Airframe Noise Modeling and Prediction

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September, 2016

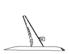
Outline

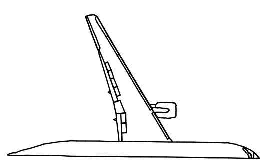
- Introduction
- Noise Source Mechanism
- Physics Based Modeling
- Validation
- Summary

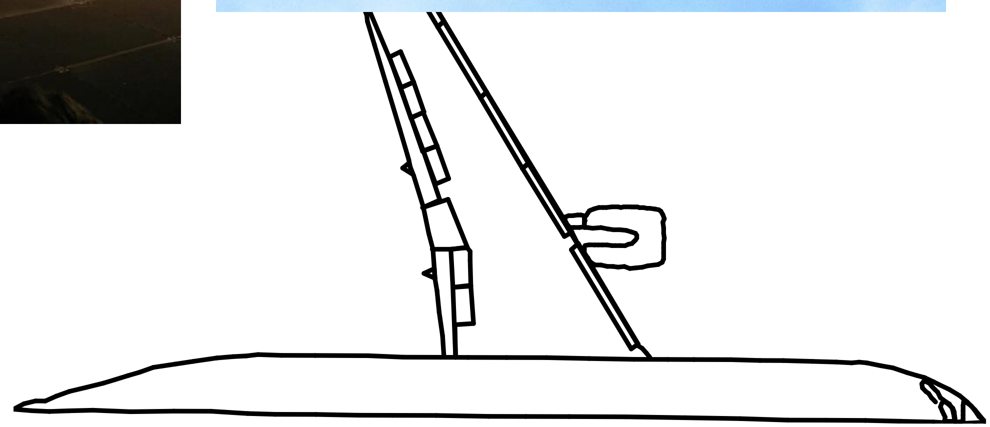
Challenges in Airframe Noise Research

- Strong aerodynamic and aeroacoustic coupling between components
  - Source flows determined by overall high lift system
  - Multiple reflection and scattering between components
- Scale and complexity of airframe structure
  - Full scale/full configuration tests very costly
  - Full-blown computation not feasible
- Scarcity of quality component data
  - Free field microphone data only for total noise
  - Potential engine noise in flight tests
  - Background noise and Reynolds number effects in WT
  - Uncertainties in component decomposition

Systematic Airframe Noise Research (777 Model)





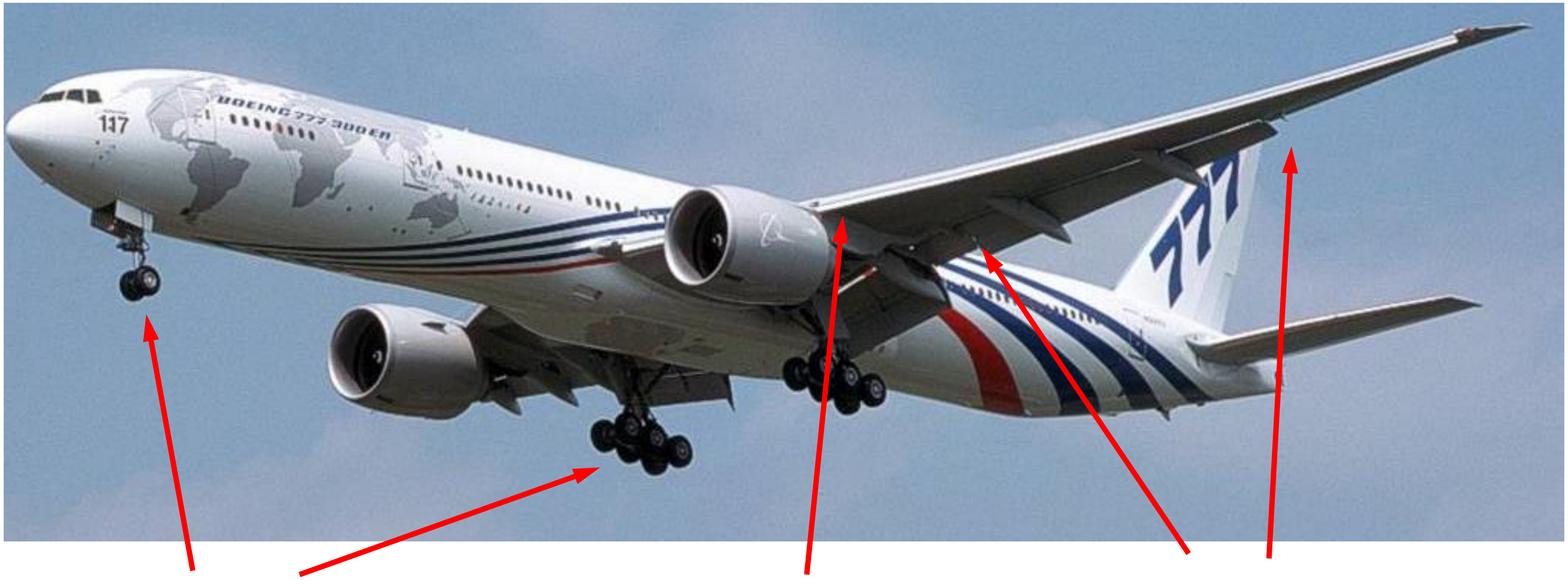


6.3% Scale Model
Boeing Low Speed Aeroacoustic Facility

26% Scale STAR Model
NASA Ames 40x80 ft Wind Tunnel

Full Scale
Boeing/NASA Quiet Technology Demonstrator (QTD1 and QTD2)

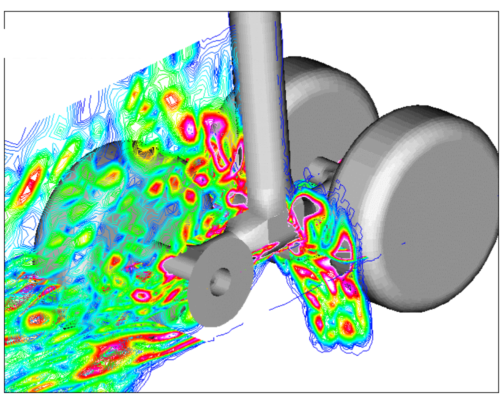
Dominant Airframe Noise Sources

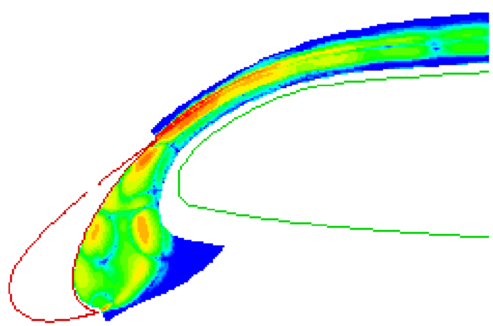


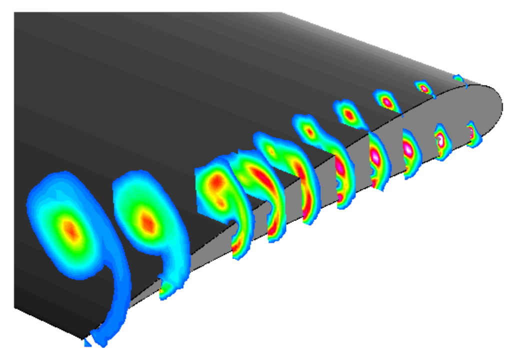
Landing Gear

Leading Edge Slat

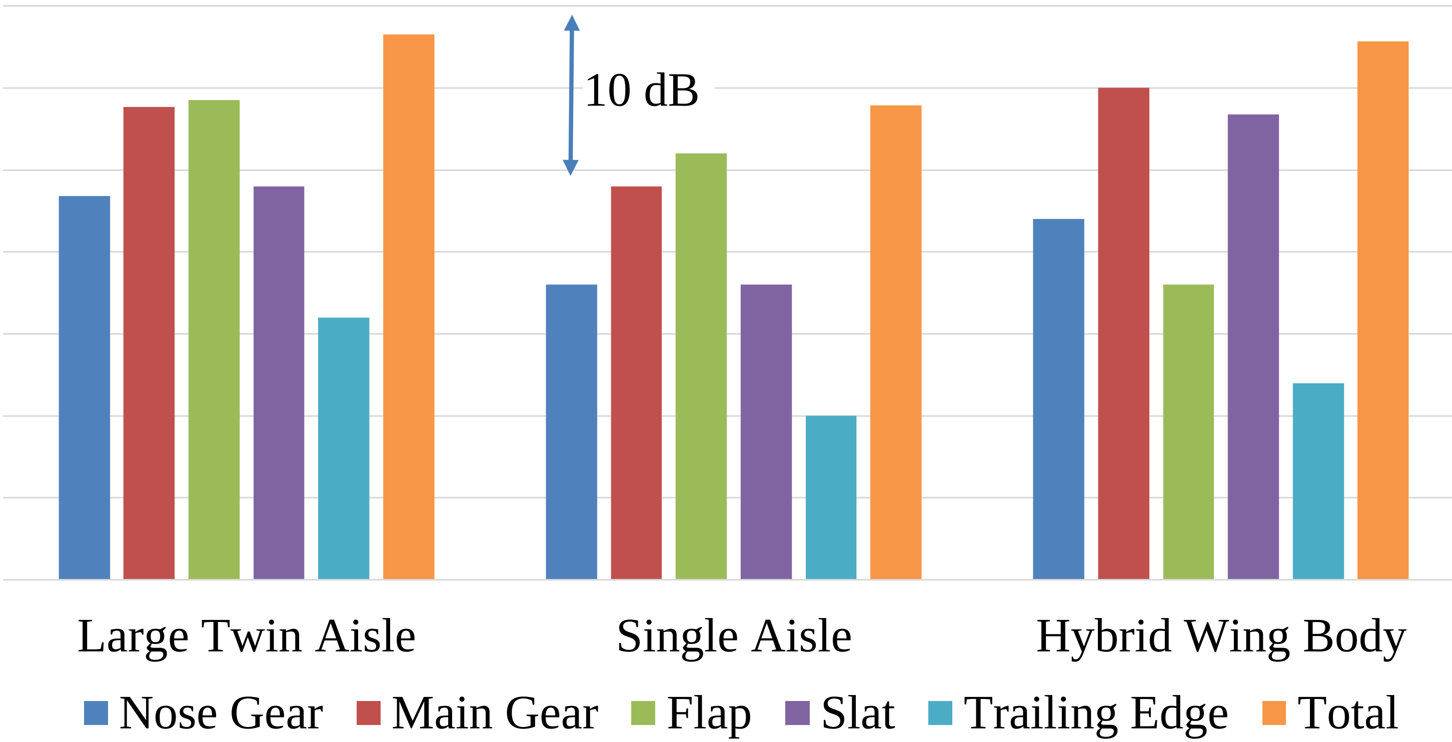
Flap Side Edge



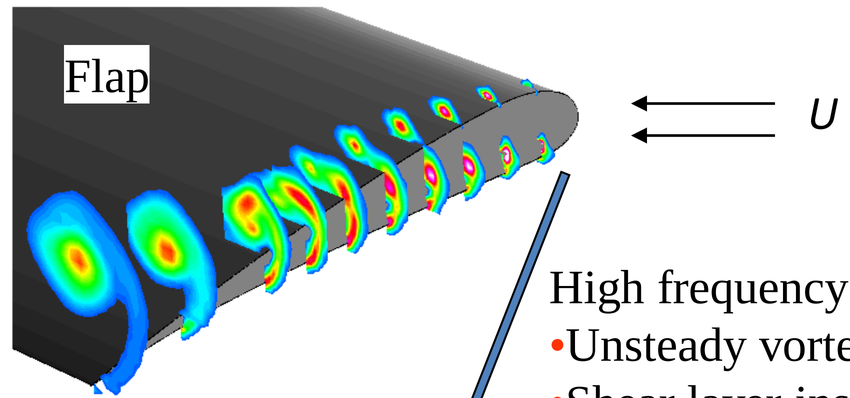




Airframe Noise Components

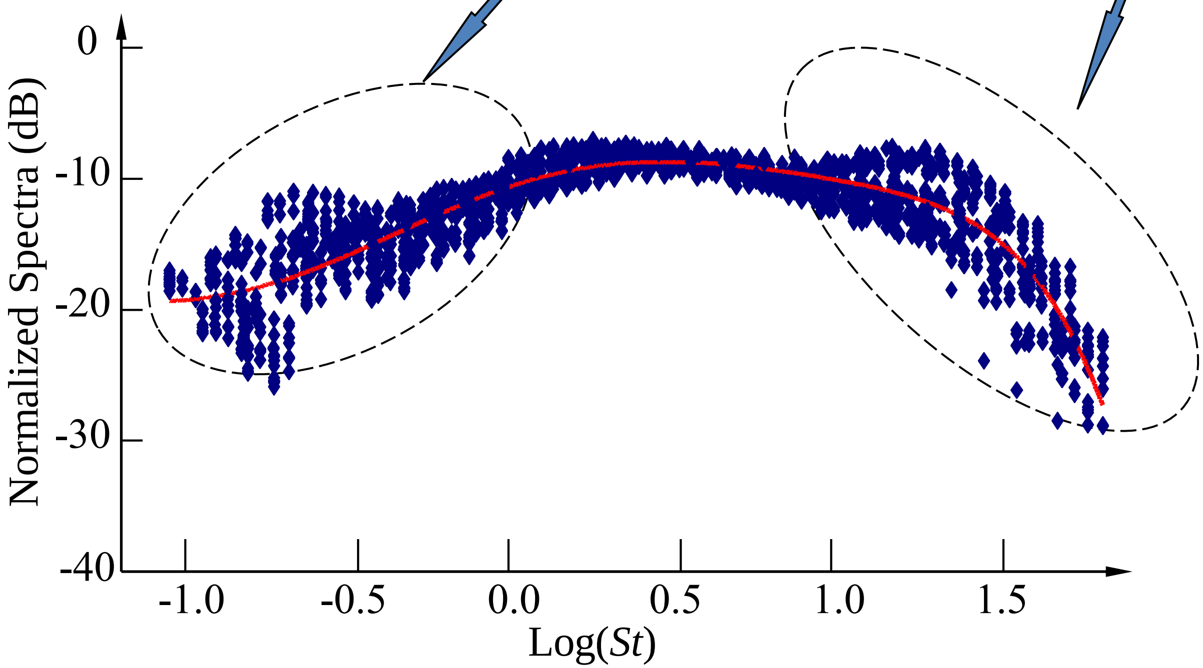


Flap Side Edge Noise Sources



Low frequency noise:
- Large scale vortex oscillation
- Vortex-edge interaction

High frequency noise:
- Unsteady vortex shedding
- Shear layer instability



233 datasets for various aircraft types at various flow and geometry conditions

Flap Side Edge Noise Characteristics

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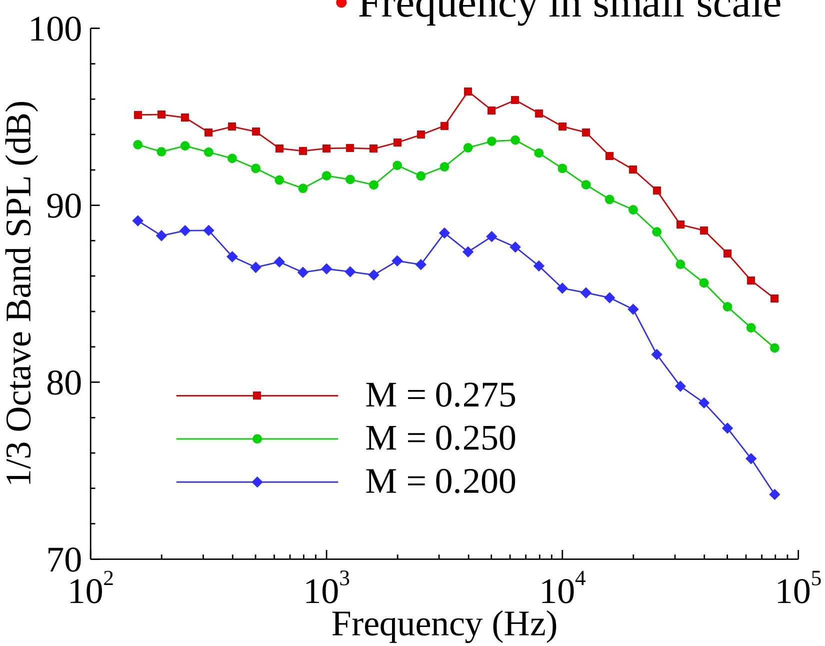
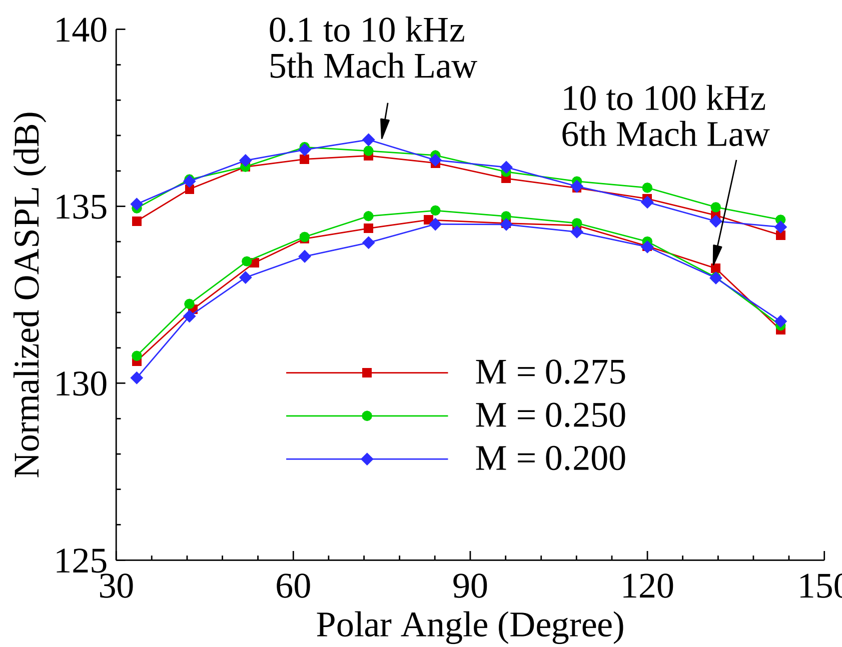
Frequency Domain	Source Mechanism	Spectrum	Mach Scaling	Peak Directivity
Low	Vortex-Edge Interaction	Gradual Variation	5^{th} Power	Overhead
High	Shear Layer Instability	Fast Falloff	6^{th} Power	Forward Quadrant

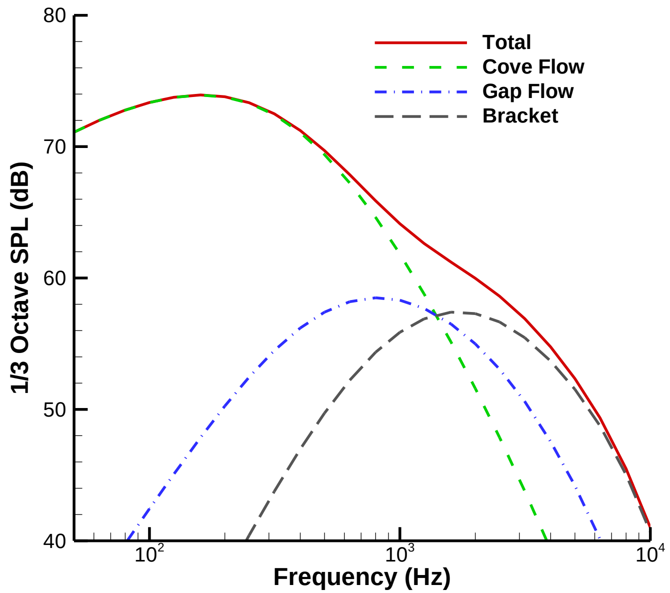
- 4.7% DC-10 model
- Slat angle = 20 degrees
- Flap angle = 50 degrees
- Frequency in small scale

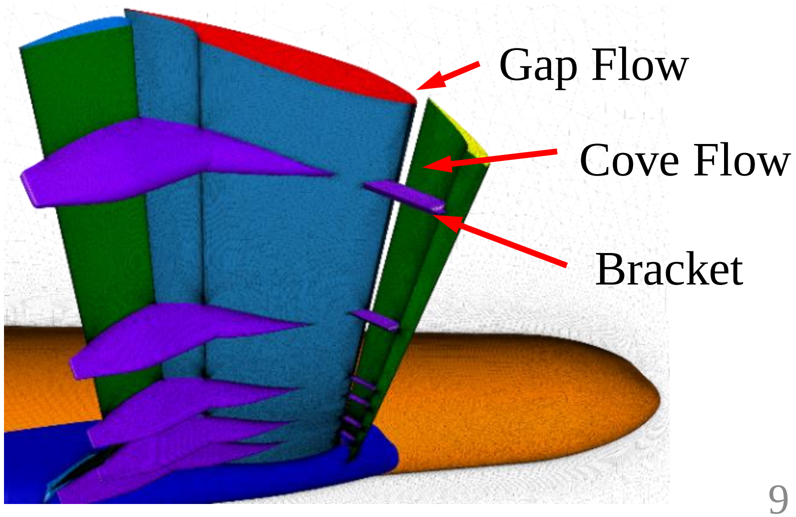




Slat Noise Sources

	Cove	Gap	Bracket
Mechanism	Flow Separation	Vortex-Edge Scattering	Bluff Body Flow
Directivity	Dipole Normal to Chord	Half Dipole	Dipole Normal to Strut
Spectrum	Low and Mid Frequency	Mid and High Frequency	Mid and High Frequency
Mach Scaling	5^{th} to 6^{th}	5^{th} to 6^{th}	6^{th} to 7^{th}
Amplitude	AOA, Gap, M	AOA, Gap, M	Local Flow, Strut, M
Length Scale	Chord	Gap Width	Strut Size
Source Size	Chord × Span	Width × Span	Size × Length





Slat Noise Characteristics

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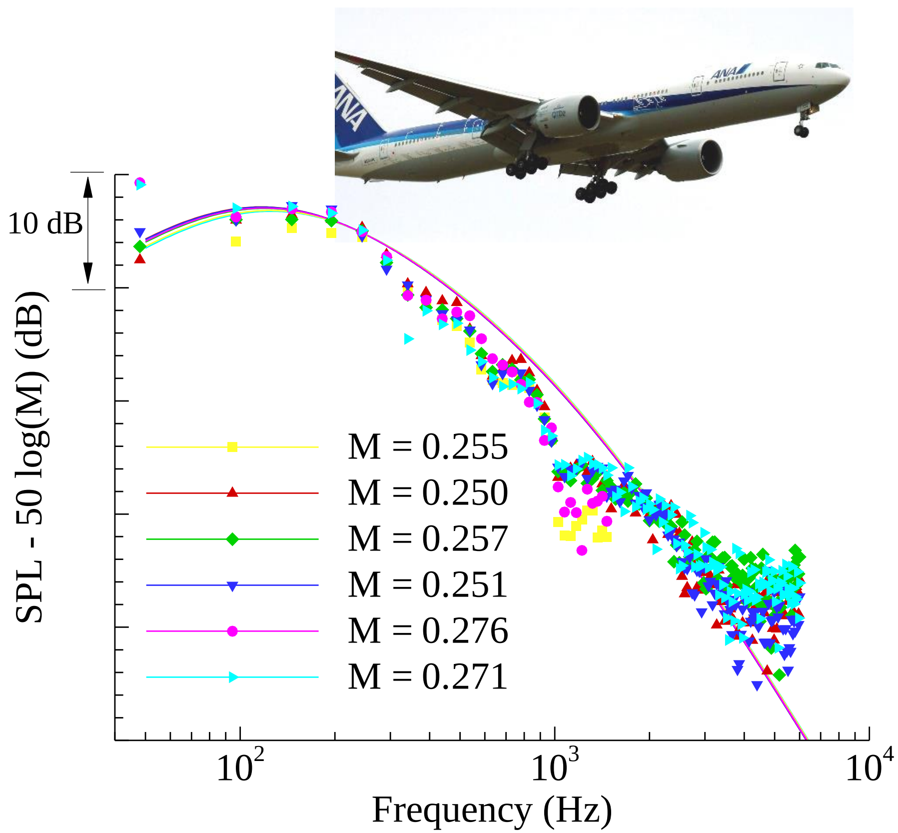
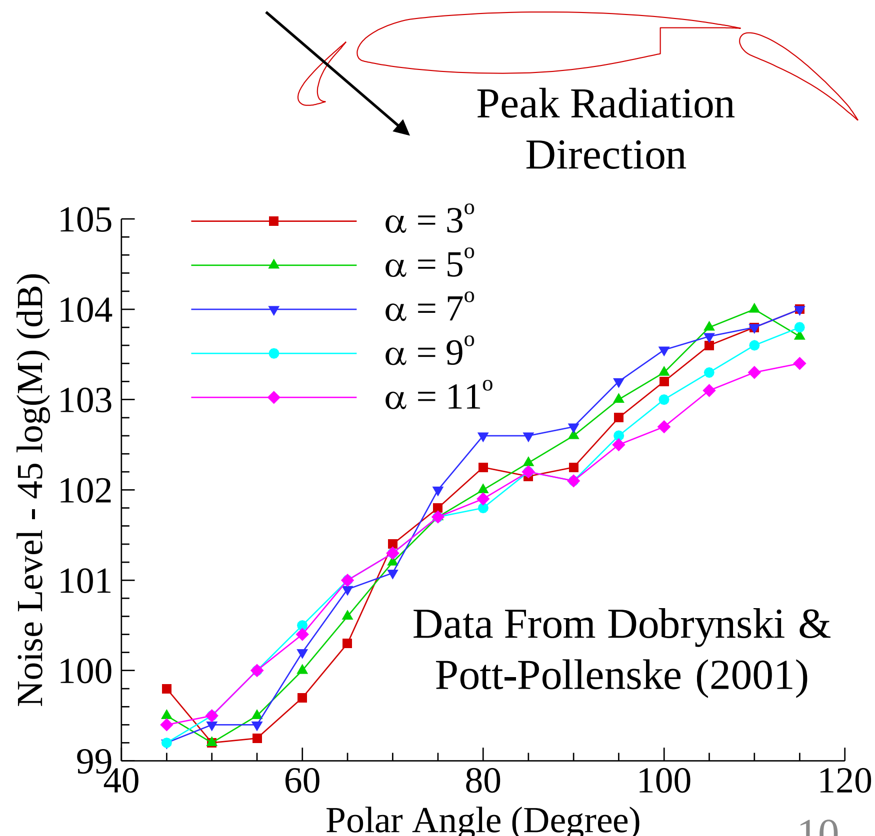
- Boeing 777 flight test
- Certification conditions
- Broadband spectra
- Fifth power scaling for Mach number
- Spectral peak scaling on slat chord



- Wind tunnel test
- Peak radiation angle in aft quadrant
- Surface dipole radiation
- Trends confirmed by other data

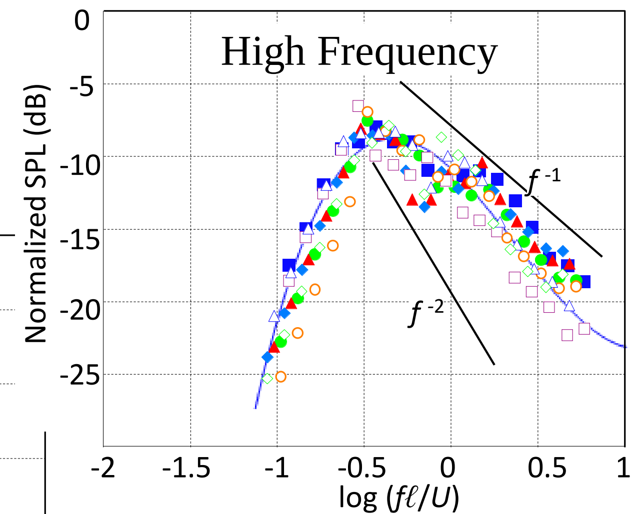


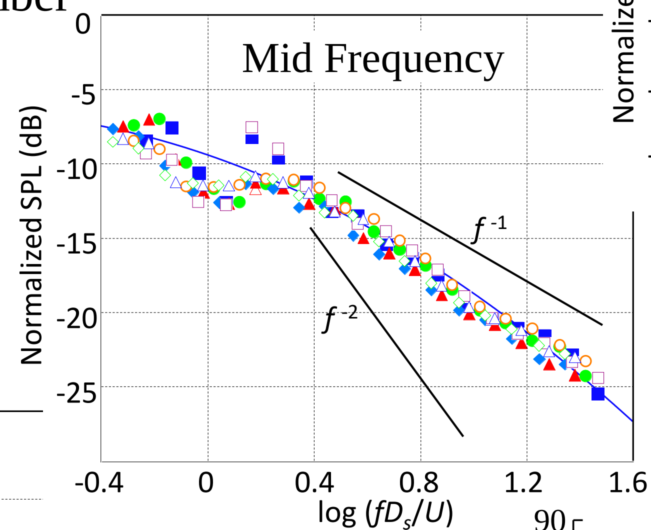
Landing Gear Noise Sources

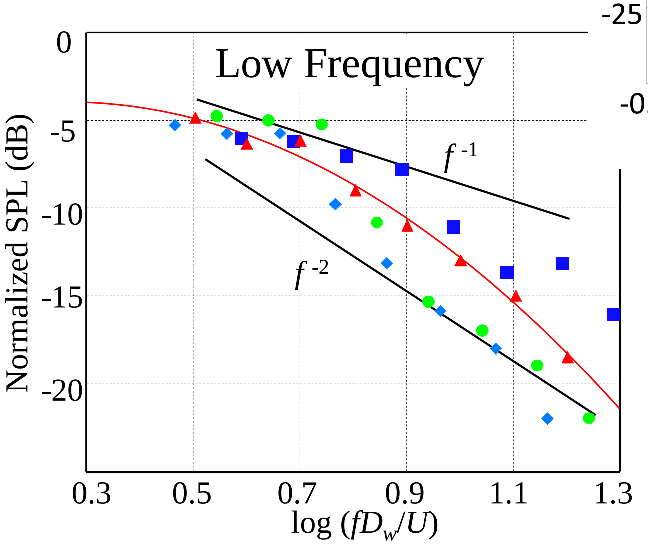
- Source mechanisms
  - Large scale separation
  - Flow/bluff body interaction
- Length scales
  - Wheels: 50 ~ 100 inches
  - Struts: 5 ~ 10 inches
  - Dressings: 0.5 ~ 1 inch
- Strouhal number range: two decades
- Three spectral domains
  - Low frequency scaled on wheel size
  - Mid frequency scaled on main struts
  - High frequency scaled on small details

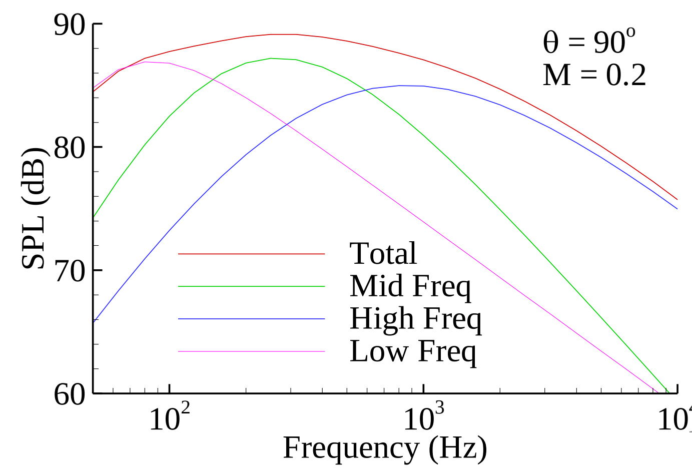
Landing Gear Noise Spectral Decomposition

- Boeing 737 main gear test
- Various flow Mach numbers
- Data collapsing in 3 frequency domains
- 6th power for Mach number
- Broadband spectra

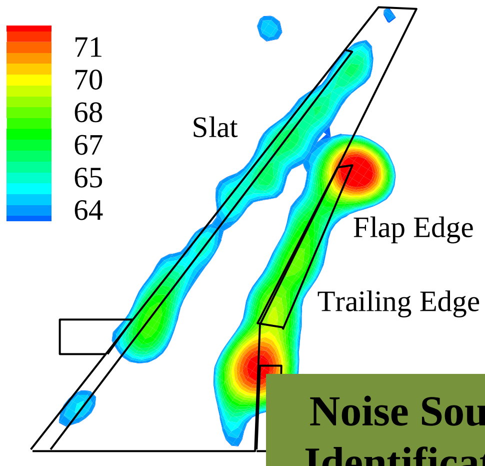


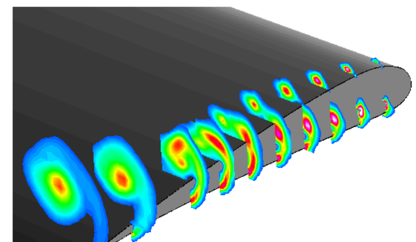




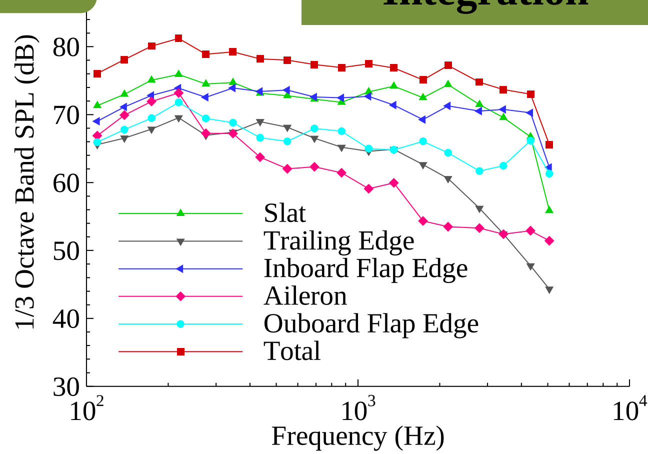


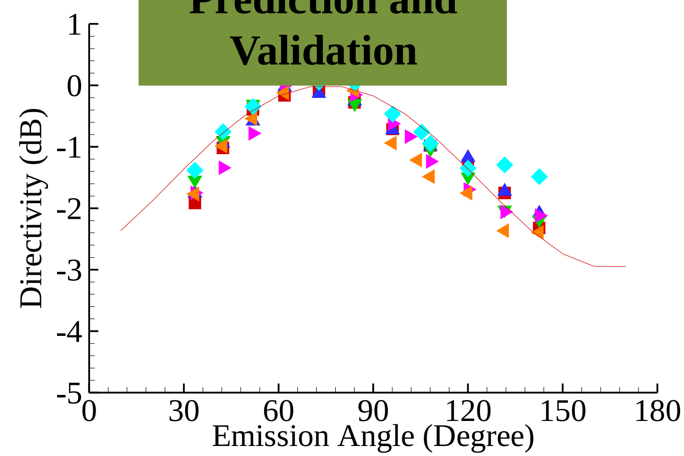
Physics Based Modeling



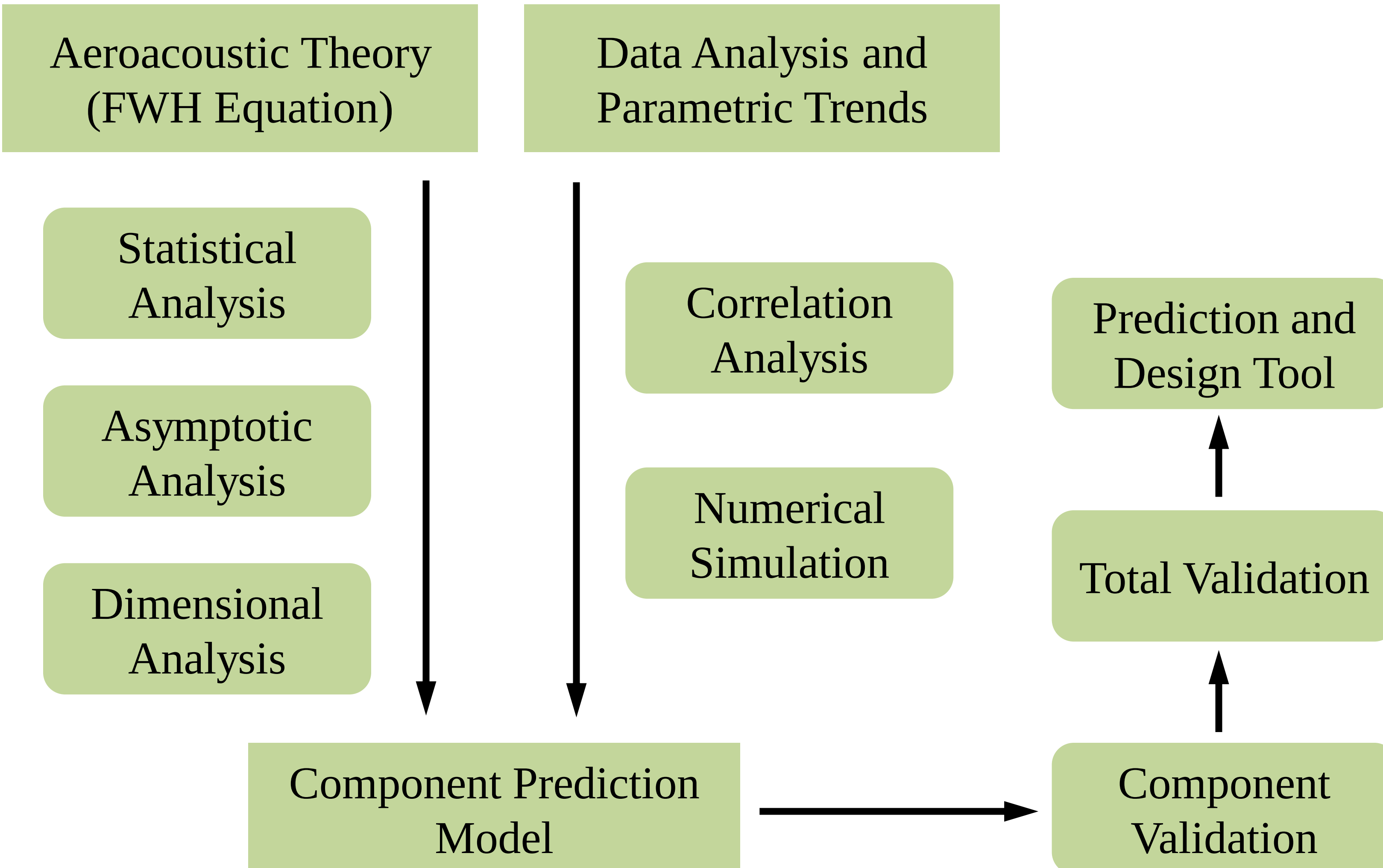


Noise Source Identification → **Flow Physics Modeling** → **Component Prediction and Validation** → **Total Noise Integration** → **Prediction Tool**





Technical Approach



Prediction Model

$$\Pi(\mathbf{x}) = \rho_0^2 c_0^4 A(\alpha,\gamma,\sigma,b,S) W(M) F(f_d, M) D(\theta,\varphi) \frac{S}{\Delta^4 r^2} e^{-\alpha_0 r}$$

Feature	Model	Modeling Approach
Ambient Medium	$(\rho_0 c_0^2)^2$	Dimensional Analysis
Amplitude	$A(\alpha,\gamma,\sigma,b,S)$	Correlation
Mach Number	$W(M)$	OASPL Scaling
Spectral Shape Function	$F(f_d, M)$	Source Statistics
Doppler Shift	f_d	Analytical
Directivity	$D(\theta,\varphi)$	Source Integration
Source Dimension	S	Dimensional Analysis
Convective Amplification	Δ^{-4}	Analytical
Spherical Spreading	r^{-2}	Analytical
Atmospheric Absorption	$e^{-\alpha_0 r}$	Empirical

Derivation of Slat Noise Spectrum

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$$\Pi = \int_{\ell}\int_{k_2} P_0(\mathbf{y})\tilde{\Phi}_1(k_1)\tilde{\Phi}_2(k_2)\tilde{\Psi}(\omega)\left| n_i \frac{\partial \tilde{G}_0}{\partial y_i}\right|^2 dk_2 d\ell$$

- Greens function

$$\left.\begin{aligned}\left|\frac{\partial \tilde{G}_0}{\partial y_i}\right|^2 &\to k_0^2 \quad \text{as} \quad k_0 \to 0\\ \left|\tilde{G}_0\right|^2 &\to \frac{1}{k_0} \quad \text{as} \quad k_0 \to \infty\end{aligned}\right\} \longrightarrow \left|\frac{\partial \tilde{G}_0}{\partial y_i}\right|^2 \sim \frac{k_0^2}{1+\mu_3 k_0}$$

- Temporal coherence

$$\Psi(\tau) = \exp\left(-2\pi \frac{\tau}{\tau_0}\right) \longrightarrow \tilde{\Psi}(f) = \frac{1}{1+\mu_0^2 St^2}$$

- Stream-wise spatial coherence

$$\Phi_1(\xi_1) = \exp\left(-2\pi\left|\frac{\xi_1}{\ell_1}\right| + 2\pi \mathrm{i}\frac{f\xi_1}{U}\right) \longrightarrow \tilde{\Phi}_1(f) = \frac{1}{1+\mu_1^2(1+M)^2 St^2},$$

- Span-wise spatial coherence

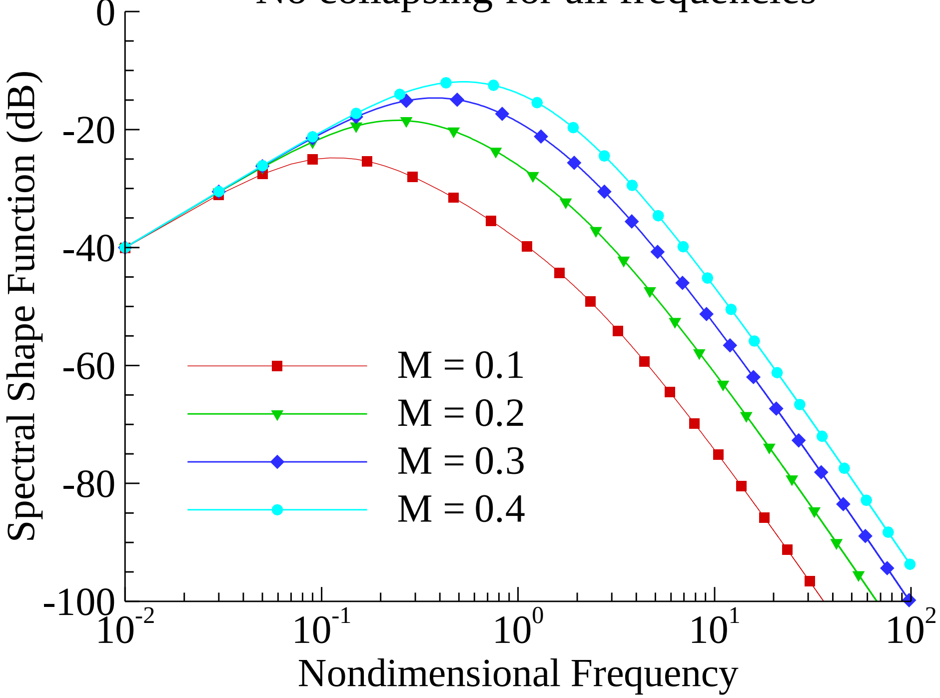
$$\Phi_2(\xi_2) = \exp\left(-2\pi\left|\frac{\xi_2}{\ell_2}\right|\right) \longrightarrow \tilde{\Phi}_3(f) = \frac{1}{1+\mu_2^2 k_0^2},$$

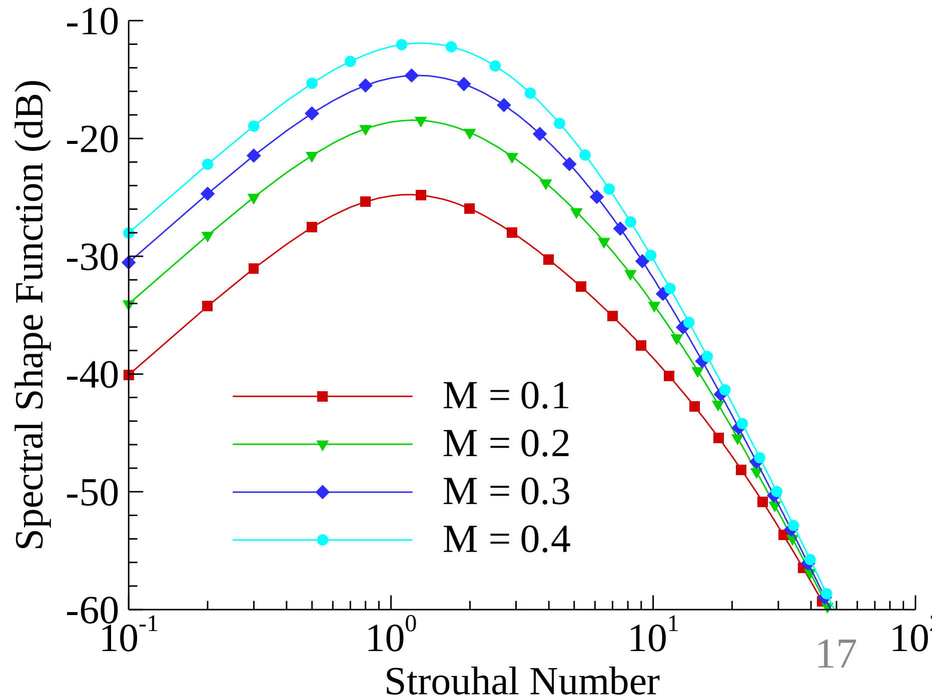
Slat Noise Spectrum

$$F(f,M) = \frac{M^2 S^2}{\left(1+\mu_0^2 S^2\right)\left(1+\mu_1^2 (1+M)^2 S^2\right)\left(1+\mu_2^2 M^2 S_2\right)\left(1+\mu_3 M S\right)}$$

- Depend on frequency and Mach number
- Proportional to f^2 at low frequencies
- Approximately f^{-2} at mid frequencies
- f^{-5} at very high frequencies
- No collapsing for all frequencies

- S = Strouhal Number
- M = Mach Number
- μ_i = Constants (i = 0,1,2,3)





Validation

- Component validation
  - Parametric trends
  - Component amplitude
- Systematic validation
  - Design variation
  - Test condition variation

Flap Noise Component Validation

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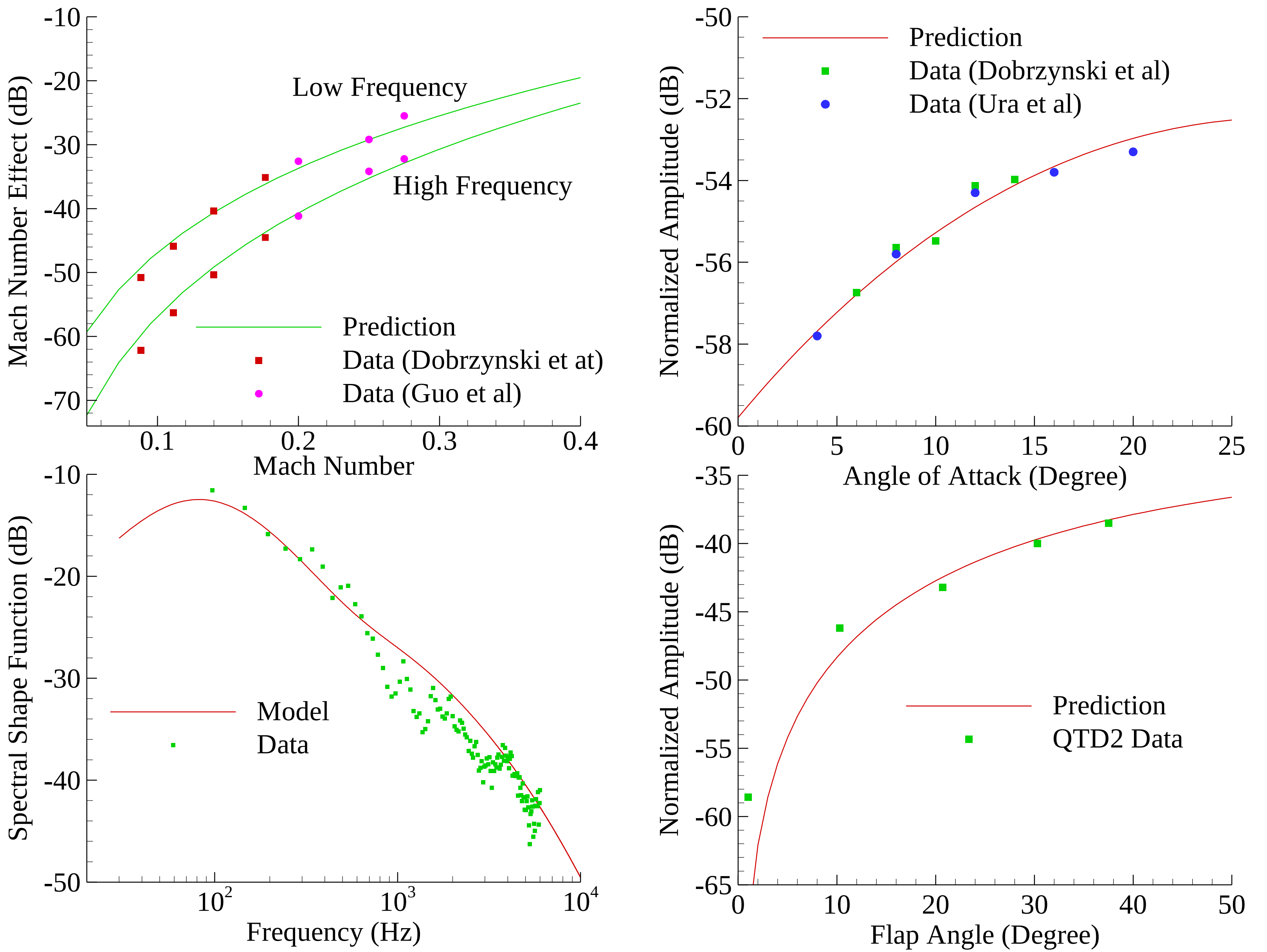

Slat Noise Component Validation

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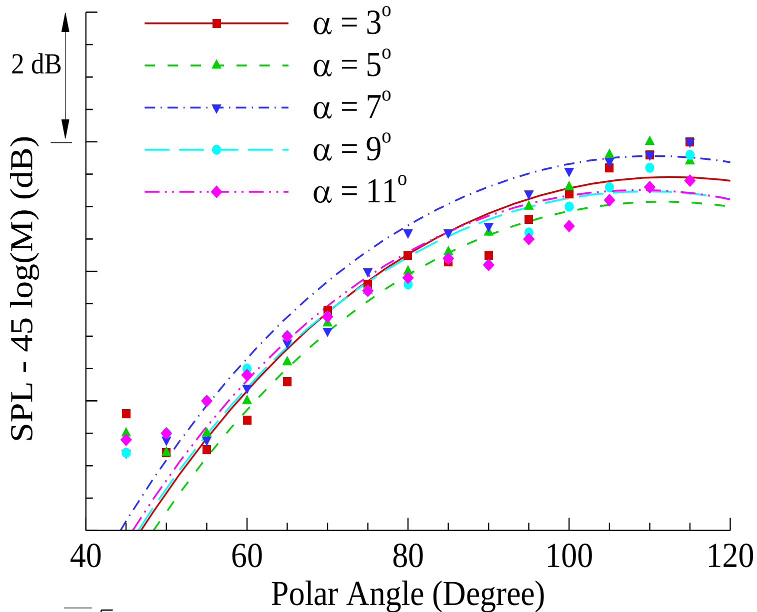

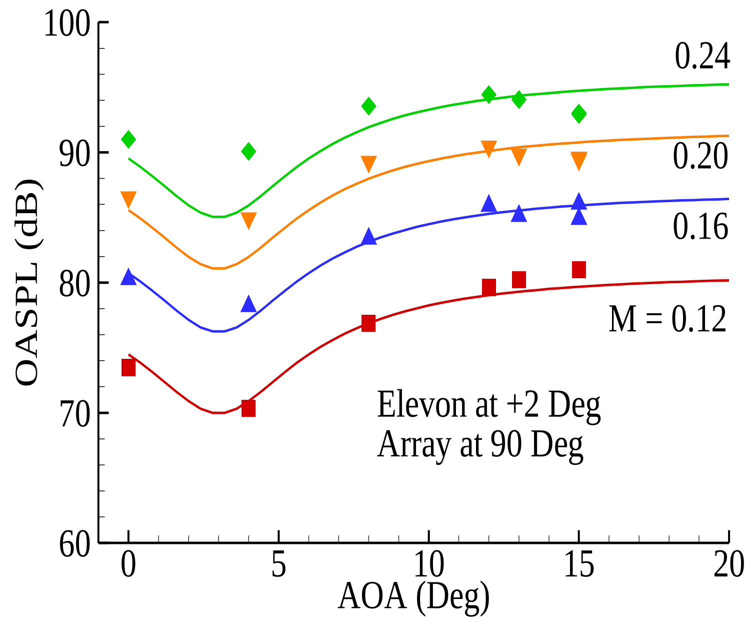

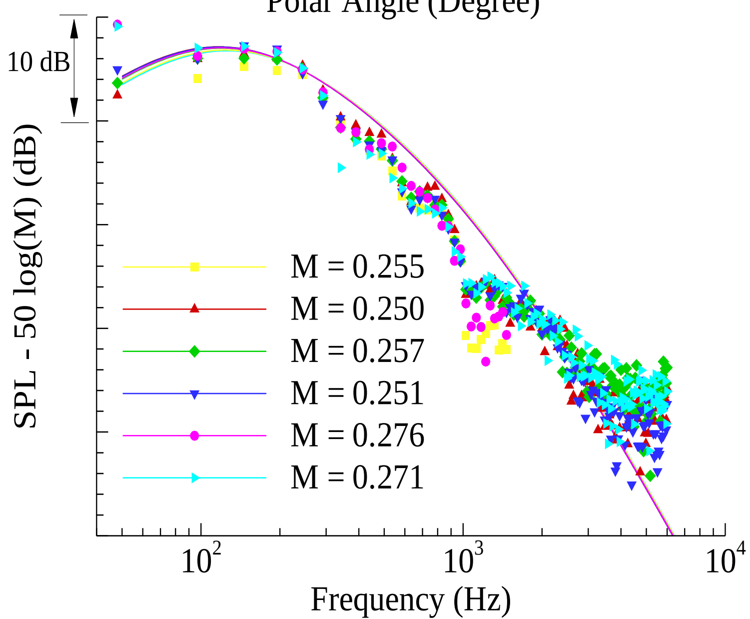

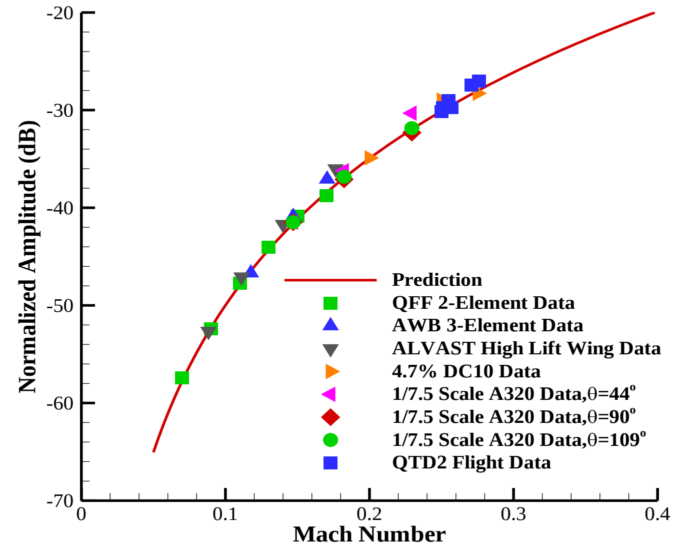

Landing Gear Noise Validation Database

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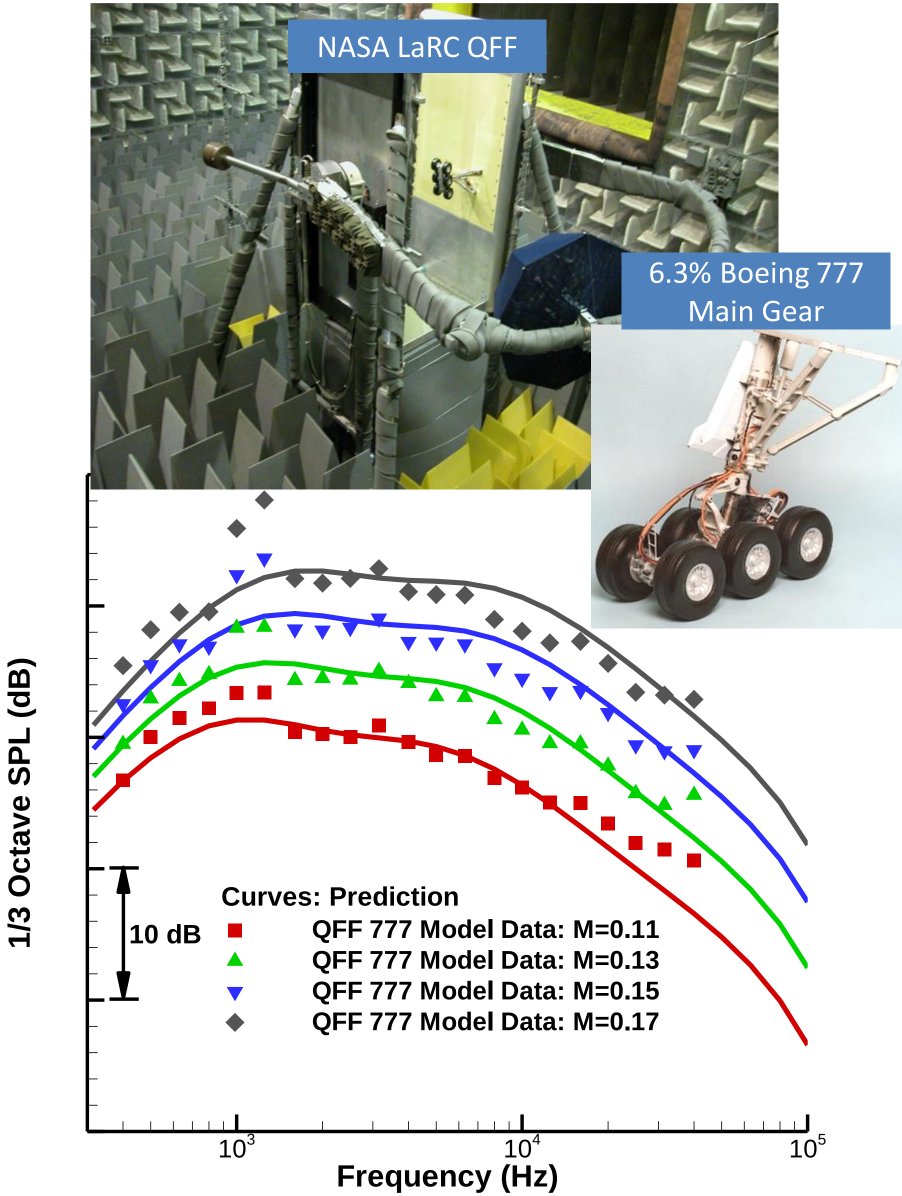
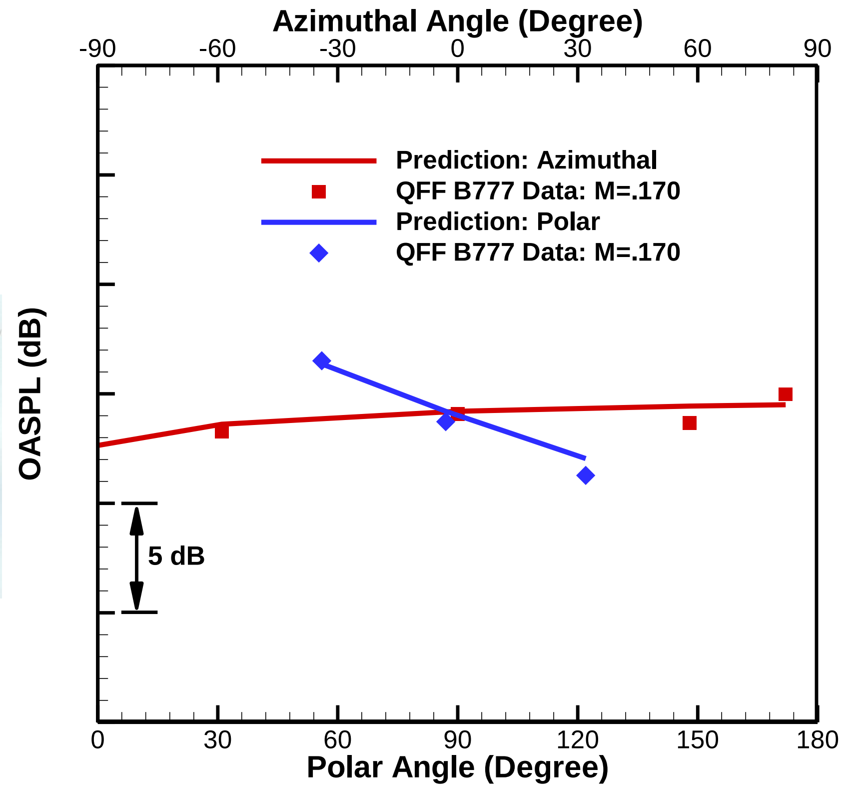
Gear Model	Configuration	Number of Wheels	Scale	Test Facility	Data Source
Boeing 777	Isolated	6	6.3%	QFF	IJA 8(5)
Regional Jet	Isolated	2	40%	RTRI	AIAA 2010-3973
Airbus 320	Isolated	2	Full Scale	DNW	AIAA 1997-1597
Airbus 320	Isolated	4	Full Scale	DNW	AIAA 1997-1597
Boeing 737	Isolated	2	Full Scale	LSAF	J Aircraft 43(2)
Airbus 340	Isolated	4	Full Scale	DNW	AIAA 2000-1971
Boeing 777 QTD1	Installed	6 & 2	Full Scale	Flight	NASA Report 2002
Boeing 777 QTD2	Installed	6 & 2	Full Scale	Flight	AIAA 2007-3457
Boeing 747	Installed	4 & 2	Full Scale	Flight	J Aircraft 19(12)
DC-10-30	Installed	4 & 2	Full Scale	Flight	AIAA 1976-0525

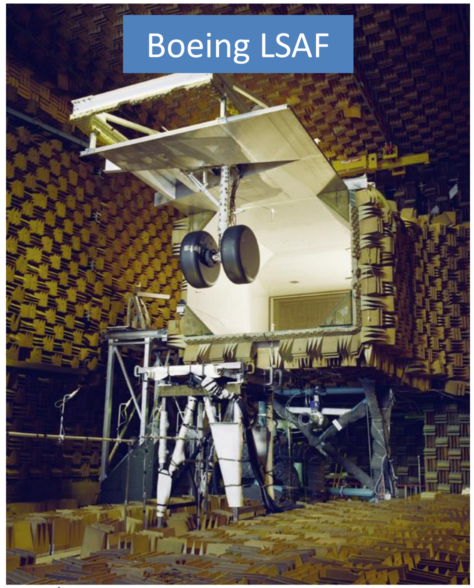
Validation by QFF Data

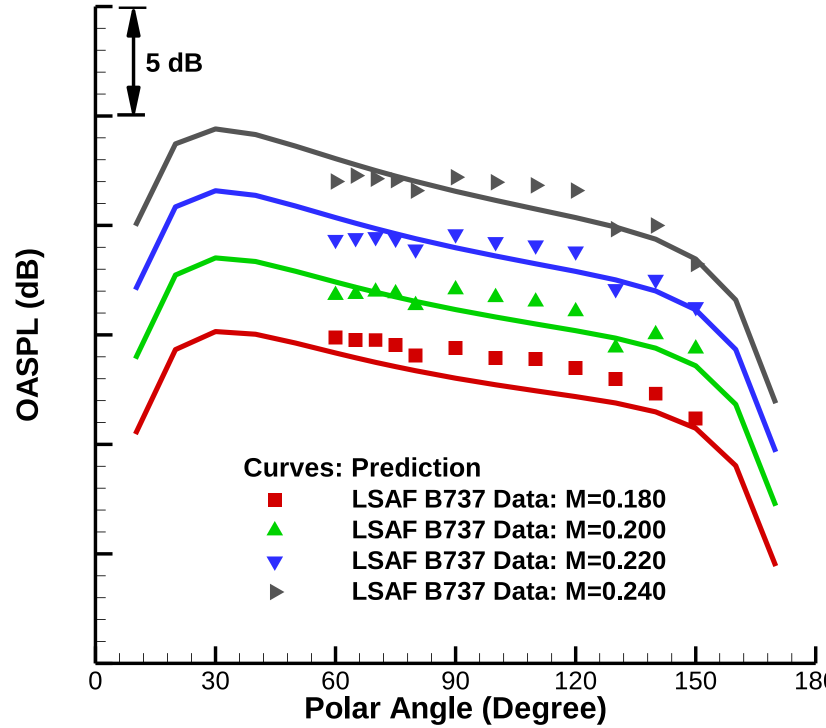


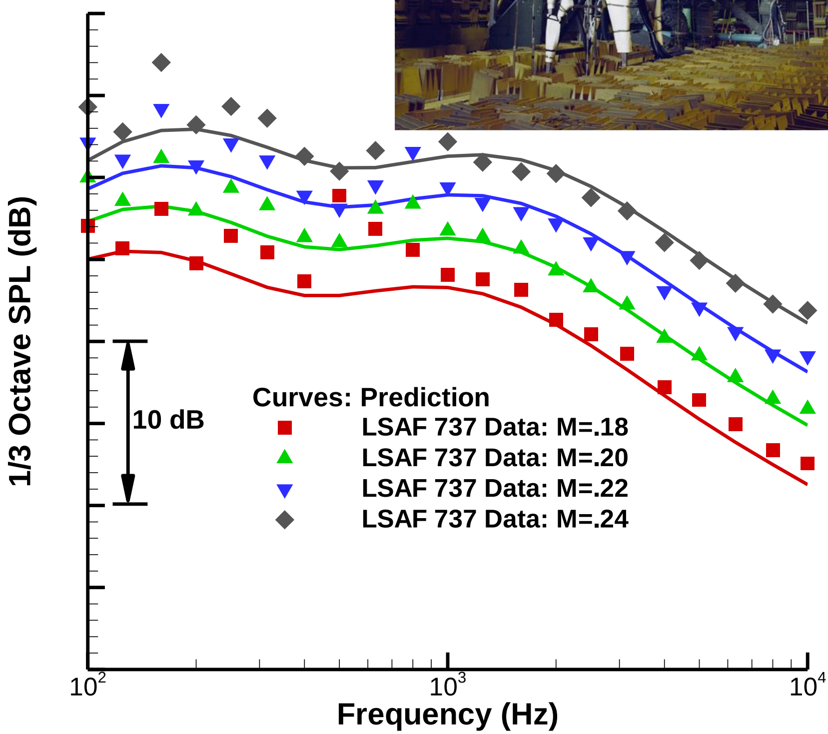


Humphreys, W. and Brooks, T., "Noise Spectra and Directivity for a Scale-Model Landing Gear," *International Journal of Aeroacoustics* **8**(5), pp. 409-443, 2009.

Validation by LSAF Data



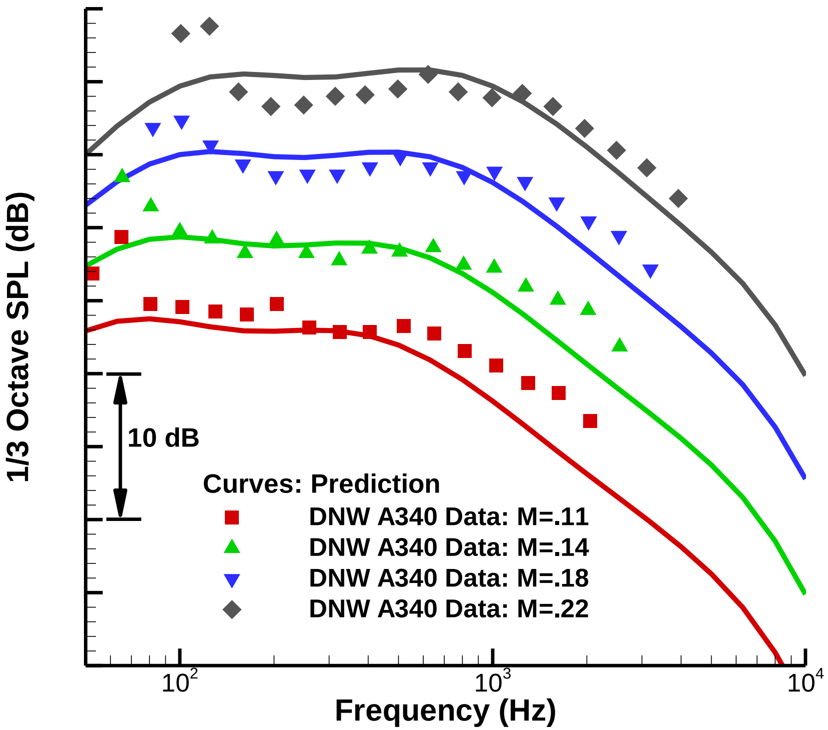




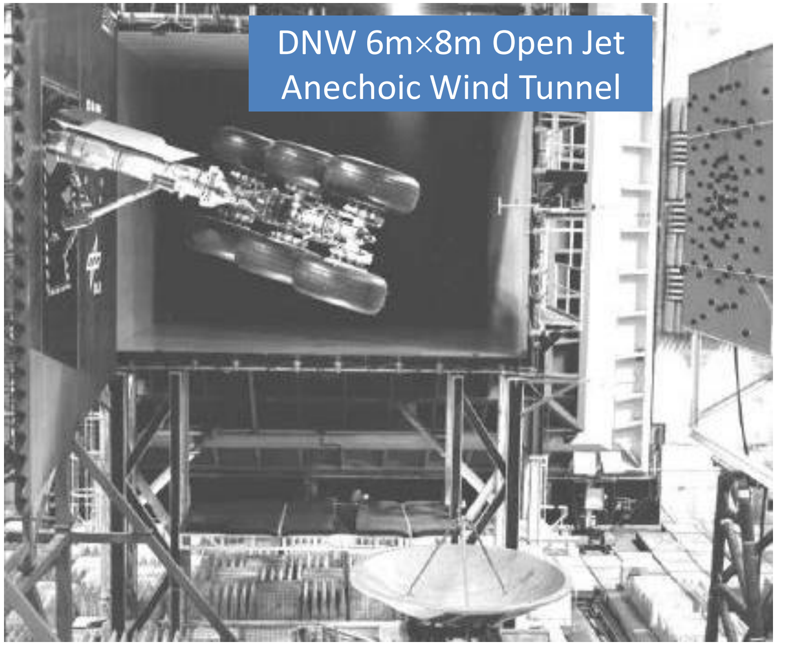
Guo, Y. P., Yamamoto, K. J. and Stoker, R. W. "Experimental Study on Aircraft Landing Gear Noise," *Journal of Aircraft* **43**(2), pp. 306-317, 2006.

Validation by DNW Data

Dobrzynski, W., Chow, L.C., Guion, P. and Shiells, D. "A European Study on Landing Gear Airframe Noise Sources," *AIAA Paper 2000-1971*.

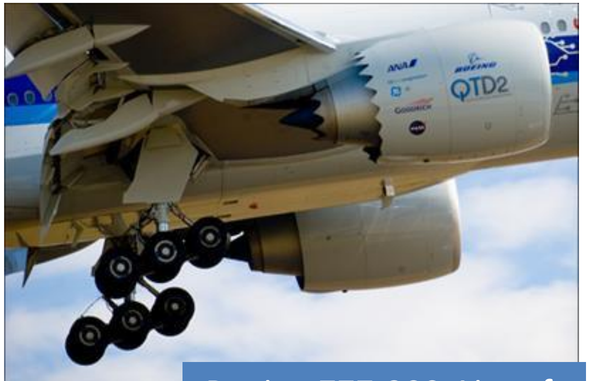


DNW 6m×8m Open Jet Anechoic Wind Tunnel



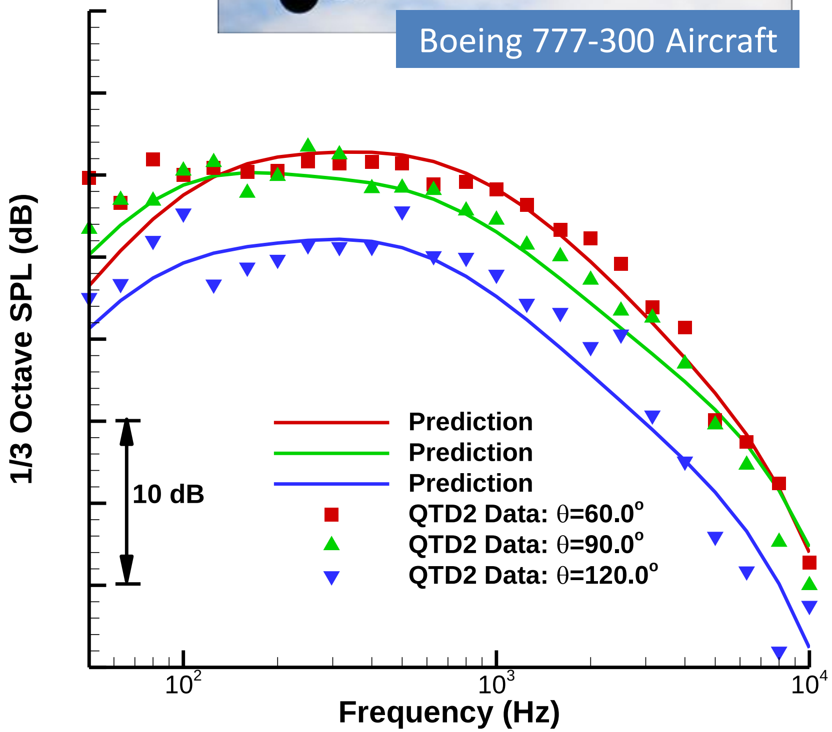
Full Scale Airbus 340 Main Gear

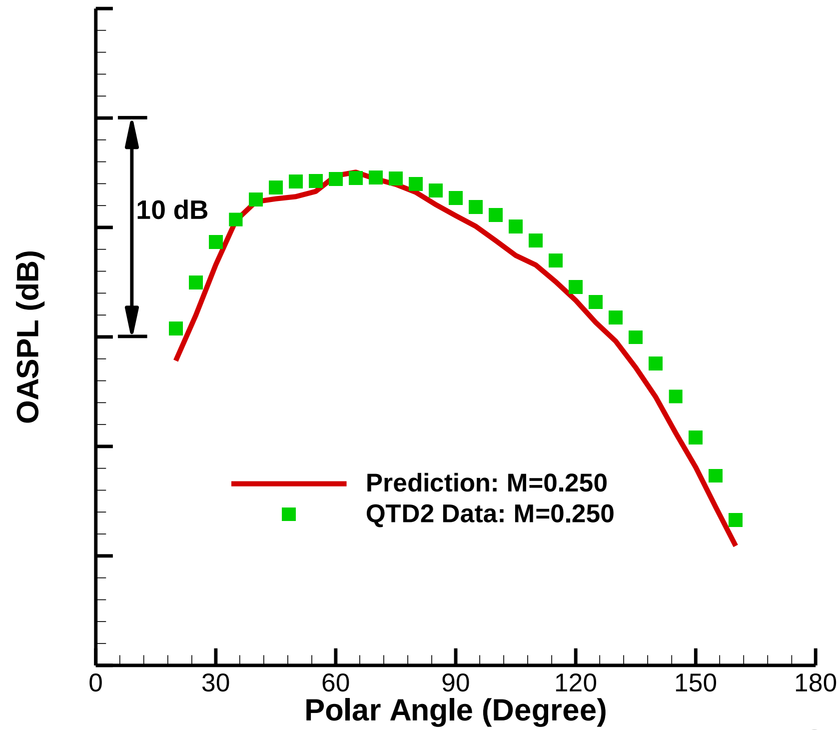
Validation by QTD2 Data



Boeing 777-300 Aircraft

Elkoby, R., Brusniak, L., Stoker, R. W., Khorrami, M. R., Abeysinghe, A. and Moe, J. W. "Airframe Noise Results from the QTD II Flight Test Program," *AIAA Paper 2007-3457*.





Summary

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- Extensive research has significantly advanced the understanding of airframe noise sources
- Physics based modeling has been developed for airframe noise prediction
- Systematic validation has demonstrated the accuracy and robustness of the approach
- Physics based prediction has been the main tool used by the aircraft industry and research institutions