Predicting the Inflow Distortion Tone Noise of the NASA Glenn Advanced Noise Control Fan with a Combined Quadrupole-Dipole Model

L. Danielle Koch
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A combined quadrupole-dipole model of fan inflow distortion tone noise has been extended to calculate tone sound power levels generated by obstructions arranged in circumferentially asymmetric locations upstream of a rotor. Trends in calculated sound power level agreed well with measurements from tests conducted in 2007 in the NASA Glenn Advanced Noise Control Fan. Calculated values of sound power levels radiated upstream were demonstrated to be sensitive to the accuracy of the modeled wakes from the cylindrical rods that were placed upstream of the fan to distort the inflow. Results indicate a continued need to obtain accurate aerodynamic predictions and measurements at the fan inlet plane as engineers work towards developing fan inflow distortion tone noise prediction tools.

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Acoustics Branch

NASA Glenn Research Center

18th AIAA/CEAS Aeroacoustics Conference

Colorado Springs, CO

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Overview

- Motivation
- Objectives
- Prediction Method
- Experiment
- Aerodynamic Validation
- Acoustic Validation
- Conclusions

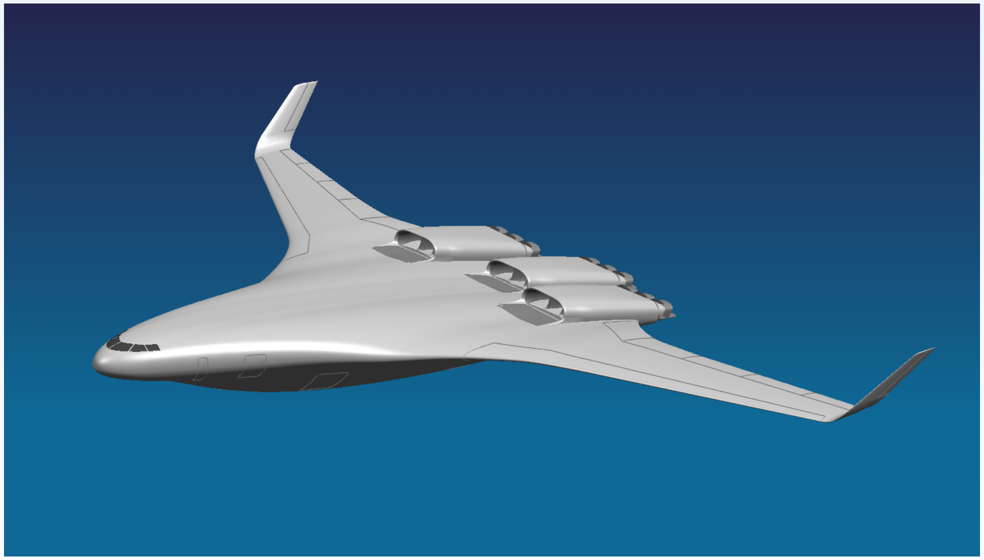
Funding for inlet distortion tone noise research is currently provided by NASA's Fundamental Aeronautics Program Subsonic Fixed Wing Project.

Predicting the Inflow Distortion Tone Noise of the NASA Glenn Advanced Noise Control Fan with a Combined Quadrupole-Dipole Model

Motivation

When a ducted axial fan ingests distorted inflow, tone noise can be produced at harmonics of the blade passing frequency.

One goal for NASA's Subsonic Fixed Wing project is to develop tools to predict the sound produced by aircraft engine fans ingesting distorted inflow resulting from new engine mounting configurations.



NASA N2B Concept

Predicting the Inflow Distortion Tone Noise of the NASA Glenn Advanced Noise Control Fan with a Combined Quadrupole-Dipole Model

Objectives

A combined quadrupole-dipole analytic model of fan inflow distortion tone noise was derived and published by Goldstein, Dittmar, and Gelder in 1974. (NASA TN-D-7676)

Their intention was to predict the upstream-radiated tone noise from a fan with a high-subsonic rotor tip speed that was ingesting flow distorted by the presence of uniformly spaced upstream struts.

The objectives of the current work were:

1) to modify the original theory to so that tone sound power levels could be calculated when the fan's inflow is distorted by obstructions placed at circumferentially asymmetric locations in the fan's inlet duct
2) to create computer codes based on the original and modified theories
3) to compare aerodynamic and acoustic data to calculated results

Predicting the Inflow Distortion Tone Noise of the NASA Glenn Advanced Noise Control Fan with a Combined Quadrupole-Dipole Model

Prediction Method

The current work is based on the theory published in

Combined Quadrupole-Dipole Model for Inlet Flow Distortion Noise from a Subsonic Fan

Marvin E. Goldstein, James H. Dittmar, and Thomas F. Gelder

NASA TN-D-7676 , May 1974.

The theory is based on a generalized version of the Ffowcs Williams and Hawkings formulation. The fan is modeled as an unrolled-rectangular duct. The rotor potential flow field is modeled as a line of free vortices, and Gaussian functions are used to model the wakes of upstream stators or vanes.

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An analytic expression was derived for the upstream radiating sound power of the blade passing frequency tones for an axial ducted fan with vanes or struts arranged uniformly in the inlet.

Sound Power, $P_{p,q,s}$ = function (number of blades, number of vanes, hub radius, tip radius, chord, axial Mach number, fan rotational speed, freestream density, freestream acoustic speed, work coefficient, wake width, wake depth, wake span, angular location of the upstream vanes)

Predicting the Inflow Distortion Tone Noise of the NASA Glenn Advanced Noise Control Fan with a Combined Quadrupole-Dipole Model

Prediction Method

The resulting expression for tone sound power contained both a quadrupole term and a dipole term. It was considered to be the first attempt at retaining the quadrupole term in a fan inflow distortion tone noise model.

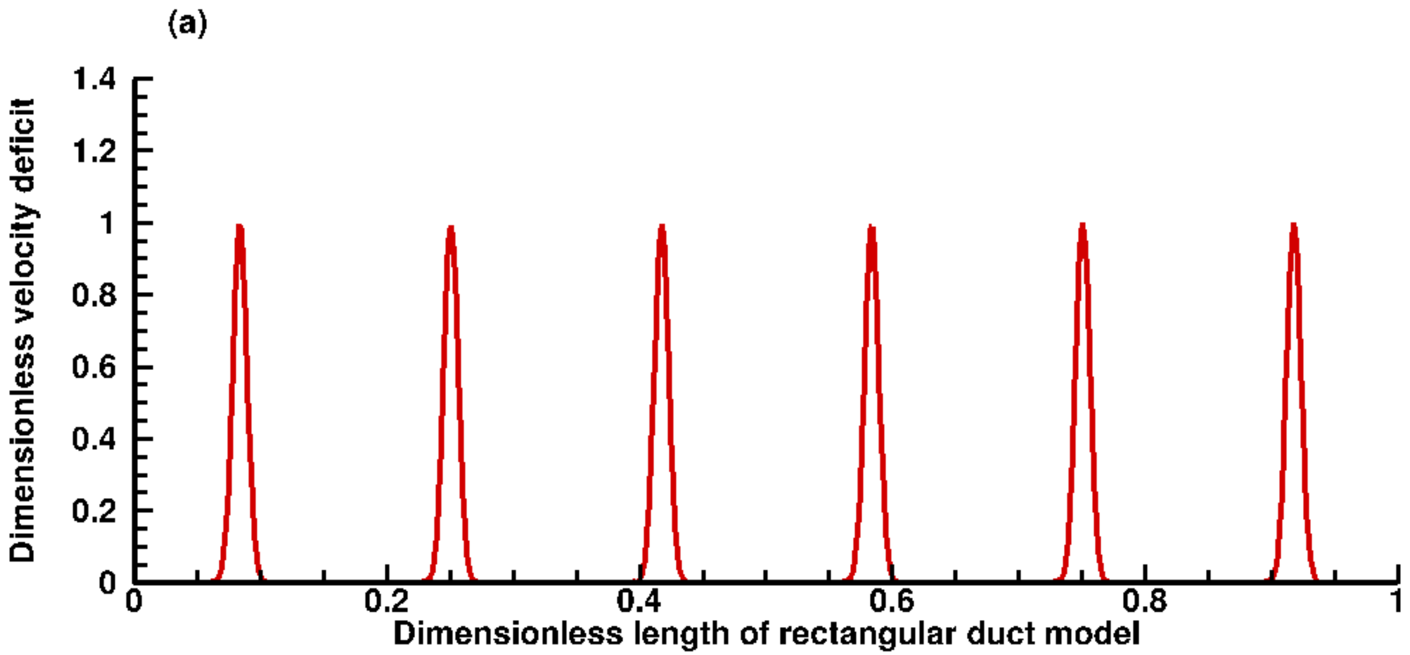
Goldstein, *et al*. chose to retain the quadrupole term in the formulation based on previous work by Morfey that suggested that sound generated by the quadrupole term could be equal to or greater than sound generated by the dipole term for fans with axial Mach numbers as low as 0.25.

They pointed out that the only the quadrupole term was a function of the work coefficient, θ, which may dominate for highly loaded, low-solidity fans.

Predicting the Inflow Distortion Tone Noise of the NASA Glenn Advanced Noise Control Fan with a Combined Quadrupole-Dipole Model

Prediction Method

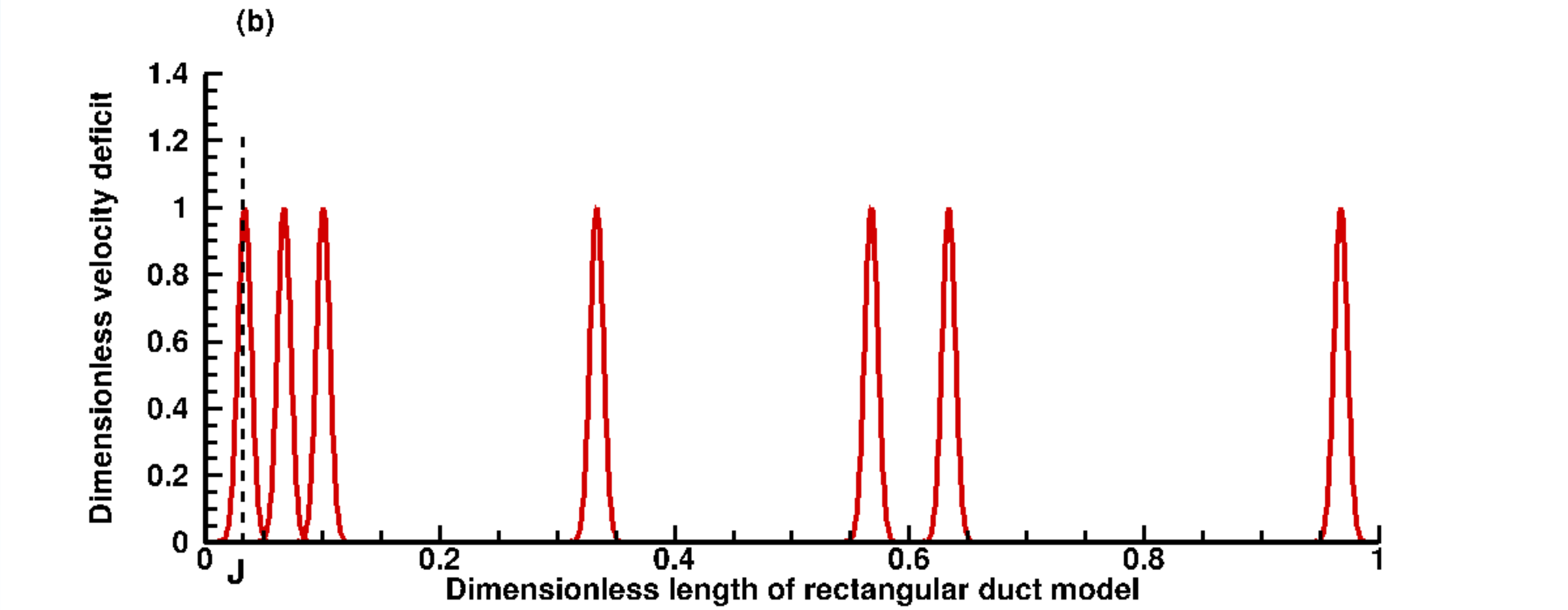
In the original theory, the axial distortion velocity in the wakes of the obstructions were modeled with uniformly-spaced Gaussian functions.



Predicting the Inflow Distortion Tone Noise of the NASA Glenn Advanced Noise Control Fan with a Combined Quadrupole-Dipole Model

Prediction Method

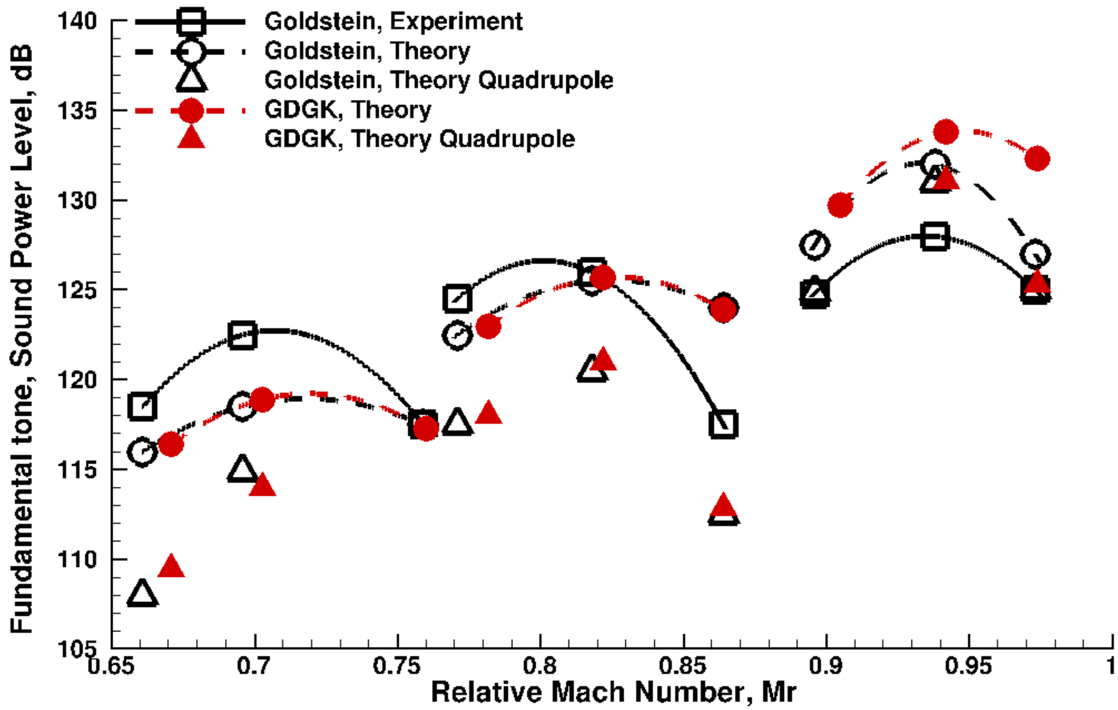
In the modified theory, the axial distortion velocity in the wakes of the obstructions were modeled with arbitrarily-spaced Gaussian functions.

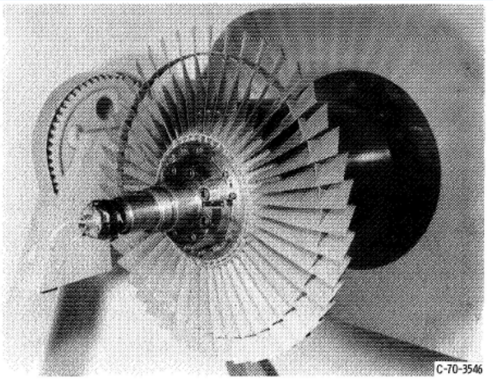


Predicting the Inflow Distortion Tone Noise of the NASA Glenn Advanced Noise Control Fan with a Combined Quadrupole-Dipole Model

Prediction Method

A Fortran 90 computer code named GDGK was written based on the theory. Output from the code was compared against original predictions published in NASA TN-D-7676 in 1974.



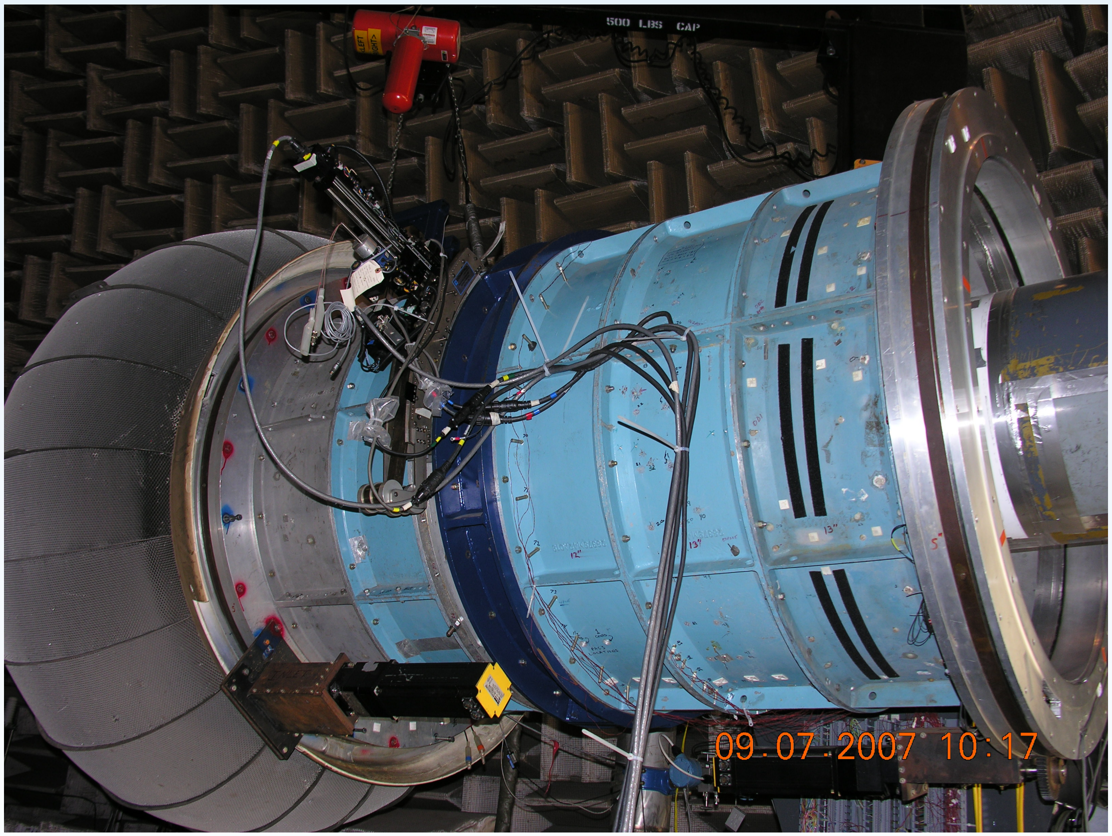


51 cm (20 in) fan model
45 blades
4 upstream struts
Tested in an indoor compressor test facility at NASA Glenn in 1971.

Output from new code closely matches original predictions. Original data appeared in plotted form only, and a complete set of input data was unavailable from the original reports.

Predicting the Inflow Distortion Tone Noise of the NASA Glenn Advanced Noise Control Fan with a Combined Quadrupole-Dipole Model

Experiment



NASA Glenn Advanced Noise Control Fan
AeroAcoustic Propulsion Lab

Fan Diameter:	48 in.
Hub Diameter:	18 in.
Number of Blades:	16
Number of Vanes:	0
Design Speed:	2000 rpm
Tip Speed:	419 fps
Bulk Inlet Mach:	0.15
Static Pressure Ratio :	1.02

Instrumentation:

Farfield Microphone Array

Inlet/Exhaust Rotating Rake

Traversing two-component hotwire probe

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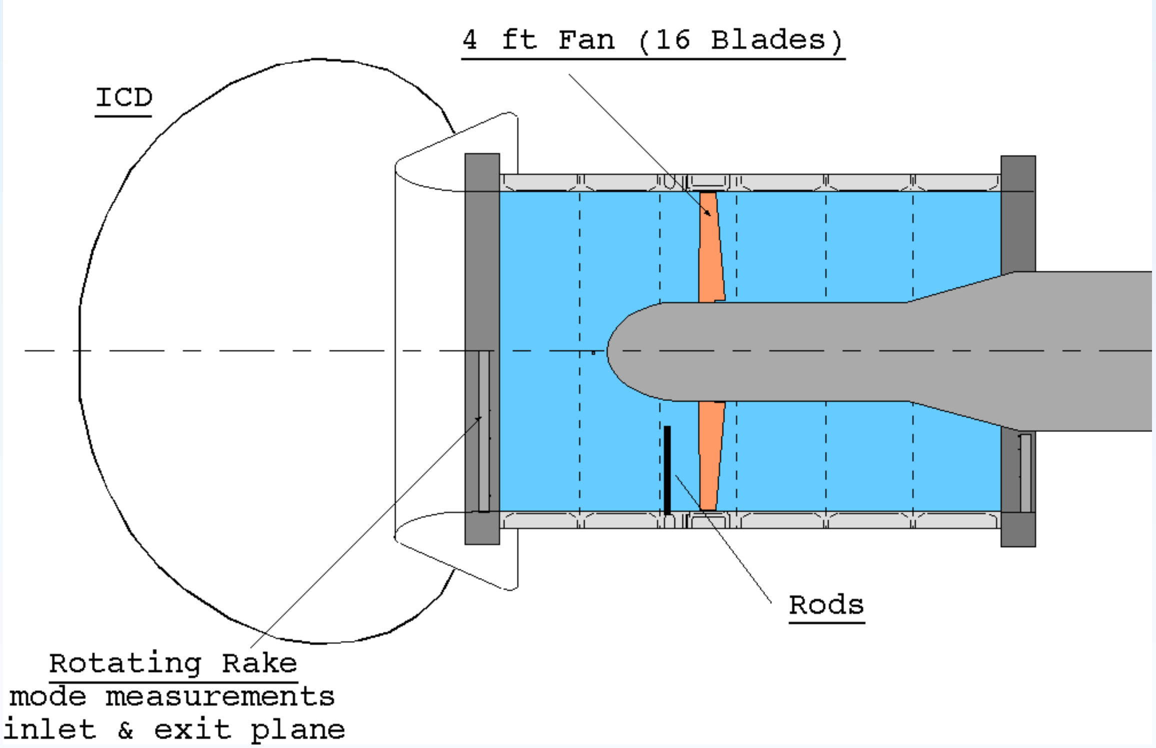
Experiment



Inflow was distorted by placing 0.5 in. diameter cylindrical rods upstream of the fan rotor.

Centerline of the rods was approximately one blade chordlength upstream of the blade leading edge tip.

2007: Four rod configurations tested

NASA Glenn Advanced Noise Control Fan
AeroAcoustic Propulsion Lab

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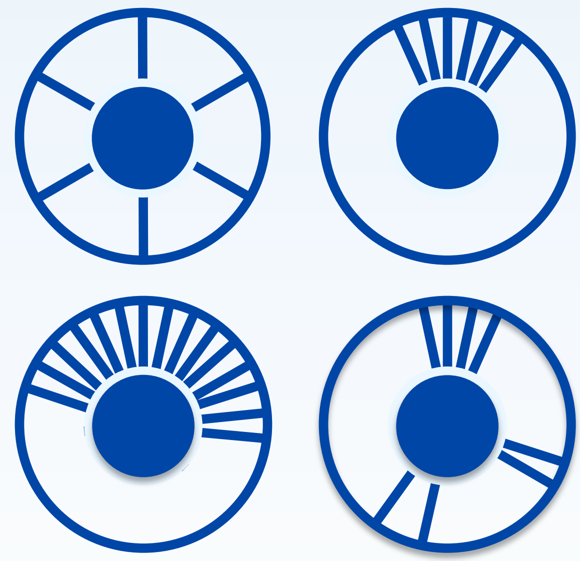
Experiment

NASA Glenn Advanced Noise Control Fan
AeroAcoustic Propulsion Lab

Four rod configurations tested in 2007

6 rods 6 rods

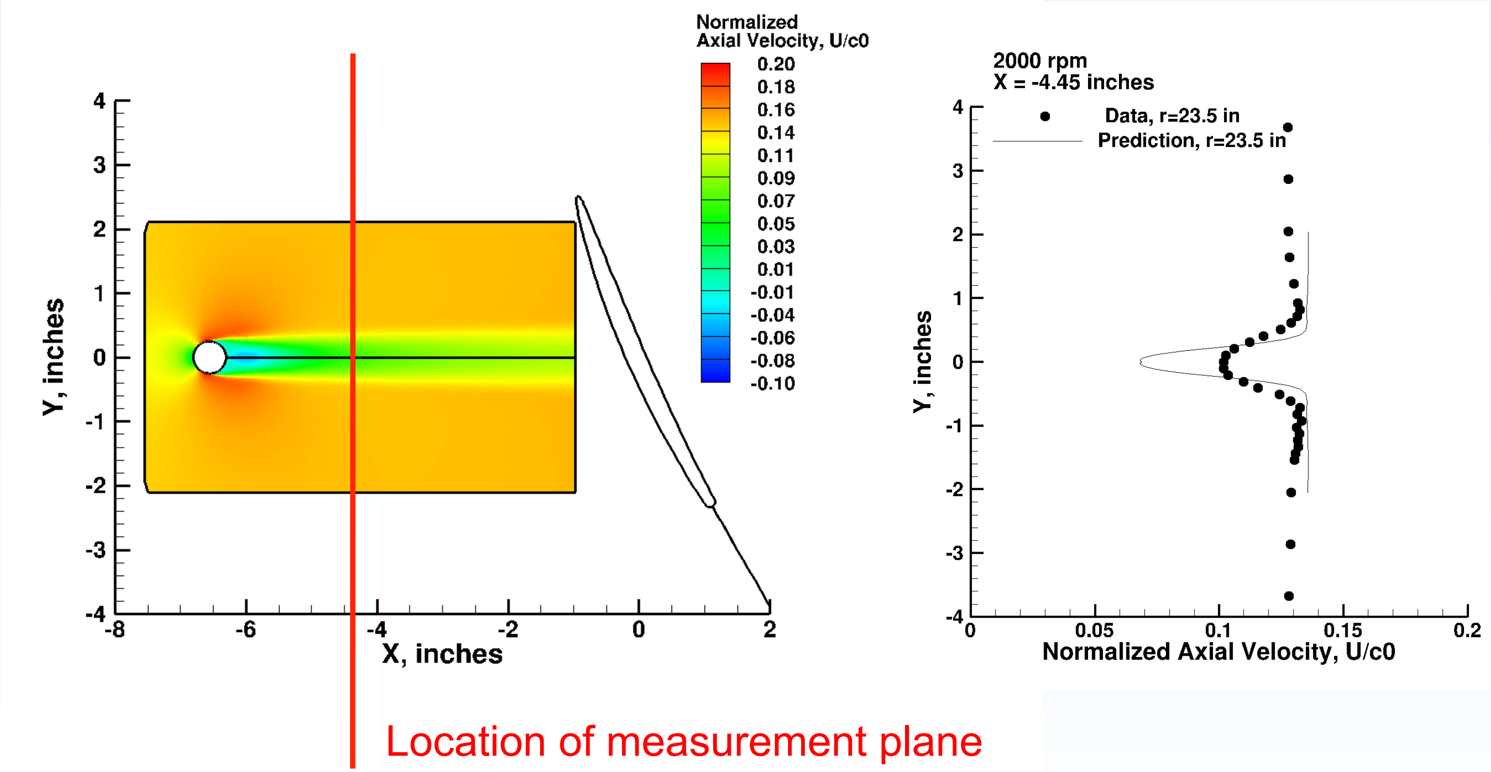


15 rods 8 rods

Predicting the Inflow Distortion Tone Noise of the NASA Glenn Advanced Noise Control Fan with a Combined Quadrupole-Dipole Model

Aerodynamic Validation

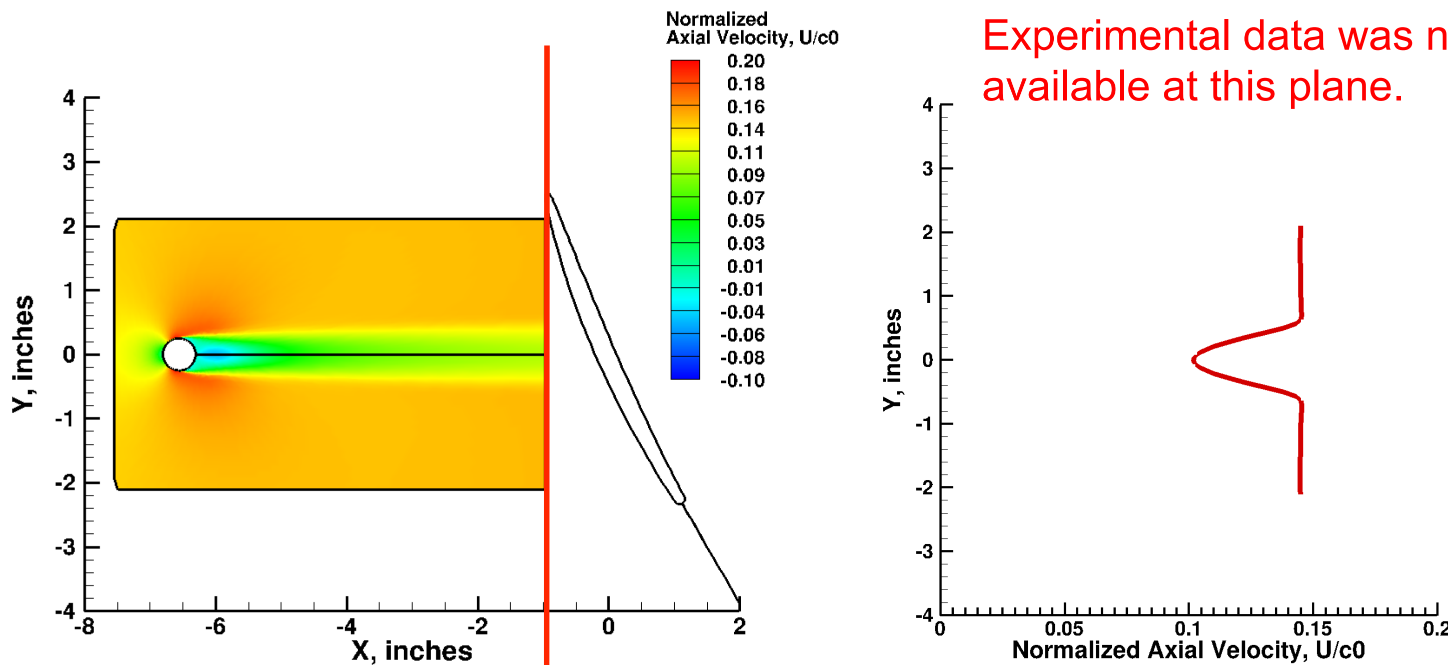
Measured velocities downstream of one of the rods were used to validate velocities calculated from TSWIFT, a Reynolds-averaged Navier-Stokes solver. Measured wakes were shallower and wider than predicted wakes.



Predicting the Inflow Distortion Tone Noise of the NASA Glenn Advanced Noise Control Fan with a Combined Quadrupole-Dipole Model

Aerodynamic Validation

CFD available at the rotor leading edge plane was used to create one set of GDGK input parameters describing the wakes.



Experimental data was not available at this plane.

Wake width, wake depth, and wake span defined for noise predictions located at rotor leading edge plane.

Predicting the Inflow Distortion Tone Noise of the NASA Glenn Advanced Noise Control Fan with a Combined Quadrupole-Dipole Model

Acoustic Validation

A series of plots will compare measured and calculated sound power levels in the inlet region of the fan.

For all four rod configurations at 2000 rpm, we will compare

- Sound power levels as a function of blade passing frequency (BPF) harmonic
- Circumferential and radial mode sound power levels for the 1 BPF tone
- Circumferential and radial mode sound power levels for the 2 BPF tone

For all four rod configurations, we will compare

- Sound power level of the 1 BPF tone for 1400, 1800, and 2000 rpm

Predicting the Inflow Distortion Tone Noise of the NASA Glenn Advanced Noise Control Fan with a Combined Quadrupole-Dipole Model

Acoustic Validation

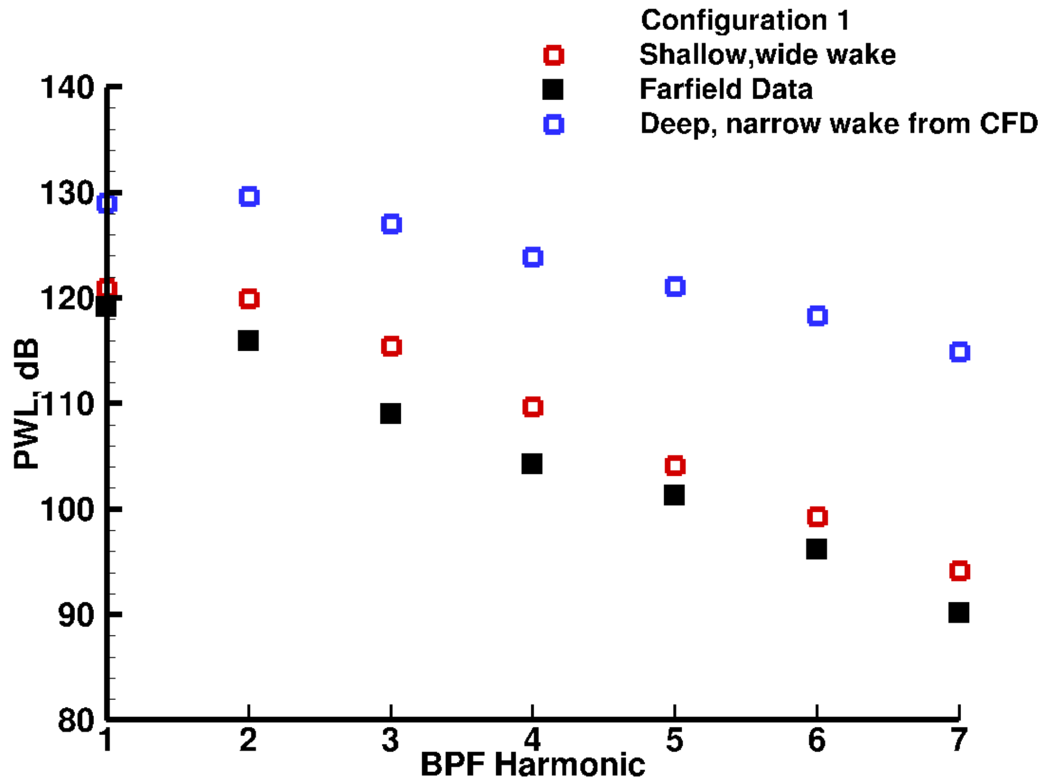
Acoustic predictions are sensitive to the accuracy of the modeled wake.

Two sets of wake parameters were defined.

Set 1: Wake parameters from CFD at the rotor leading edge were used to generate the noise predictions in blue.

Set 2: Wake parameters were arbitrarily adjusted to model a wider, shallower wake to generate noise predictions in red.

No experimental data were available to validate wake parameters at rotor leading edge.



Predicting the Inflow Distortion Tone Noise of the NASA Glenn Advanced Noise Control Fan with a Combined Quadrupole-Dipole Model

Acoustic Validation

Accurate axial velocities are needed at the rotor leading edge plane.

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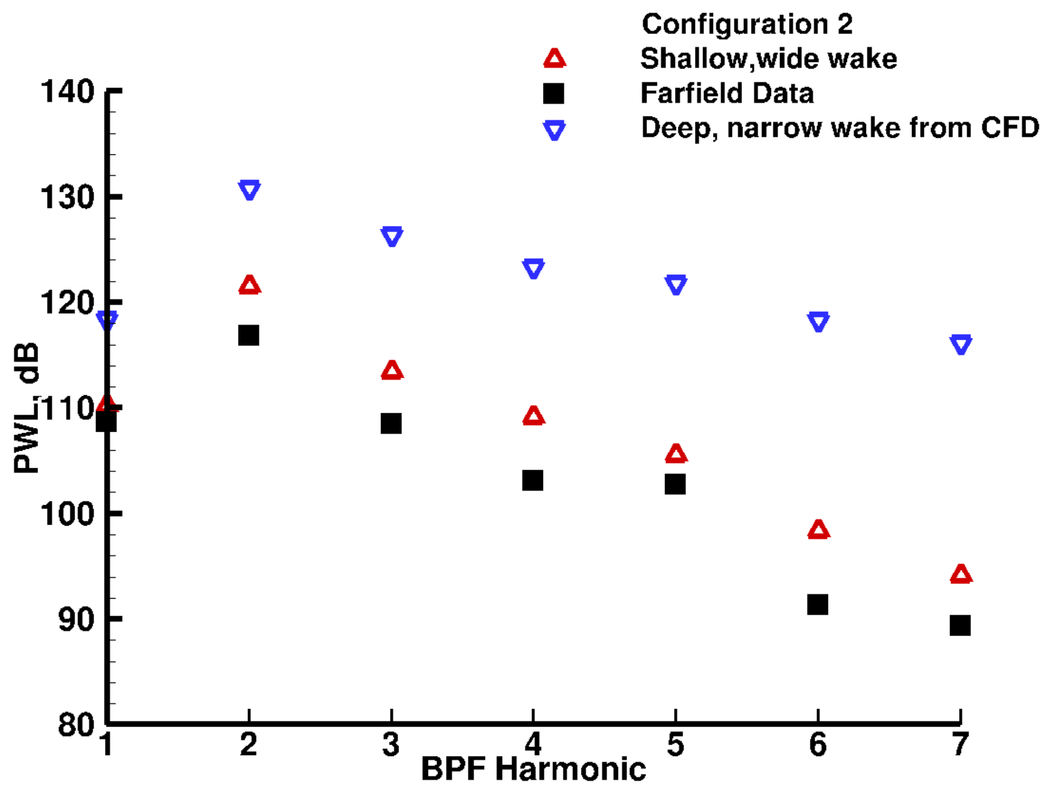

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Acoustic Validation

Attention to the design of aerodynamic test configurations is recommended.

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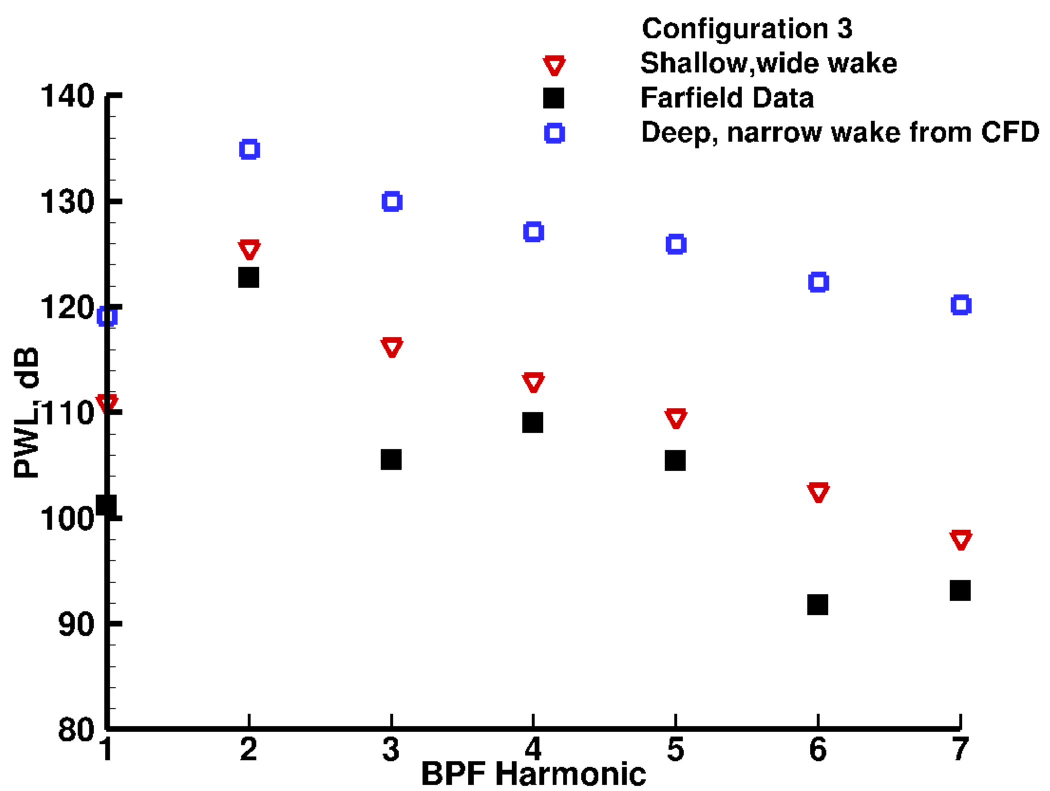
Set 2: Wake parameters were arbitrarily adjusted to model a wider, shallower wake to generate noise predictions in red.

No experimental data were available to validate wake parameters at rotor leading edge.



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Acoustic Validation

Alternately, had the rods been placed closer to the rotor, higher harmonics could have significantly contributed to the overall tone sound power level of the fan.

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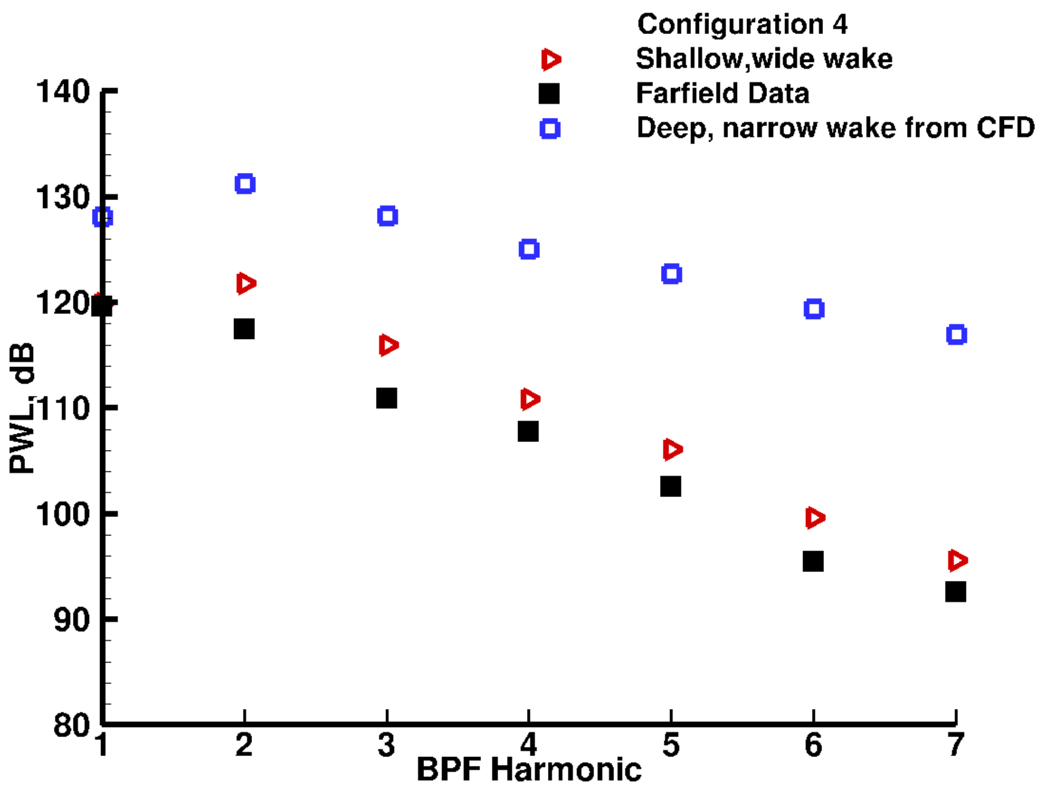


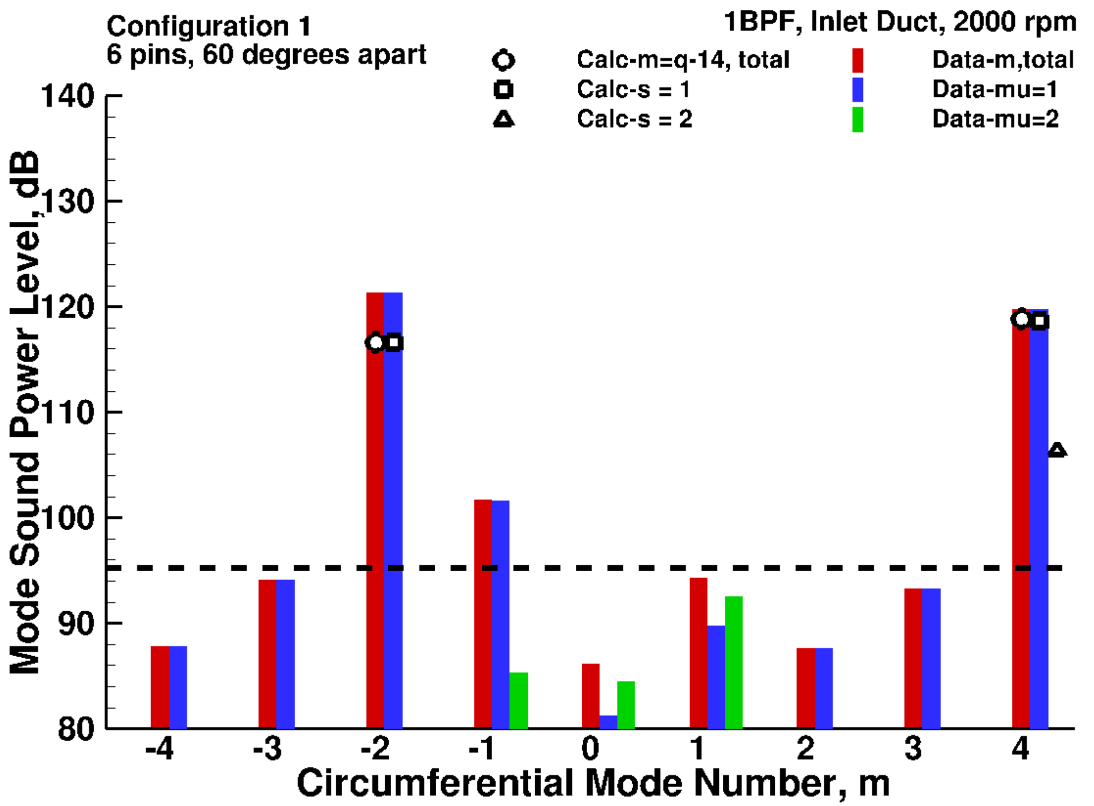
Predicting the Inflow Distortion Tone Noise of the NASA Glenn Advanced Noise Control Fan with a Combined Quadrupole-Dipole Model

Acoustic Validation

The model captures overall trends in circumferential mode sound power levels reasonably well.

Set 2 wake parameters were used to predict the mode sound power levels.

The dashed black line indicates the noise floor of the data set.



Predicting the Inflow Distortion Tone Noise of the NASA Glenn Advanced Noise Control Fan with a Combined Quadrupole-Dipole Model

Acoustic Validation

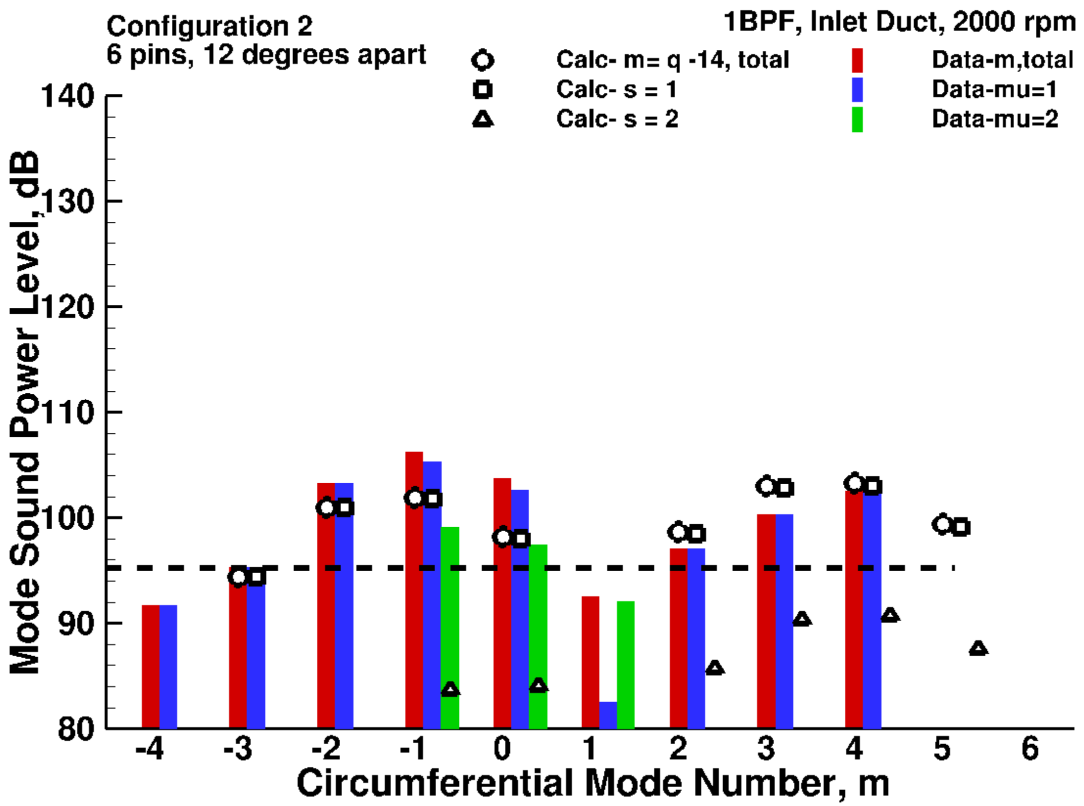
Differences between the measured and the calculated modes results from the different duct models used.

Set 2 wake parameters were used to predict the mode sound power levels.

The dashed black line indicates the noise floor of the data set.

The Rotating Rake data were processed using an annular duct model.

The GDGK predictions were based on an unrolled rectangular duct model.



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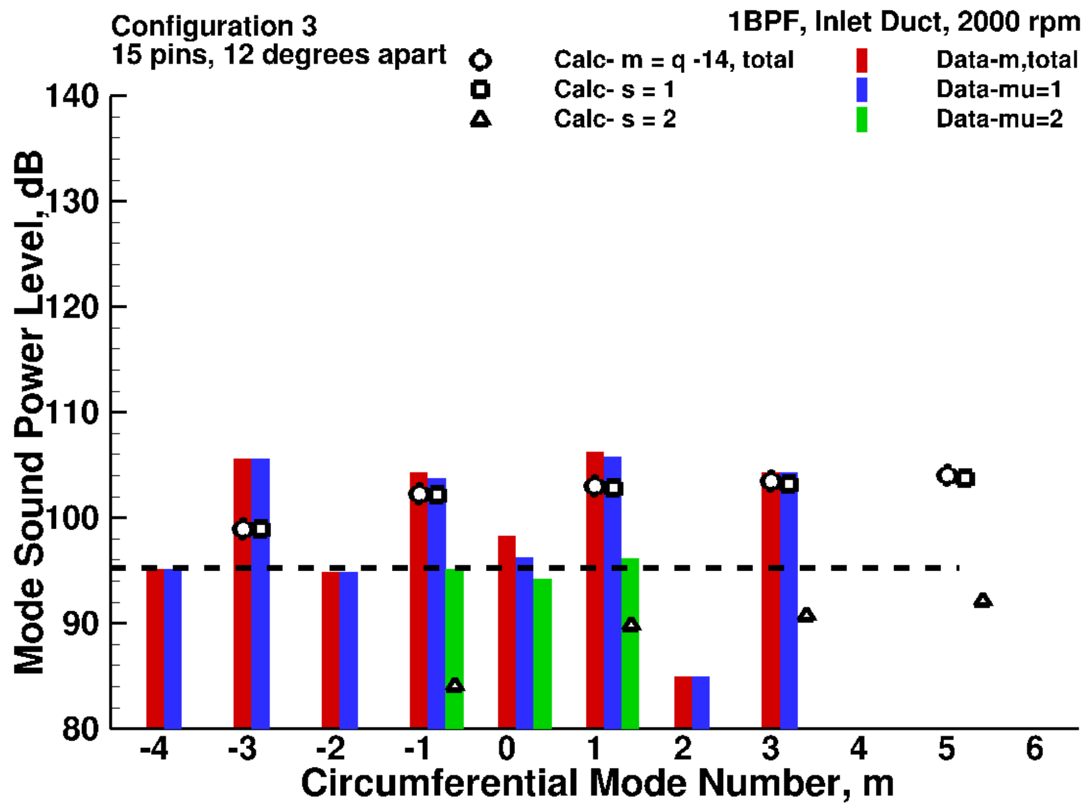

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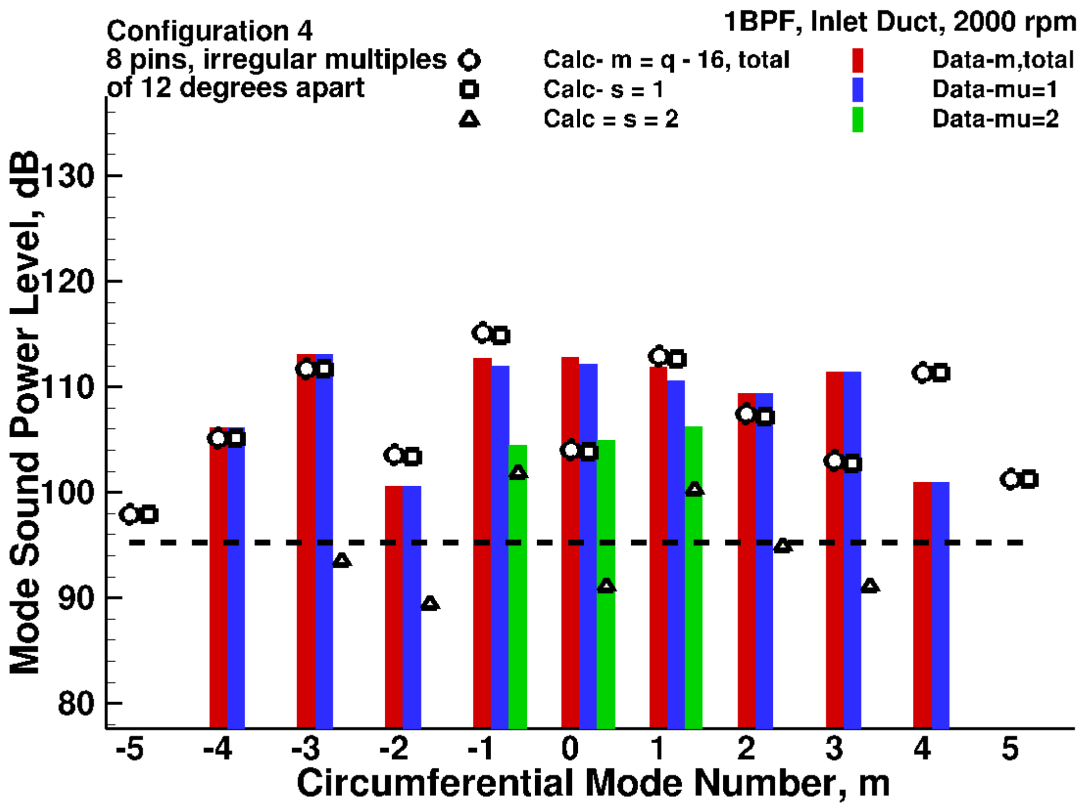

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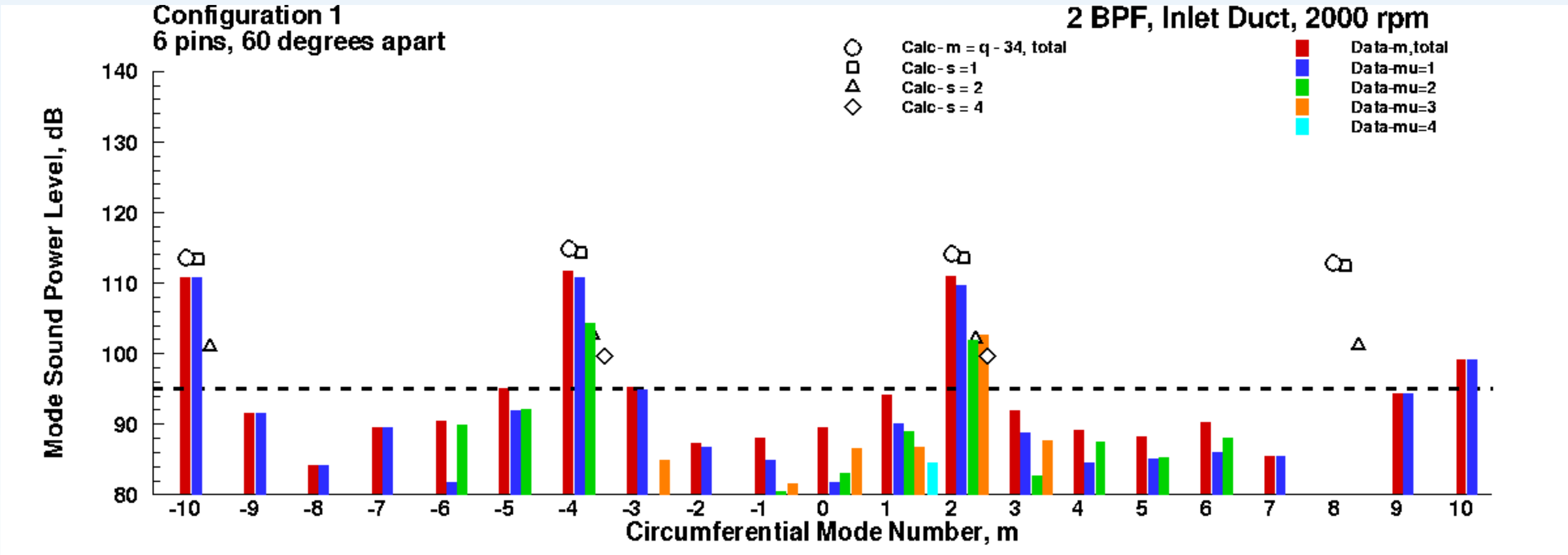

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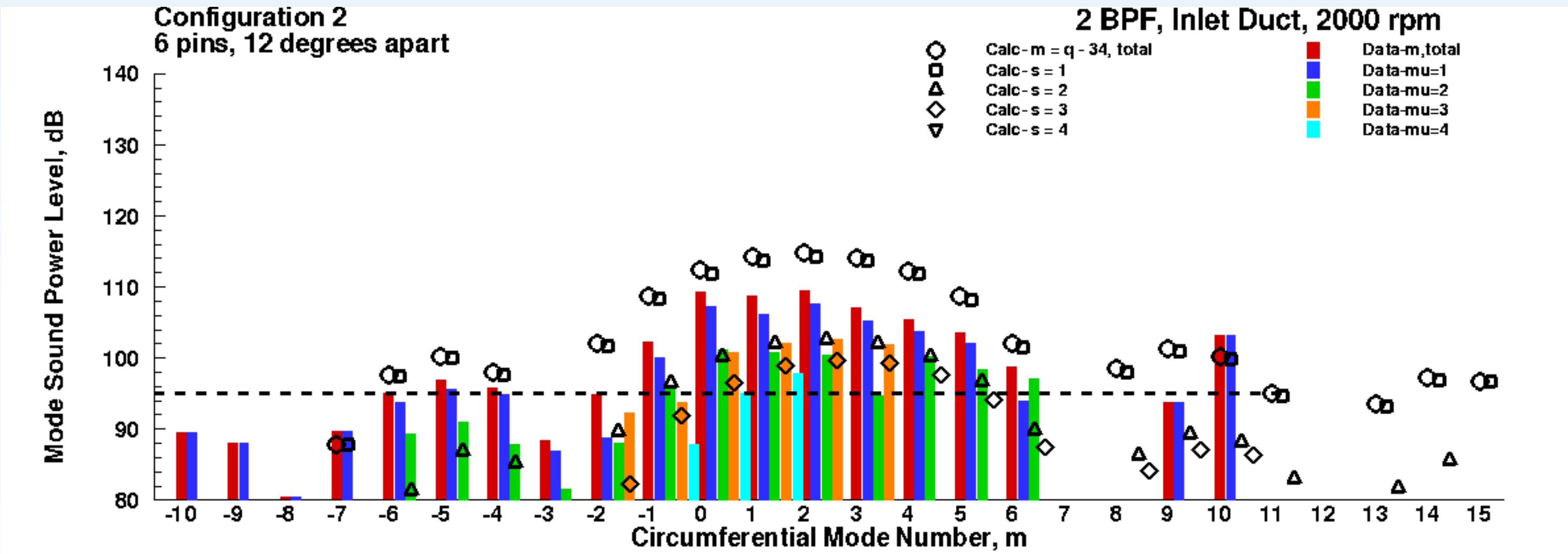

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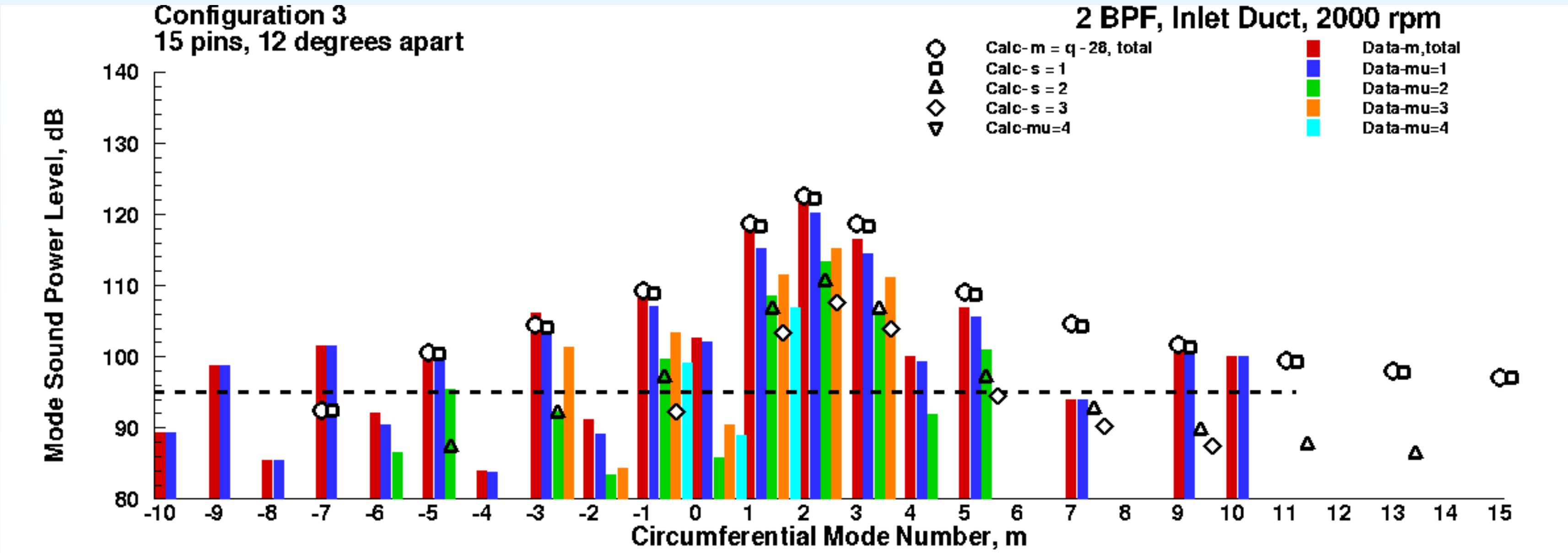

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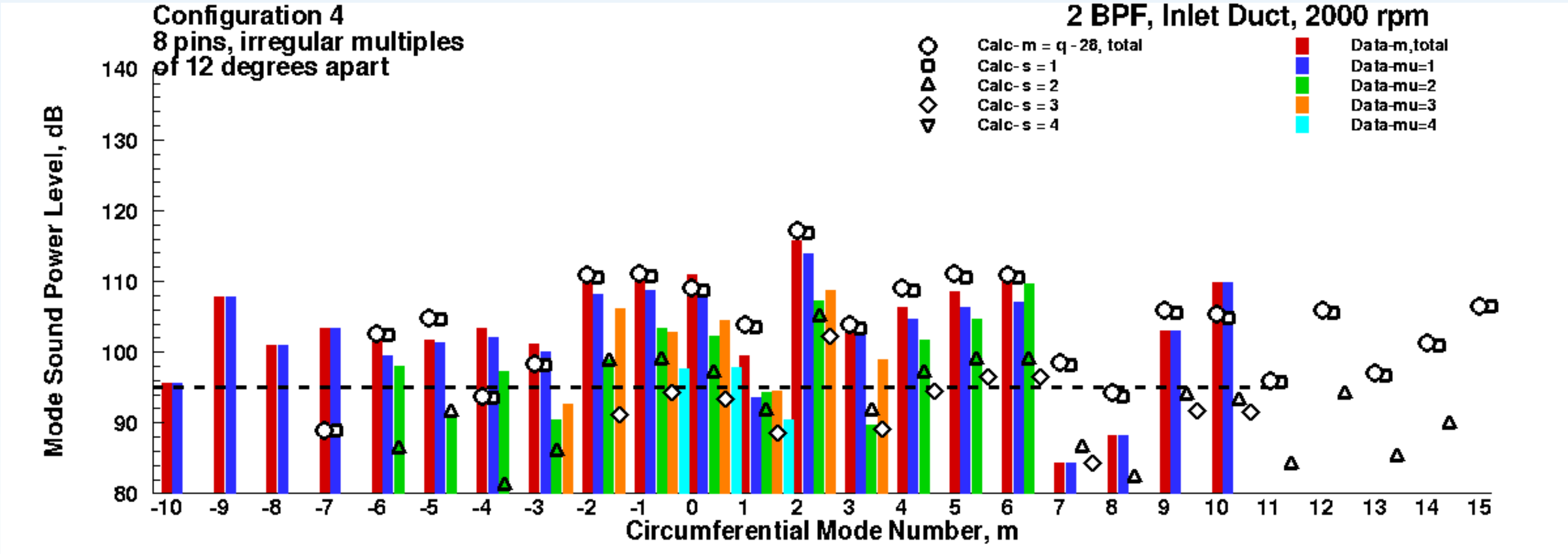

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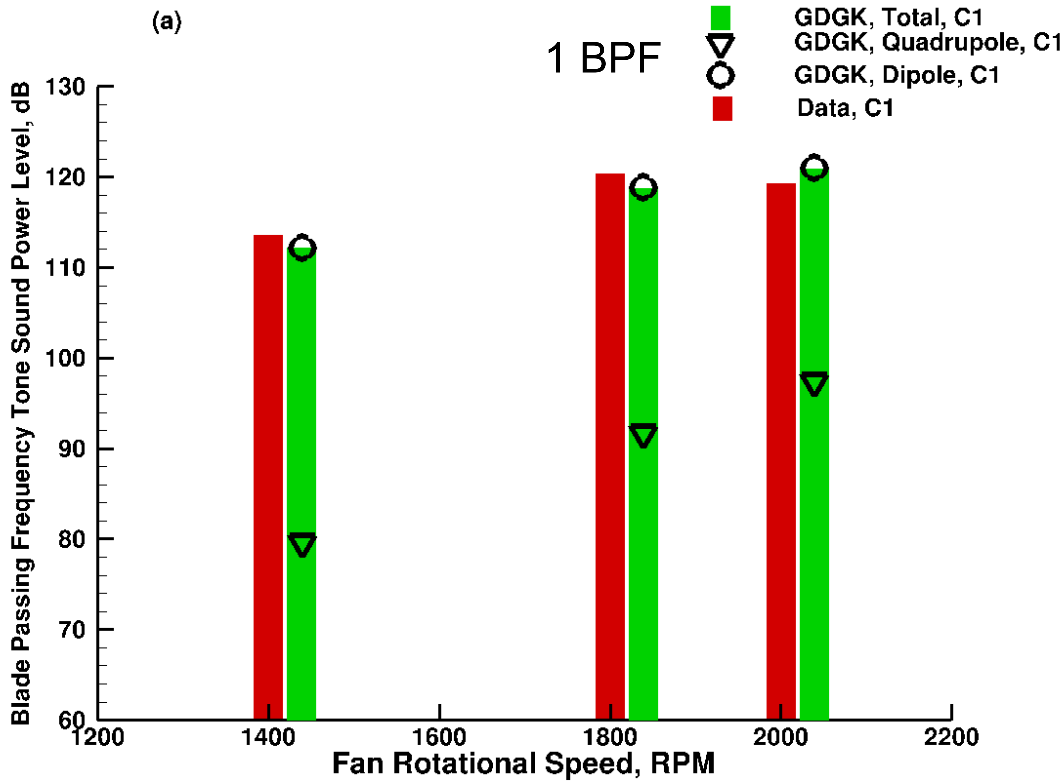
Acoustic Validation

Sound power level of the quadrupole term predicted to increase with rotor speed.

Set 2 wake parameters were used to predict the mode sound power levels for all three fan speeds.

The data was acquired from the farfield microphone array in the inlet region of the fan.



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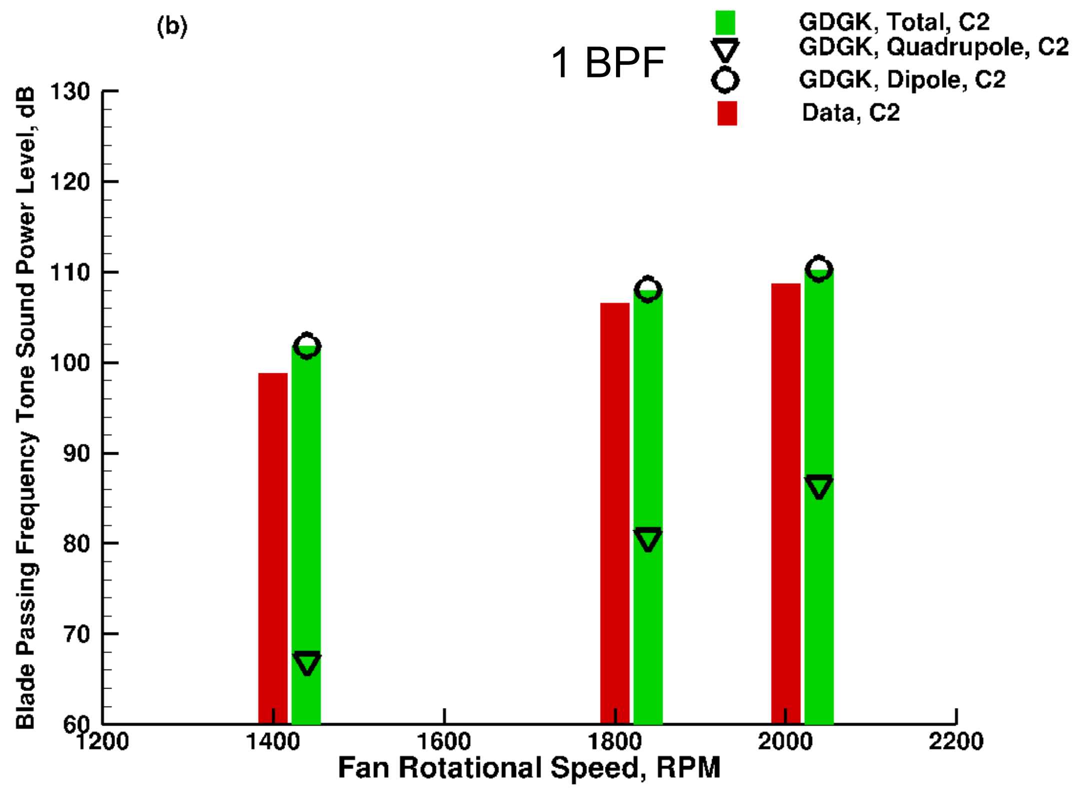

Predicting the Inflow Distortion Tone Noise of the NASA Glenn Advanced Noise Control Fan with a Combined Quadrupole-Dipole Model

Acoustic Validation

Aerodynamic and acoustic datasets for more highly loaded fans are needed to more fully validate this acoustic prediction method.

Set 2 wake parameters were used to predict the mode sound power levels for all three fan speeds.

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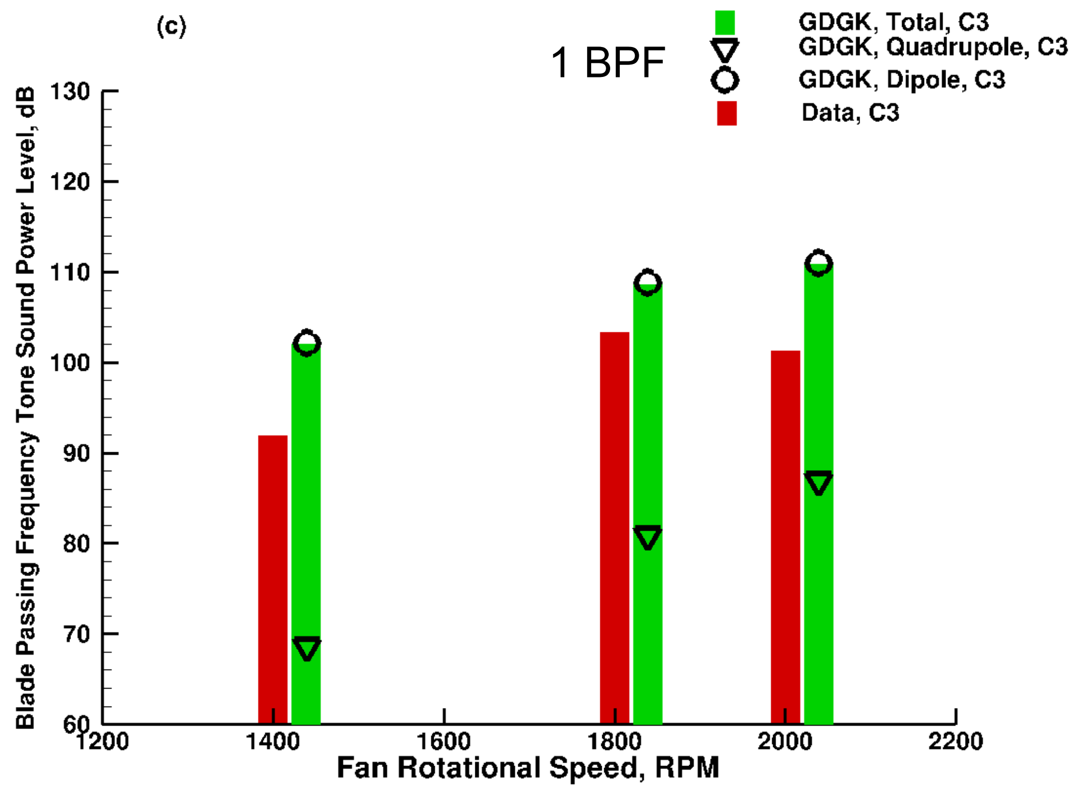

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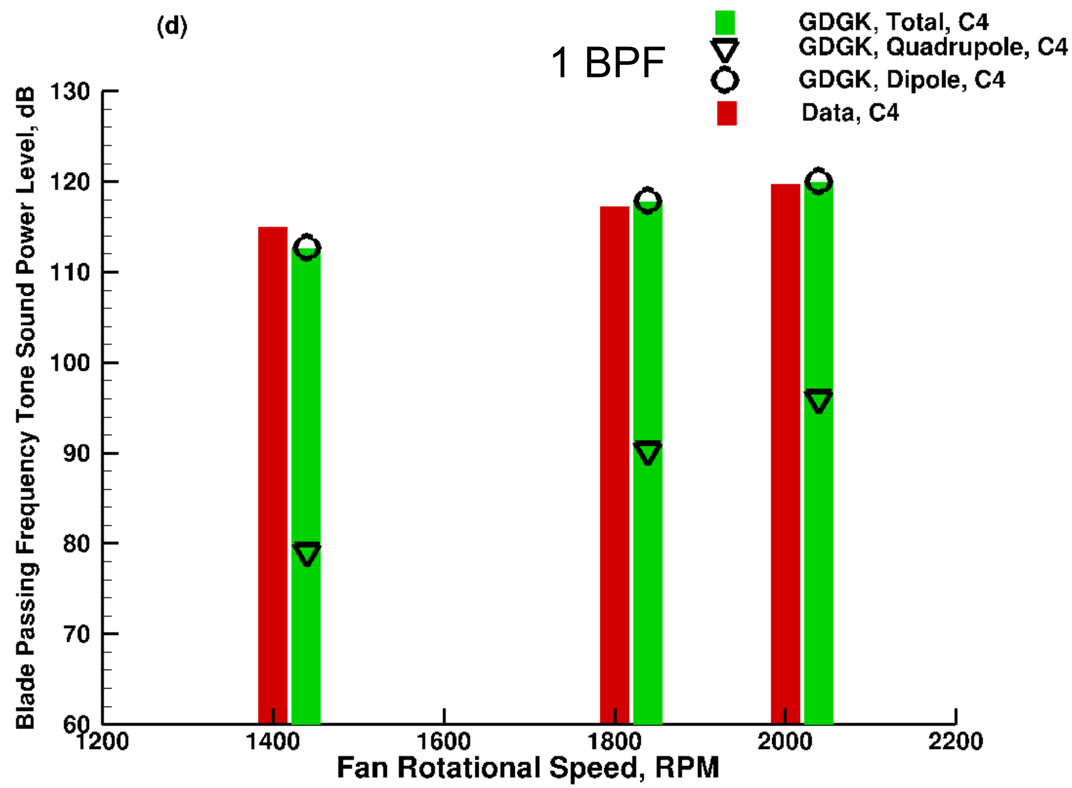

Predicting the Inflow Distortion Tone Noise of the NASA Glenn Advanced Noise Control Fan with a Combined Quadrupole-Dipole Model

Conclusions

A combined quadrupole-dipole model of inflow distortion tone noise, derived and initially validated by Goldstein, Dittmar and Gelder in 1974, serves as the theoretical basis for a new Fortran 90 computer code, GDGK.

The theory has been extended to model the wakes from obstructions placed in circumferentially asymmetric locations in the fan inlet duct.

Calculated results were compared to original and new experimental data, and good agreement was seen between trends, given the simplicity of the model.

Results indicate get that calculated sound power levels are sensitive to the accuracy of the modeled wake.

Aerodynamic and acoustic datasets for more highly loaded fans are needed to more fully validate this acoustic prediction method.

Predicting the Inflow Distortion Tone Noise of the NASA Glenn Advanced Noise Control Fan with a Combined Quadrupole-Dipole Model

Prediction Method

The sound power levels of the harmonics of blade passing frequency, P_p, is approximated by the following expression given in NASA TN-D-7676:

$$\frac{P_p}{\rho_0 c_0^3 Bb\Delta} = \frac{(MM_t)^2 pM_t}{4} \sum_{\substack{\text{all q and all s}\geq 0 \text{ with} \\ p^2M_t^2 > \beta^2\left[\left(p-\frac{q}{B}\right)^2+\left(\frac{\sigma'}{2b}\right)^2\right]}} (1+\delta_{s,0}) \frac{\left|\Theta_{p,q,s}\right|^2 \left|A_{q,s}\right|^2}{(M_t p + MK_{p,q,s})^2 K_{p,q,s}}$$

where

$$\Theta_{p,q,s} \equiv \underbrace{-\theta \overline{H}_{p,q,s}\left(MM_t p + K_{p,q,s}\right)}_{\text{quadrupole}} + \underbrace{i\psi S\left(\sigma_q\right)\left[\frac{M(pB-q)\beta^2}{B} - M_t(MM_t p + K_{p,q,s})\right]}_{\text{dipole}}$$

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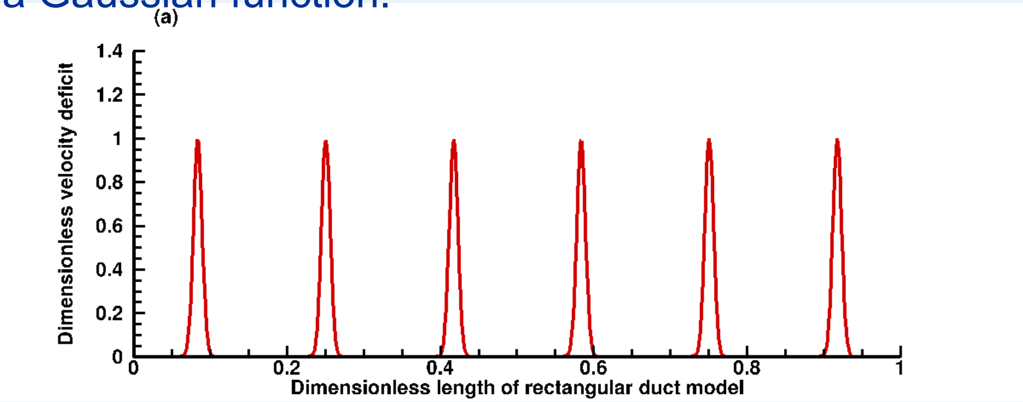
The Fourier coefficients of the axial distortion velocity profile were assumed to be:

$$A_{q,s} = I a_q d_s$$

Predicting the Inflow Distortion Tone Noise of the NASA Glenn Advanced Noise Control Fan with a Combined Quadrupole-Dipole Model

Prediction Method

In the original theory, the obstructions were uniformly spaced, and the axial distortion velocity profiles were modeled with a Gaussian function.



$$A_{q,s} = I a_q d_s$$

$$a_q = \frac{1}{\delta}\int_0^{\delta} e^{-2\pi i q y_2/\delta} f(y_2)\,dy_2$$

$$f(y_2) = \exp\left[\frac{-\left(\frac{y_2}{\delta} - \frac{1+2j}{2N}\right)^2}{(\sigma')^2}\right]\left\{\frac{\frac{j\delta}{N} < y_2 < \frac{(j+1)\delta}{N}}{\text{for j } = 0,1,\ldots N}\right\}$$

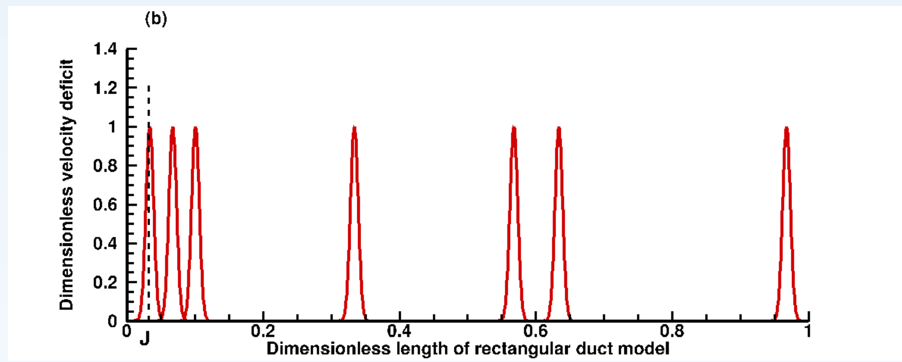
$$a_q = \sqrt{\pi}\, N\sigma' e^{\frac{-i\pi q}{N}} e^{-\pi^2 q^2 (\sigma')^2}\,\mathrm{Re}\left[erf\left(\frac{1}{2N\sigma'} + \pi i q \sigma'\right)\right]$$

for q = 0, ±N, ±2N, …

Predicting the Inflow Distortion Tone Noise of the NASA Glenn Advanced Noise Control Fan with a Combined Quadrupole-Dipole Model

Prediction Method

In the modified theory, the obstructions could be arbitrarily spaced, and the axial distortion velocity profiles were modeled with a Gaussian function.



$$A_{q,s} = I a_q d_s$$

$$a_q = \frac{1}{\delta}\int_0^{\delta} e^{-2\pi i q y_2/\delta} f(y_2)\,dy_2$$

$$f(y_2) = \exp\left[\frac{-\left(\frac{y_2}{\delta} - J_j\right)^2}{(\sigma')^2}\right]\left\{\frac{0 \le \frac{y_2}{\delta} \le 1}{\text{for j } = 0,1,2\ldots\text{N}}\right\}$$

for all q

$$a_q = \frac{\sigma'\sqrt{\pi}}{2} e^{-2\pi q i J_j} e^{-(\pi q \sigma')^2} \sum_{j\ge 0}\left[erf\left(\frac{J_j}{\sigma'} - i\pi q\sigma'\right) + erf\left(\frac{1 - J_j + i\pi q \sigma'^2}{\sigma'}\right)\right]$$