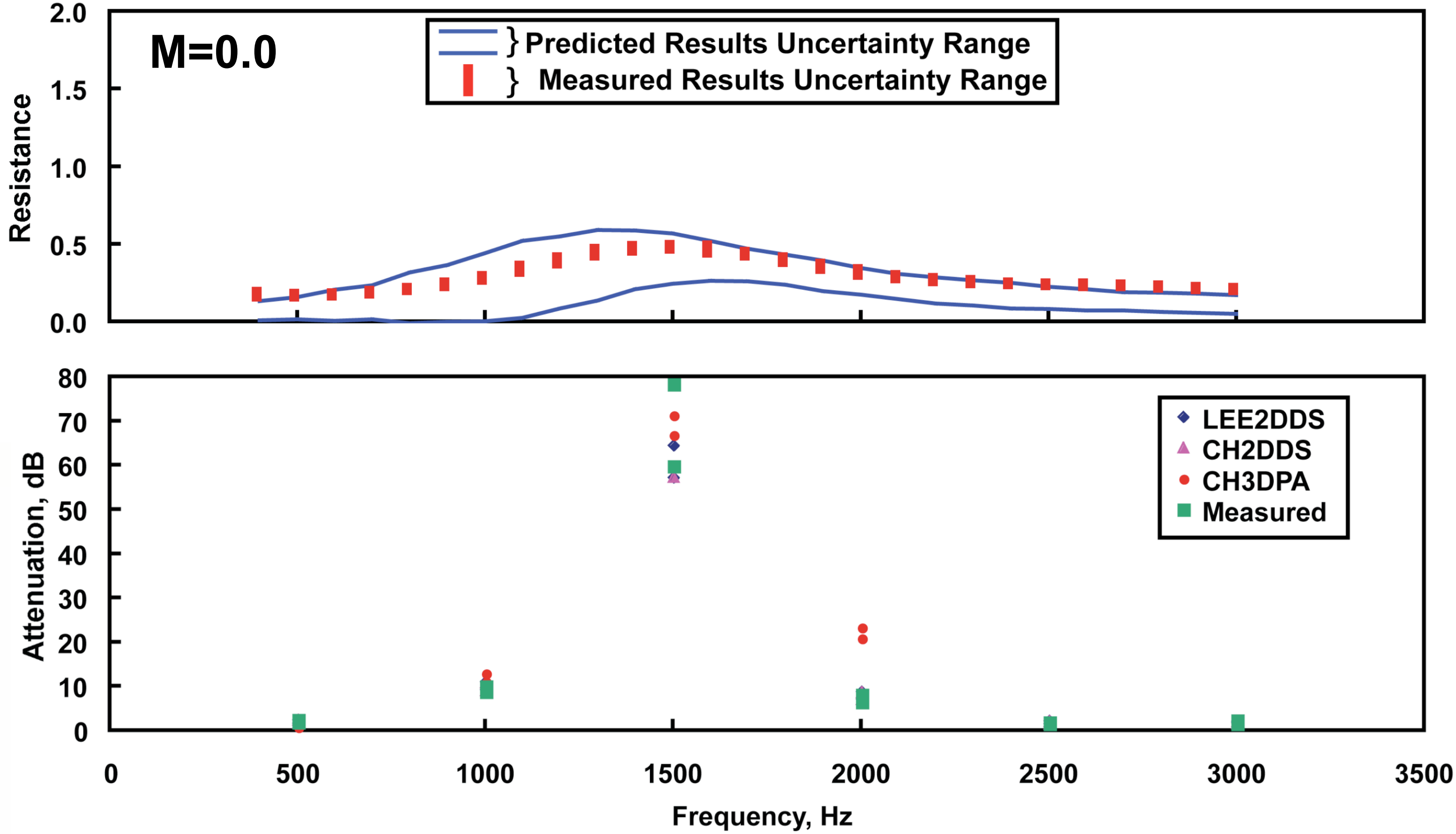
Attenuation

$$\Delta dB = 10\log_{10}\left(\frac{\phi(z_u)}{\phi(z_d)}\right)$$



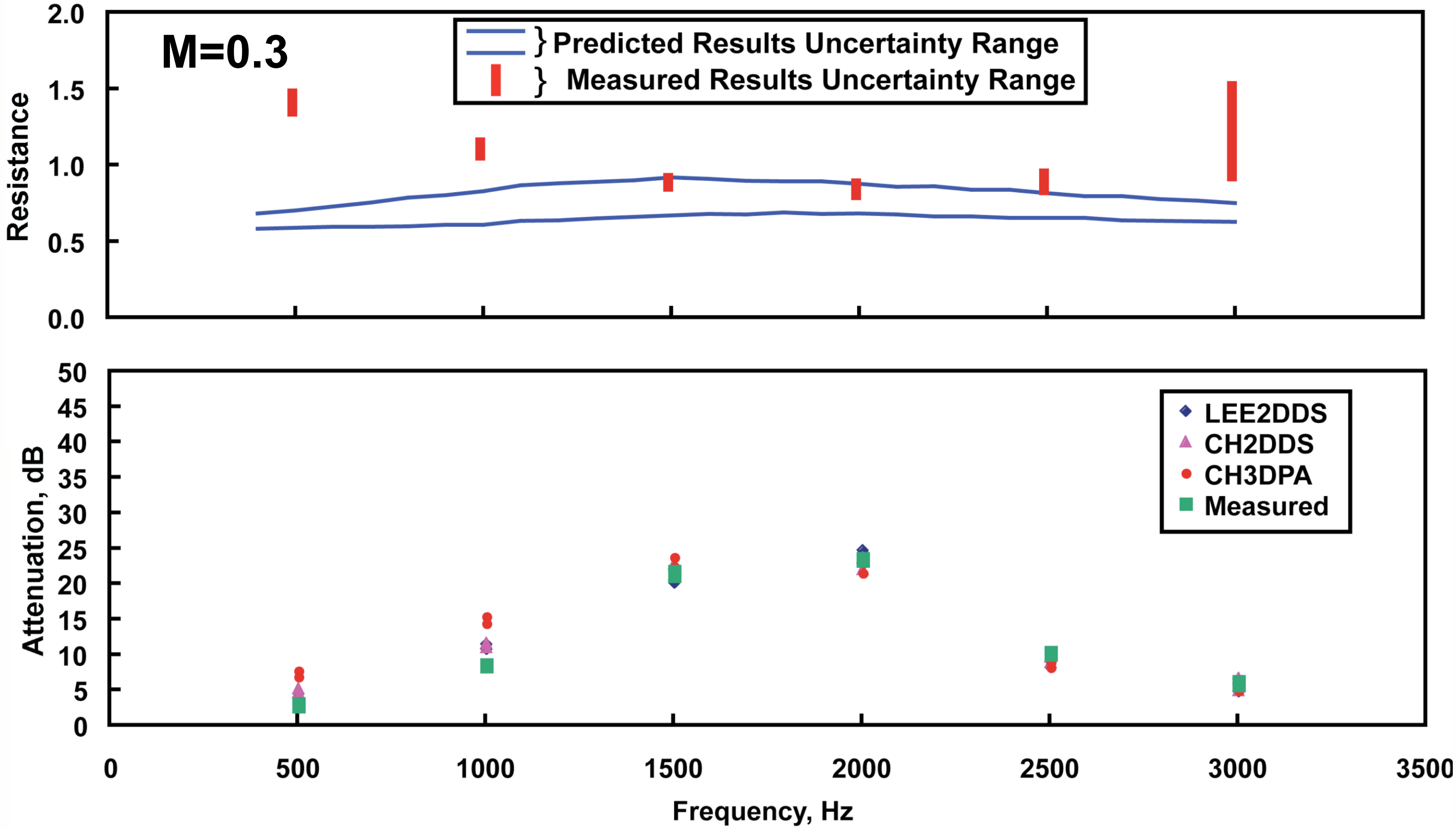
Liner Physics / Duct Acoustics

Comparison of representative measured and predicted confidence intervals for typical single-layer perforate-over-honeycomb liner



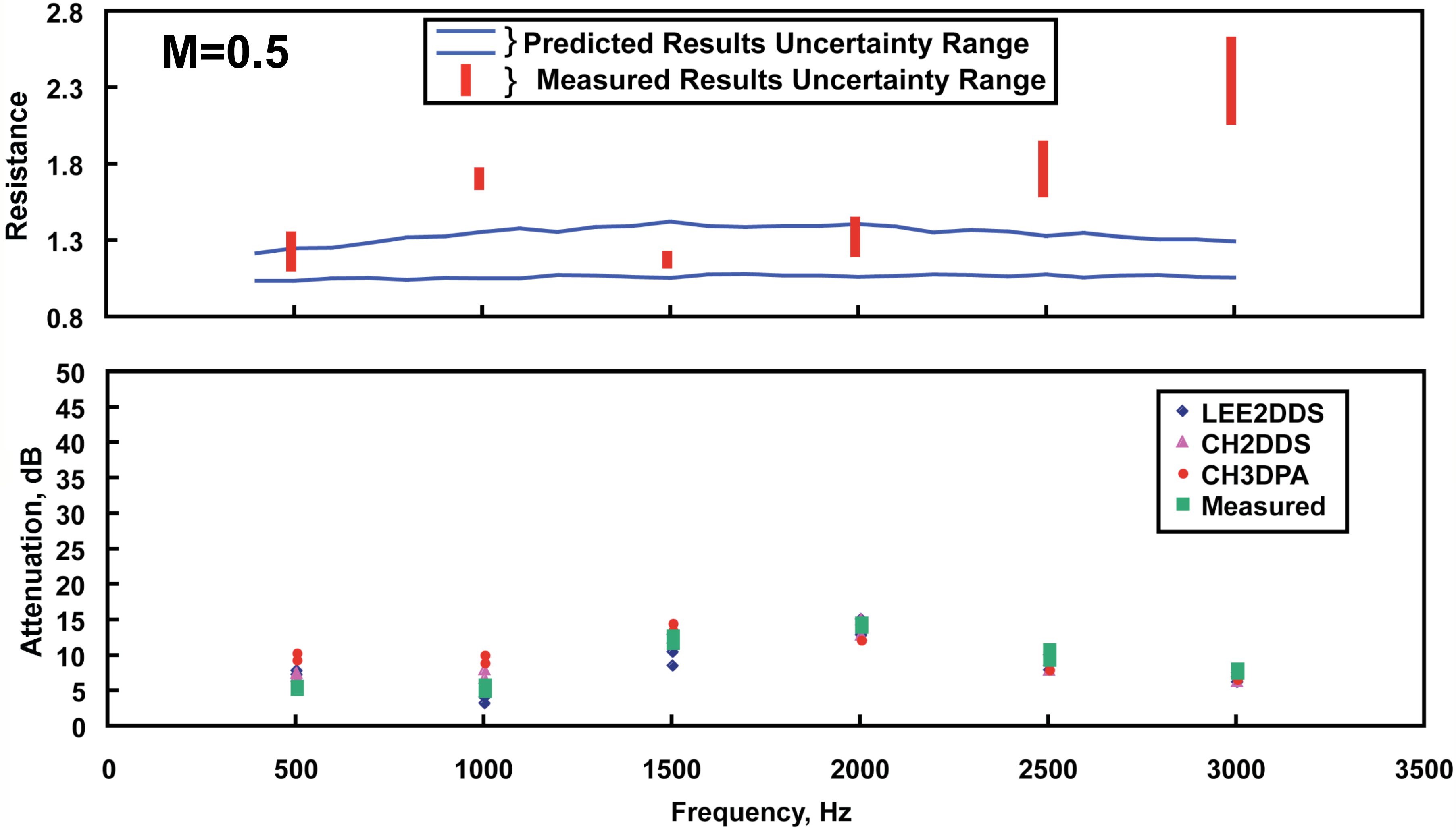
Liner Physics / Duct Acoustics

Comparison of representative measured and predicted confidence intervals for typical single-layer perforate-over-honeycomb liner



Liner Physics / Duct Acoustics

Comparison of representative measured and predicted confidence intervals for typical single-layer perforate-over-honeycomb liner



Liner Physics / Duct Acoustics

Key Findings

- Consistent trends observed in computational results
  - Comparison of four impedance prediction models
  - Comparison of five propagation codes
- Difference between predicted and measured results increases with mean flow velocity
- Impedance prediction and SPL attenuation confidence intervals are inversely related
- Measured confidence intervals tend to be much smaller for reactance than for resistance
- Differences between predicted and measured SPL attenuations are accentuated by choice of single-layer liner
  - Due to dominance of resonance effect
  - Expect less frequency dependence for two and three-layer liners

Liner Physics / Duct Acoustics

Plans

- Incorporate 3-D aeroacoustic effects into the impedance eduction model
  - Non-uniform mean flow
  - Boundary layer growth (evaluate with new Grazing Flow Impedance Tube)
  - Effects of geometry (evaluate curvature with Curved Duct Test Rig)
  - Higher-order modes
- Conduct tests with multiple “calibration” liners to validate eduction model
  - Linear (independent of mean flow and SPL)
  - Liner impedance can be predicted from first principles
- Conduct impedance prediction & propagation model input-parameter sensitivity studies
- Incorporate more efficient parallel solvers
  - Increase fidelity
  - Reduce computational time
- Provide increased fidelity propagation/radiation modules for use in system analysis tools (e.g., ANOPP)

Concluding Remarks

- Individual topics summarized throughout the presentation, systems and components
- Sample of results presented
- Over 40 contributors to this assessment
- Detailed results to be given in a forthcoming NASA Technical Publication

Concluding Remarks

Computational predictions are important, they contribute to:

- MDAO capability
- Supplement and guide experiments and testing
- System performance for certification

Establish credibility by following verification and validation practices in noise prediction:

- Primary means of assessing accuracy
- Gives confidence in computed results