Diffraction by Sharp Edges of Noncanonical Shape with Mean Flow and Surface Impedance

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Outline

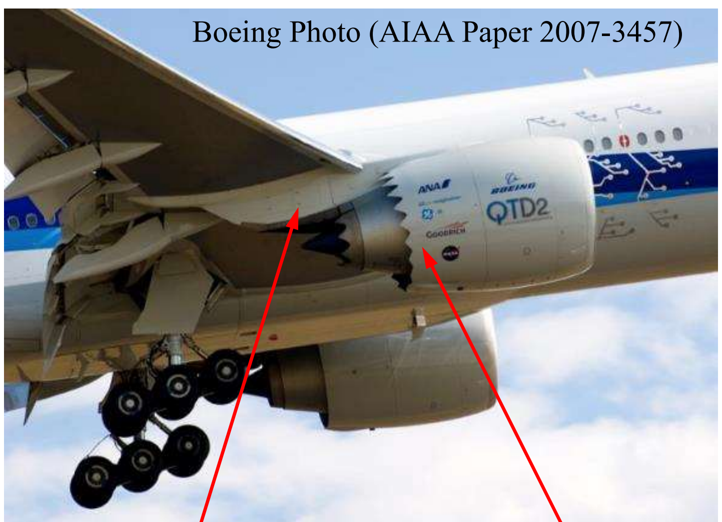
- Introduction
- Formulation
- Asymptotic analysis
- Singularity treatment
- Validation
- Parametric study
- Summary

Previous Studies on Sharp-Edge Diffraction

- Semi-infinite plate
  - Wiener-Hopf factorization
  - Straight edge, rigid surface, and static medium
- Infinite wedge
  - Image source synthesis
  - Straight edge, rigid surface, and static medium
- Kirchhoff integration method
  - Kirchhoff approximation (underprediction)
  - Rigid surface and static medium

Features in Aircraft Noise Scattering

- Noncanonical geometry
- Mean flow
- Potential acoustic treatment



Boeing Photo (AIAA Paper 2007-3457)

Curved Pylon Edge

Curved Nozzle Exit

Curved Trailing Edge

Curved Nozzle Exit

Objective

- Develop new solution for sharp-edge diffraction, accounting for features important for aircraft noise applications

Formulation

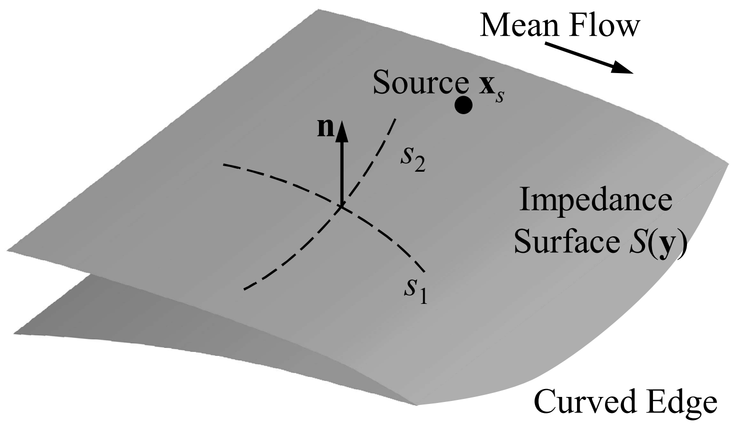
- Governing equation and boundary condition in local region

$$\nabla^2 p - \left(-\mathrm{i}k_0 + \mathbf{M}\cdot\nabla\right)^2 p = q$$

$$\rho_0 c_0 \left(-\mathrm{i}k_0 + \mathbf{M}\cdot\nabla\right)^2 p + \mathrm{i}k_0 Z \mathbf{n}\cdot\nabla p = 0$$

- Integral representation by Green's theorem

$$p_D(\mathbf{x}) = \int_{S(\mathbf{y})} \left(\mathbf{n}\cdot\nabla G + G\frac{\rho_0 c_0}{\mathrm{i}k_0 Z}\left(-\mathrm{i}k_0 + \mathbf{M}\cdot\nabla\right)^2 \right)\left(1 + C_R + C_D\right) p_I(\mathbf{y}) ds_1 ds_2$$



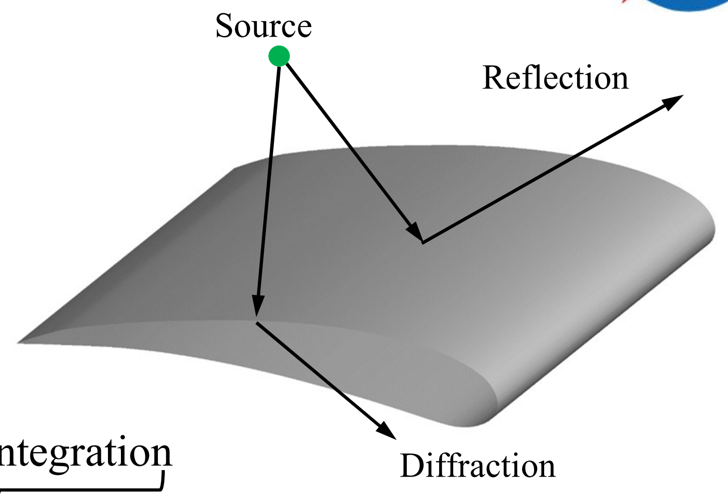
- All three features included (noncanonical geometry S, mean flow $\mathbf{M}$, and surface impedance Z)
- Integral equation with unknowns on right-hand side (not likely to have exact analytical solution or numerical solution)
- All wave quantities in integrand (amplitude and phase)
- Asymptotic analysis to reduce integral equation to algebraic equation

Asymptotic Analysis

- Integral equation

$$p_D(\mathbf{x}) = \frac{\mathrm{i}\kappa_0 q_0 e^{-\mathrm{i}\kappa_0(\mathbf{x}-\mathbf{x}_s)}}{(4\pi)^2} \int_{S(\mathbf{y})} f(\mathbf{y}) e^{\mathrm{i}\kappa_0 \psi} ds_1 ds_2$$

Gradually Varying Amplitude — Rapidly Varying Phase



- Suitable for the method of stationary phase
- First-order solution = Stationary point contribution (Reflection) + Contour integration (Diffraction)

$$p_D(\mathbf{x}) = \frac{q_0 e^{-\mathrm{i}\kappa_0(\mathbf{x}-\mathbf{x}_s)}}{(4\pi)^2} \sum_{n=1}^{N} \sum_{k=1}^{3} A(s_k) f(s_k) \frac{\tilde{\nabla}\psi \cdot \mathbf{n}_c}{\left|\tilde{\nabla}\psi\right|^2} e^{\mathrm{i}\kappa_0 \psi(s_k)}$$

  - Summation over n for N edge segments
  - Summation over k for stationary point and two ends of each segment

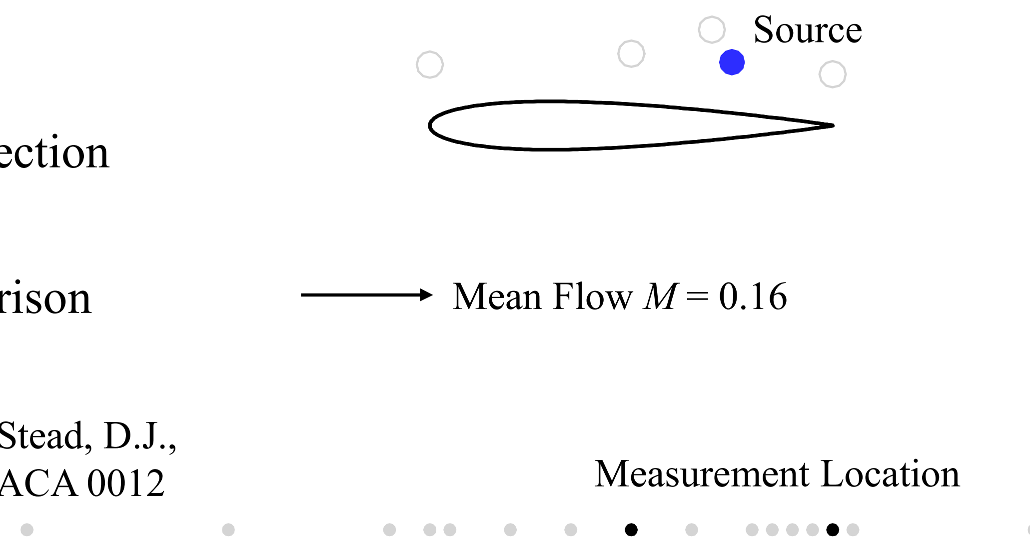
- Successive analysis applicable to any higher order

Singularity Treatment

- Singularities in first-order solution not physical but entirely due to first-order approximation
- Possible causes
  - First-order solution not leading-order solution at and/or near singularity locations
  - Certain mathematical steps not applicable at and/or near singularity locations
- Possible corrections
  - Carry out asymptotic analysis to the next order (or any higher order as needed)
  - Use Fresnel function to model diffraction near singularities
- Examples in paper with mathematical details

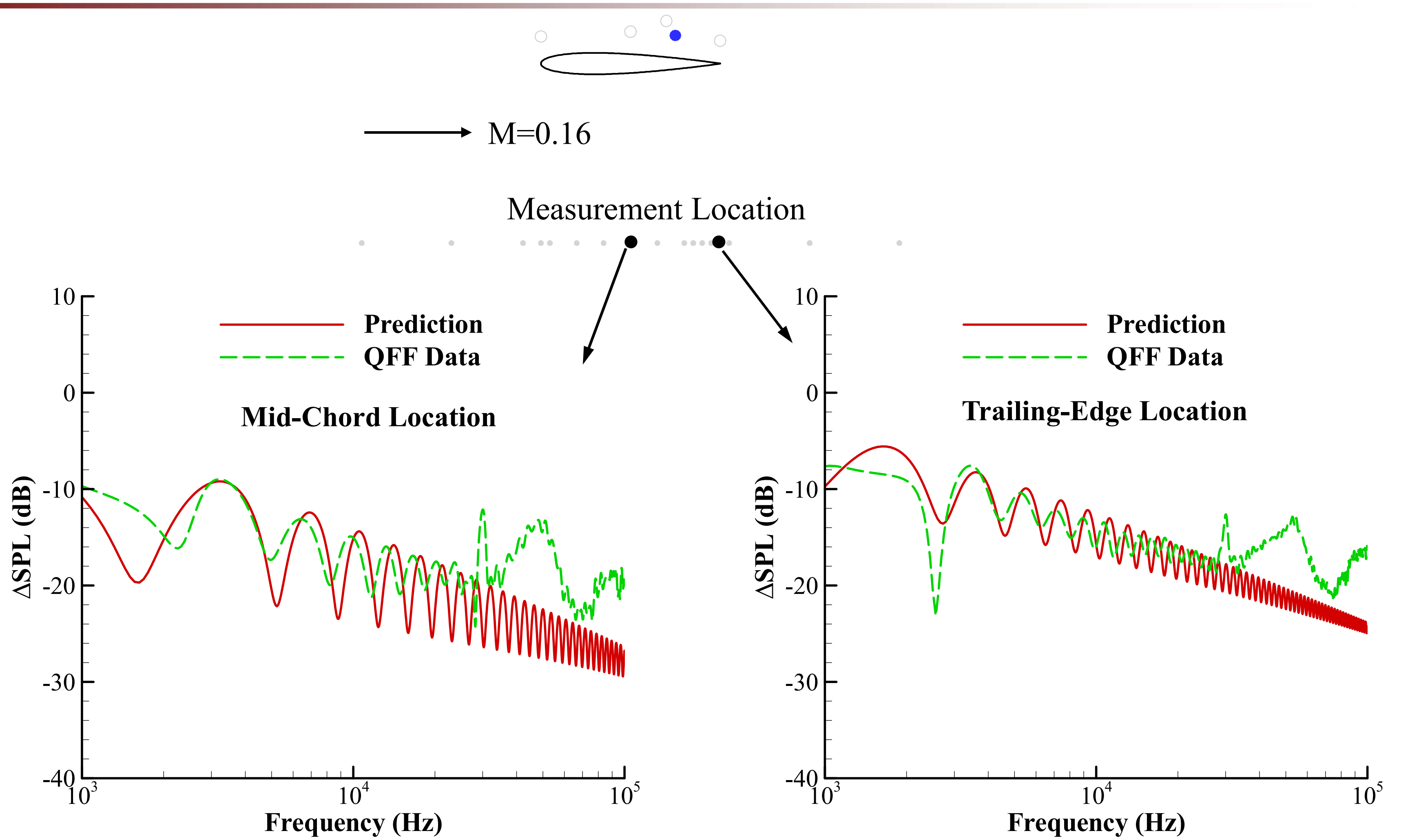
Test Setup for Validation Case

- Test facility: NASA LaRC Quiet Flow Facility (QFF)
- Test model: NACA 0012 airfoil with 0.2 m chord
- Extensive test matrix, but only one case presented here
- Source (blue circle): Laser spark at 75% chord from leading edge
- Measurement:
  - Opposite side of source
  - One chord below airfoil in flow direction
  - Black dots for spectral comparison
  - Gray dots for spatial pattern comparison

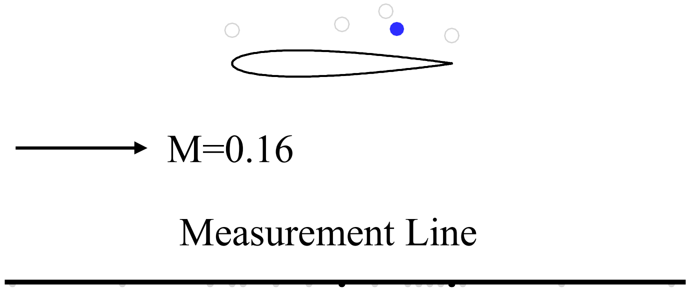


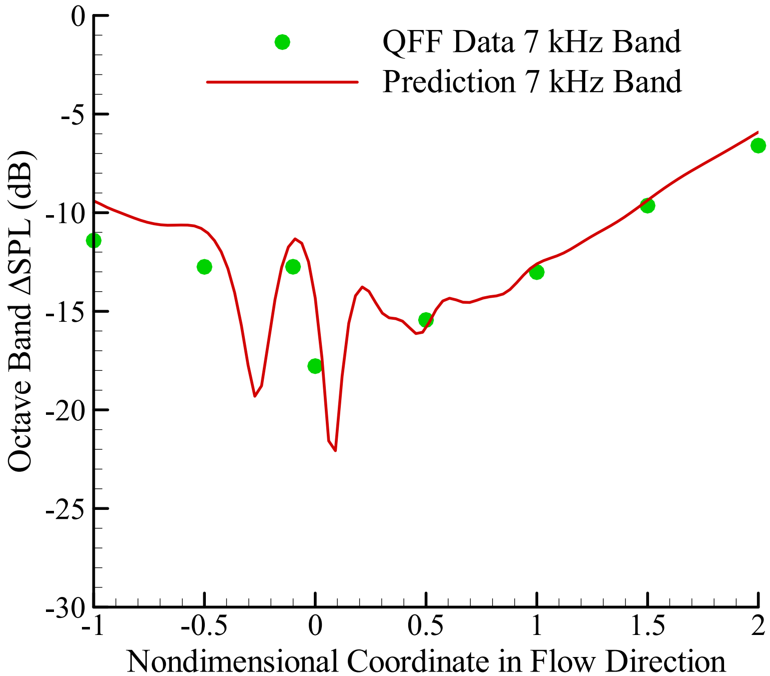
Hutcheson, F.V., Bahr, C.J., Thomas, R.H., and Stead, D.J., "Experimental Study of Noise Shielding by a NACA 0012 Airfoil," AIAA Paper 2018-2821, June 2018.

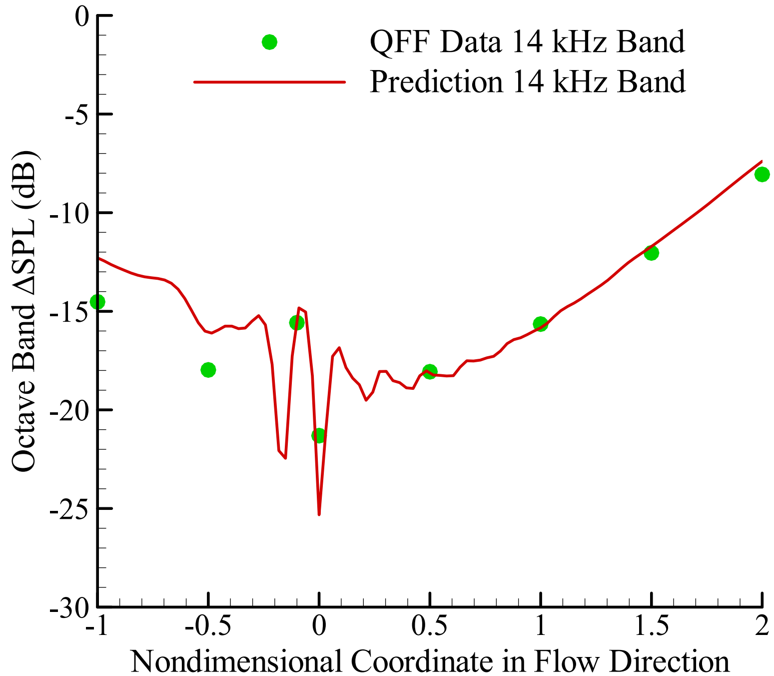
Spectrum Comparison



Spatial Pattern Comparison

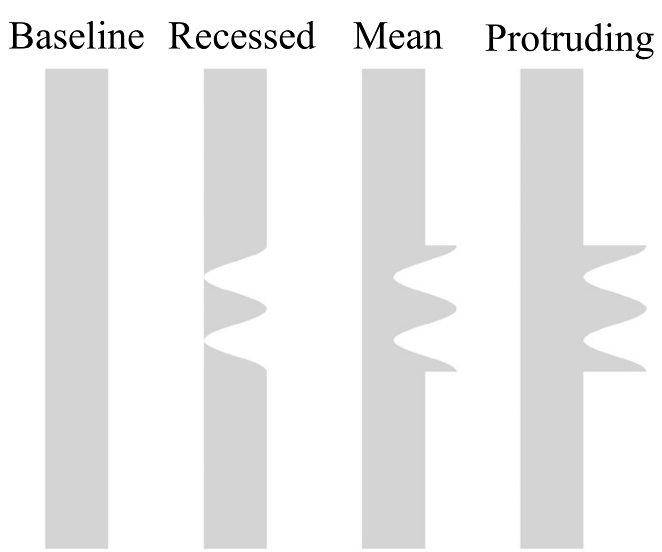


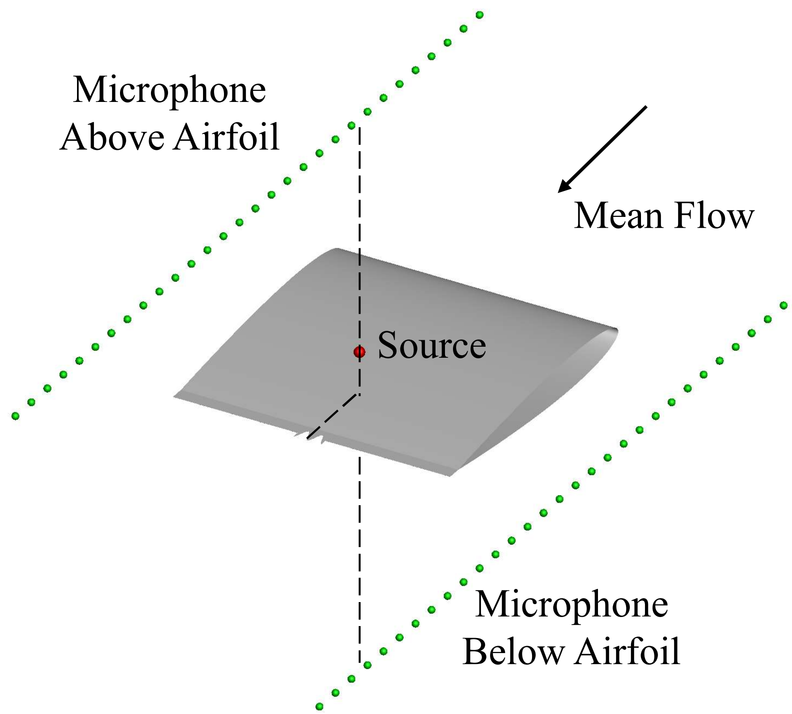




Parametric Study

- QFF test model as baseline with source at 75% chord from leading edge and at 10 kHz
- Three wavy trailing edge shapes in different positions in flow direction
- Mach number variations
- Rigid and treated edges
- Extra measurement line above airfoil

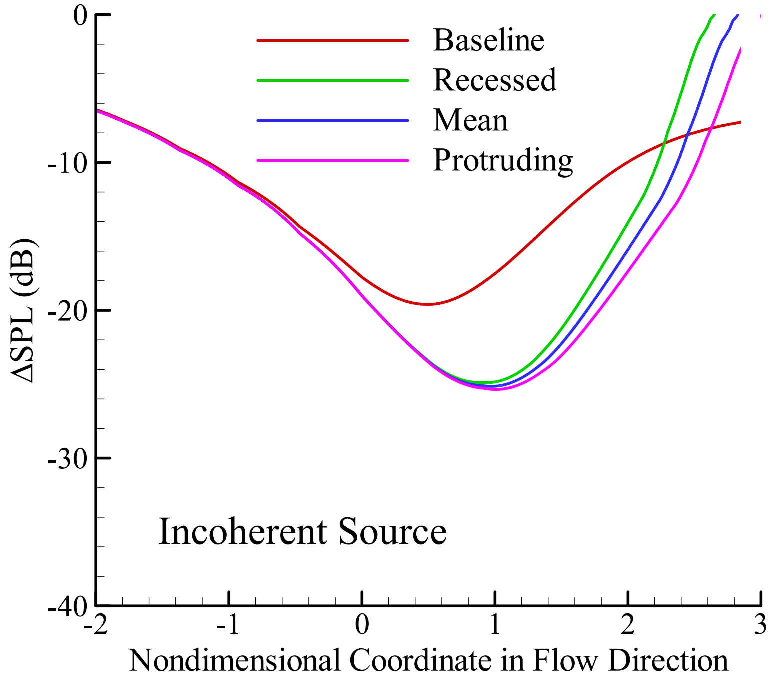


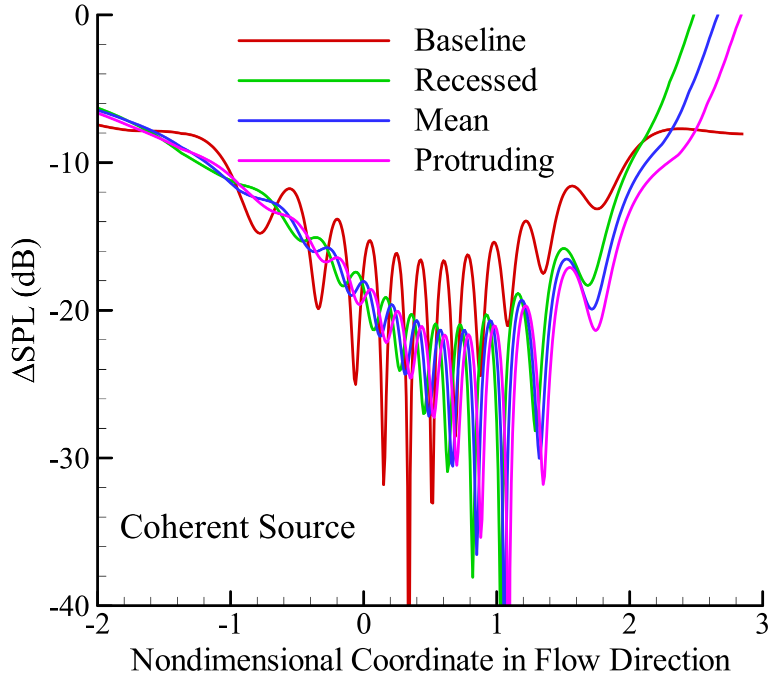


Edge-Shape Effect on Diffraction

M=0 and f=10 kHz

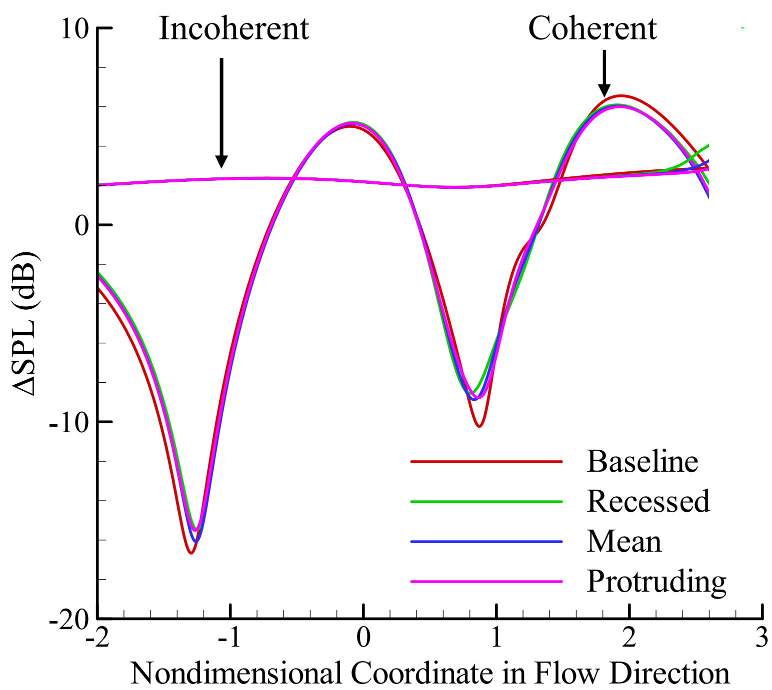
Measurement Line

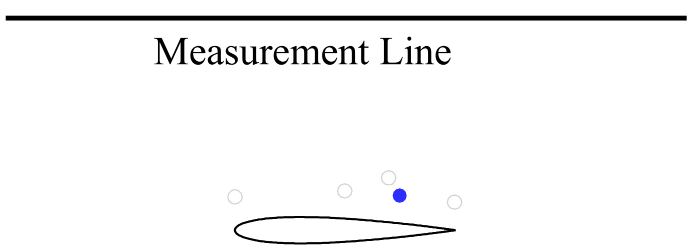




Edge-Shape Effect on Total Scattering

M=0 and f=10 kHz

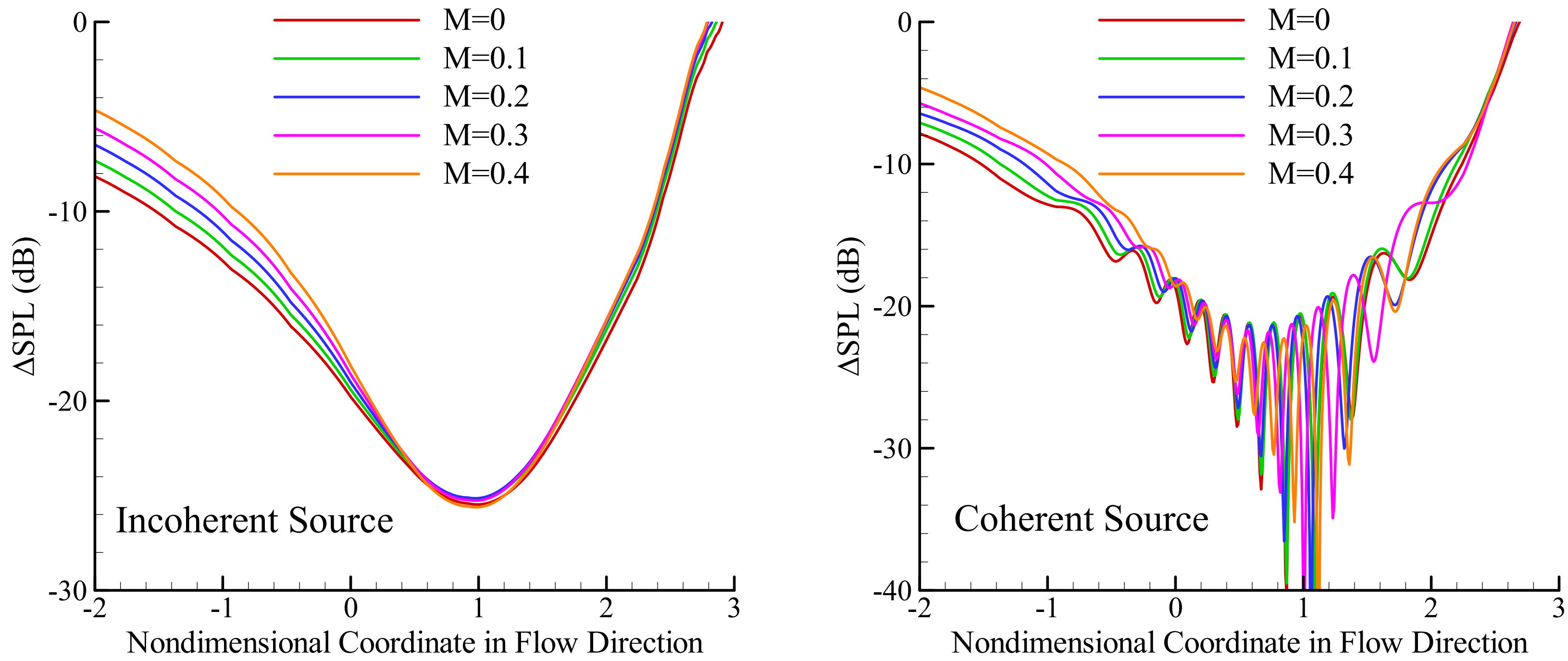




Flow Effect on Mean Wavy Edge

f=10 kHz

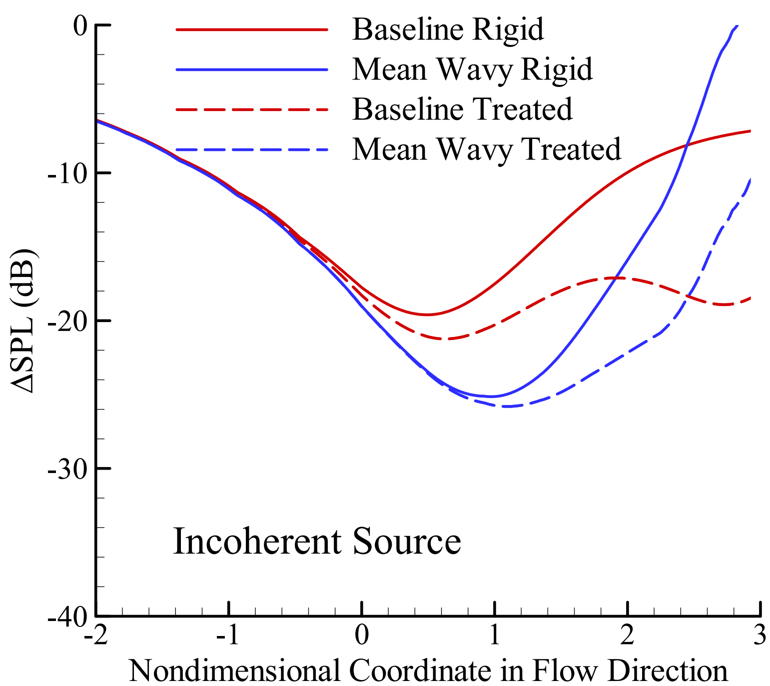
Measurement Line

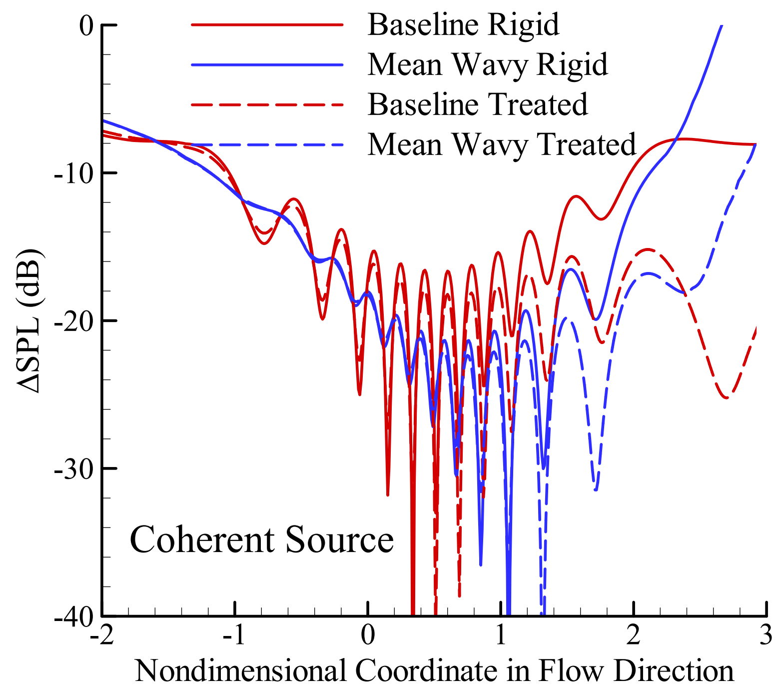


Effect of Edge Treatment

M=0 and f=10 kHz
Nondimensional impedance (2,-0.5)

Measurement Line





Summary

- Derived sharp-edge diffraction solution for aircraft noise applications, including important features
  - Noncanonical edge shape
  - Mean flow
  - Surface impedance
- Validated solution with test data for NACA 0012 airfoil with mean flow as first step in planned systematic validation with curved edges and edges with acoustic treatment
- Demonstrated the effects of edge features and the potential for diffraction control by edge shaping and liner treatment

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