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

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Abstract

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.

Nomenclature

$A_{q,s}$	Fourier coefficient of axial distortion velocity
a_q	circumferential Fourier coefficients of the axial distortion velocity profile
AR	aspect ratio
B	number of rotor blades
b	blade height
c_0	speed of sound
c	rotor chord length
D	compressibility correction factor defined by Equation (8)
d_s	radial Fourier coefficients of axial distortion velocity profile defined by Equation (2)
$H_{p,q,s}$	complex conjugate of $H_{p,q,s}$
$\bar{H}_{p,q,s}$	complex conjugate of $H_{p,q,s}$
i	$\sqrt{-1}$
I	ratio of maximum distortion velocity to mean axial velocity U
$K_{p,q,s}$	defined by Equation (3)
J_j	dimensionless circumferential location of inlet obstructions
M	axial Mach number, U/c_0
M_r	relative Mach number, U_r/c_0
M_t	rotor tip Mach number, U_t/c_0
N	number of upstream vanes or struts, integer 1, 2, ...
\mathcal{P}_p	total acoustic power radiated upstream in the p^{th} harmonic of the blade passing frequency
\bar{R}	mean radius
$S(\sigma_q)$	Sears function, defined in Equation (6)
U	axial flow velocity
Ur	relative velocity, $-\sqrt{U_t + U^2}$
U_t	cascade (rotor) velocity
y_i	coordinates of source point

w_i	phase-locked rotor velocity field relative velocity field
β	$\sqrt{1 - M^2}$
β_r	$\sqrt{1 - M_r^2}$
Δ	interblade spacing
δ	circumferential distance, $B\Delta$
$\delta_{i,j}$	Kronecker delta
$\Theta_{p,q,s}$	defined by Equation (4)
θ	work coefficient, $-\Delta w_2 / U_t$
ρ_0	background density
σ'	half-width of Gaussian/step profile
σ_q	reduced frequency, $\frac{q\Omega c}{2U_r}$
$\tilde{\sigma}$	dimensionless radial height of axial distortion velocity profile
ψ	defined by Equation (5)
Ω	shaft rotational frequency, $\frac{2\pi U_t}{\delta}$

Subscripts

i, j, k	integer 1, 2, 3, ...
s	integer 0, 1, 2, ...
p, q	integer, 0, ± 1 , ± 2 , ...

Introduction

A combined quadrupole-dipole analytic model of fan inflow distortion tone noise was published by Goldstein, Dittmar, and Gelder in 1974 (Ref. 1). 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. They chose to retain the quadrupole source term in a generalized version of the Ffowcs Williams and Hawkings (Refs. 2 and 3) formulation based on a previous suggestion of Morfey (Ref. 4), whose simplified analysis suggested that sound generated by the quadrupole term may be equal to or greater than the sound generated by a dipole term for axial Mach numbers of the inflow as low as 0.25. Indeed, upon examining the final form of the equations of the combined quadrupole-dipole model, Goldstein et al. noted that the dipole term was independent of the work coefficient of the fan, but that the quadrupole term would be greater than the dipole term for highly-loaded, low-solidity fans. A limited amount of experimental data accompanied the original derivation in Reference 1.

The current paper describes an extension of the theory presented by Goldstein, et al. (Ref. 1). The original theory has been extended so that tone sound power levels can be calculated when obstructions are placed at circumferentially asymmetric locations upstream of the rotor to distort the inflow. A computer code called GDGK has been written based on the theory of Goldstein, Dittmar, Gelder extended and programmed by Koch. Computed results are compared here against data from a test conducted with the NASA Glenn Advanced Noise Control Fan (ANCF) in 2007. Data from the ANCF experiments is considered to be a partial validation of this model, as the quadrupole generation mechanism was not a dominant component of the inflow distortion tones for this low-speed, lightly loaded fan.

Prediction Method

Goldstein et al. presented a derivation of the following equations to estimate sound power of the blade passing frequency (BPF) harmonic tones radiated upstream of a fan ingesting distorted inflow (see pp. 12, and 25 to 28 of Ref. 1). Many assumptions were made to arrive at these equations; such as modeling the

fan duct as an unrolled rectangular duct, modeling the rotor potential flow field as a line of free vortices, and using a Gaussian function to model the wakes of the upstream stators or vanes. These original equations were incorporated into the first version of the computer code GDGK.v1. The first term of Equation (4) is associated with the quadrupole mechanism, and the second term in Equation (4) is associated with the dipole mechanism.

$$\frac{P_p}{\rho_0 c_0^3 B b \Delta} = \frac{(MM_t)^2 p M_t}{4} \sum (1 + \delta_{s,0}) \frac{|\Theta_{p,q,s}|^2 |A_{q,s}|^2}{(M_t p + MK_{p,q,s})^2 K_{p,q,s}} \quad (1)$$

all q and all $s \geq 0$ with

$$p^2 M_t^2 > \beta^2 \left[\left(p - \frac{q}{B} \right)^2 + \left(\frac{\sigma'}{2b} \right)^2 \right]$$

$$H_{p,q,s} = \frac{\left(p - \frac{q}{B} \right) \beta^2 - iD(MM_t p + K_{p,q,s})}{p\beta_r - iK_{p,q,s}} \quad (2)$$

$$K_{p,q,s} = \sqrt{p^2 M_t^2 - \beta^2 \left[\left(p - \frac{q}{B} \right)^2 + \left(\frac{s\Delta}{2b} \right)^2 \right]} \quad (3)$$

$$\Theta_{p,q,s} \equiv -\theta \bar{H}_{p,q,s} (MM_t p + K_{p,q,s}) + i\psi S(\sigma_q) \left[\frac{M(pB - q)\beta^2}{B} - M_t (MM_t p + K_{p,q,s}) \right] \quad (4)$$

$$\psi = \frac{1}{2M_r} \left(\frac{c}{\Delta} \right) \left[\frac{2\pi AR}{AR + 2 \left(\frac{AR + 4}{AR + 2} \right)} \right] \quad (5)$$

$$S(\sigma_q) = \frac{\exp(-i\sigma_q) \left[1 - \frac{\pi^2}{2(1 + 2\pi|\sigma_q|)} \right]}{\sqrt{1 + 2\pi|\sigma_q|}} \quad (6)$$

$$\sigma_q = \frac{q\pi M_t}{BM_r} \left(\frac{c}{\Delta} \right) \quad (7)$$

$$D \equiv \frac{\beta_r + iMM_t}{\beta^2} \quad (8)$$

In order to evaluate Equation (1), it is necessary to determine values for $A_{q,s}$, the Fourier coefficients of the axial distortion velocity profile. Goldstein, et al. described one way in Reference 1 that is partially repeated here. If you assume

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

$$a_q = \frac{1}{\delta} \int_0^{\delta} e^{-2\pi i q y_2 / \delta} f(y_2) dy_2 \quad (9)$$

When the flow distortion is represented by N uniformly spaced Gaussian profiles in the circumferential direction such that

$$f(y_2) = \exp \left[\frac{-\left(\frac{y_2}{\delta} - \frac{1+2j}{2N}\right)^2}{(\sigma')^2} \right] \left\{ \begin{array}{l} \frac{j\delta}{N} < y_2 < \frac{(j+1)\delta}{N} \\ \text{for } j = 0, 1, \dots, N \end{array} \right\} \quad (10)$$

$$a_q = \sqrt{\pi} N \sigma' e^{-\frac{i\pi q}{N}} e^{-\pi^2 q^2 (\sigma')^2} \operatorname{Re} \left[\operatorname{erf} \left(\frac{1}{2N\sigma'} + \pi i q \sigma' \right) \right] \text{ for } q = 0, \pm N, \pm 2N, \dots \quad (11)$$

$$a_q = 0 \text{ for } q \neq 0, \pm N, \pm 2N, \dots \quad (12)$$

In the radial direction,

$$d_s = \delta_{s,0} \text{ if the flow distortion is uniform in the radial direction, or} \quad (13)$$

$$d_s = \frac{2(-1)^s}{\pi s(1+\delta_{s,0})} \sin(\pi s \tilde{\sigma}) \text{ if the flow distortion is a square wave concentrated around the tip region} \quad (14)$$

However, sound power level can also be calculated for circumferentially asymmetric obstructions in the inlet duct if one chooses a more general form of Equation (10), resulting in a slightly different form for a_q , the circumferential Fourier coefficients of axial distortion velocity profile, where J_j is the dimensionless circumferential location of the upstream obstructions in the flow.

$$f(y_2) = \exp \left[\frac{-\left(\frac{y_2}{\delta} - J_j\right)^2}{(\sigma')^2} \right] \left\{ \begin{array}{l} 0 \leq \frac{y_2}{\delta} \leq 1 \\ \text{for } j = 0, 1, 2, \dots, N \end{array} \right\} \quad (15)$$

$$a_q = \frac{\sigma' \sqrt{\pi}}{2} e^{-2\pi i q J_j} e^{-(\pi q \sigma')^2} \sum_{j \geq 0} \left[\operatorname{erf} \left(\frac{J_j}{\sigma'} - i\pi q \sigma' \right) + \operatorname{erf} \left(\frac{1 - J_j + i\pi q \sigma'^2}{\sigma'} \right) \right] \text{ for all } q \quad (16)$$

This model was incorporated into the second version of the computer code, GDGK.v2. Figure 1 shows the notional differences between symmetric and asymmetrically arranged Gaussian curves that can be used to model the wakes. In the final form of the sound power level calculations, wake depth, width, radial extent, and circumferential placement are set using variables I , σ' , $\tilde{\sigma}$, and J_j , respectively.

Predictions from the new GDGK code were generated for the 51-cm fan studied in Reference 1. Figure 2 shows the original published results and the new calculations from the GDGK.v1 and GDGK.v2 codes. Generally, there is good agreement between the original and new predictions. Results from GDGK.v1 and GDGK.v2 were identical. Some of the differences between the original and new predictions are attributed to uncertainties in the input values for the calculations. While the original reports included values for most of the input quantities, the experimental value for fan inlet temperature was not presented which is needed to determine fan corrected speed and inflow variables. So for the new

GDGK predictions, it was assumed that the rotor speed settings were 10,666, 9,333, and 8,000 rpm; and that density was 0.800 kg/m^3 and acoustic speed was 336 m/s. Also, since sound power levels were not published in tabular form, there may be some errors in the historical values presented in Figure 2, which were determined by a manual inspection of the original plot.

Experiment

A fan inlet distortion experiment was conducted in 2007 using the NASA Glenn Advanced Noise Control Fan that is housed within AeroAcoustic Propulsion Laboratory (AAPL), as shown in Figure 3. The ANCF is 1.2 m (48 in.) in diameter and the centerline of the fan is 3.0 m (10 ft) above the floor. For both tests, no stator vanes were installed downstream of the rotor. The rotor had 16 blades set at a 28° pitch angle for all test conditions.

An Inflow Control Device (ICD) was used to condition the flow entering the fan, removing large-scale turbulence and ground vortices. The inlet plane was located 0.920 m (36.2 in.) or approximately 0.750 L/D ahead of the leading edge of the fan at the tip location. The exhaust plane was located 1.20 m (45.4 in.) or approximately 1.0 L/D downstream of the trailing edge of the fan at the tip location. Downstream of the test section, the centerbody diameter increases to 0.710 m (24.0 in.) to mimic a nozzle area contraction, yielding a hub-to-tip ratio of, $\sigma = 0.500$. The hub diameter at the rotor leading edge was 0.460 m (18.0 in.), yielding a hub-to-tip ratio of, $\sigma = 0.375$.

The inflow to the rotor was distorted by installing smooth cylindrical rods upstream of the rotor, as shown in Figure 4. The rods were 1.27 cm (0.500 in.) in diameter and were 31.8 cm (12.5 in.) long, resulting in a 6.35 cm (2.50 in.) gap between the bottom of the rods and the rotor hub. The centerline of the rods was 14.3 cm (5.63 in.) upstream of the rotor leading edge at the tip, or approximately one rotor chord length upstream. Data were recorded at three speed settings: 1400, 1800, and 2000 rpm. Four distortion patterns were tested in the 2007 experiment, as shown in Figure 5. A 30-rod mounting ring allowed rods to be placed at circumferential locations separated by increments of 12° . The experiment is described in more detail in References 5 to 7.

Two 15-microphone arrays were used to record the farfield sound distribution from the ANCF. Farfield microphone measurements were acquired synchronously with shaft speed at a rate of 256 samples per revolution, which allow for processing up to the 128th harmonic of the shaft frequency, or equivalently, up to the 8th harmonic of the blade passing frequency for this test (Ref. 8).

In-duct acoustic pressure measurements upstream and downstream of the rotor were acquired with the Rotating Rake system. The Rotating Rake system is a continuously rotating radial microphone rake that was inserted into the duct, at either the inlet entrance or exhaust exit plane. The system utilizes annular duct spinning mode theory and Doppler-shift physics to separate circumferential modes and the cylindrical wave equation solution to reduce the radial modes. It provides a complete map of the acoustic duct modal magnitudes and phases present in the fan duct. For these experiments the data were processed for the first two harmonics of blade passing frequency (Ref. 9).

The axial and tangential velocities downstream of a cylindrical rod were experimentally measured with a two-component hotwire probe. The probe was installed in radial and circumferential actuators mounted to the outside of the duct. The maximum traverse span for the circumferential actuator was 30° . Data were recorded at four radial locations: 0.330 m (13.5 in.), 0.419 m (16.5 in.), 0.508 m (20.0 in.), and 0.570 m (23.5 in.).

Comparison of Calculated and Measured Sound Power Levels

Calculated values of the sound power levels radiated upstream were generated using the GDGK.v2 code for the four configurations tested in the ANCF during the 2007 inlet distortion test. Figures 6 through 8 show the computed and measured wakes from the rods, which were used to determine the wake width and depth parameters needed for the sound power level calculation. Figure 6 show the normalized

axial velocity distribution at a radial station near the tip of the rotor, $\bar{R} = 0.591$ m (23.25 in.), which was the value used to determine the length of the unrolled rectangular duct modeling the fan, taken here to be the radius at 5 percent of the blade span from the tip. Figure 7 shows that the calculated wake depth decreases and the calculated wake width slightly increases as the flow approaches the inlet to the fan. TSWIFT, a Reynolds-averaged Navier Stokes solver was used to generate the mean flow predictions. Figure 8 shows predicted and measured distribution of the normalized axial velocity at a position slightly closer to the rotor tip ($\bar{R} = 0.597$ m (23.5 in.) and at an axial location of $X = -0.113$ m (-4.45 in.). Comparisons indicate that the measured wake was significantly wider and shallower than the predicted wake.

Figures 9 show plots of calculated sound power levels radiated upstream as a function of blade passing frequency (BPF) harmonic. The measurements on these plots are from the inlet duct farfield microphone array. Using non-dimensional wake width ($\sigma' = 0.0039$) and depth ($I = 0.299$) parameters based on the computational fluid dynamics (CFD) solution at $X = 0.0254$ m (-1.00 in.), calculated sound power levels were greater than measurements, showing a more gradual decrease in amplitude for the higher harmonics than was indicated by the experiment. However, by choosing parameters to model a wider, shallower wake ($\sigma' = 0.0060$, $I = 0.080$) at the fan inlet, which is consistent with the measured trends, better agreement between calculated and measured sound power level trends can be achieved. Experimental data in the wake of the rods at this axial location near the rotor leading edge were not available.

One may also hypothesize, given the results shown in Figure 9, that had the rods been placed closer to the fan leading edge, the overall levels of tone sound power levels could be significantly increased. Deeper and narrower wakes interacting with the rotor may raise the sound power levels of the higher harmonics. This may be of particular concern to aircraft and spacecraft ventilation system designers who may be faced with installing fans in convoluted ducts or near other system obstructions that can significantly distort the fan inflow. Alternately, aircraft engine designers will need accurate aerodynamic predictions and measurements near the fan inlet in order to conduct useful inlet duct acoustic design studies.

Figure 10 through 12 compare the calculated and measured sound power levels for the circumferential and radial modes in the inlet duct for the 1 BPF and 2 BPF tones for the four tested configurations at 2000 rpm. The measurements were obtained from the Rotating Rake installed in the inlet to the fan. The algorithm used to process the Rotating Rake microphone signals is based on an annular duct model. The reader is reminded that the sound power level calculations are based on an unrolled rectangular duct model. These modeling differences result in the differences between the sets of propagating modes. Figures 10 through 12 assume a wide, shallow wake ($\sigma' = 0.006$, $I = 0.08$) at the fan inlet. There was generally good agreement between the measured and calculated trends.

Finally, comparison between the measured and calculated sound power levels of the fundamental tone for all three tested speeds and all rod configurations are shown in Figure 13. The green bars indicate the sound power levels computed by the combination of the dipole and quadrupole terms. The sound power levels of the dipole term were computed, as well as the sound power levels of the quadrupole terms, which also appear on Figure 13. The reader is reminded that when the quadrupole and dipole terms are combined, cancellation is possible. The quadrupole mechanism did not contribute significantly to the generation of the blade passing tones since the work coefficient parameter, θ , for this fan was small ($\theta = 0.04$). The sound power level calculated from the quadrupole term did increase as fan speed increased. In general, the variation of the sound power level of the fundamental tone with speed was small and agreement between measured and calculated trends was good. The greatest differences between measured and calculated sound power levels are observed for all speeds of Configuration 3, warranting further study. Wake parameters were held constant for all the calculated results in Figure 13 ($\sigma' = 0.006$, $I = 0.08$).

Conclusion

A combined quadrupole-dipole model of inflow distortion tone noise, derived and initially validated by Goldstein, Dittmar, and Gelder in 1974 currently serves as the theoretical basis for a new Fortran 90 computer code, GDGK. The first version of the code, GDGK.v1 embodies the original theory and can be used to generate estimates of the tone sound power radiated upstream of a fan ingesting distorted inflow. In this version of the code, it is assumed that multiple obstructions in the inlet are equally spaced in the circumferential direction. Good agreement was shown between calculations from the GDGK.v1 code and the experimental data published in the original report.

The second version of the code, GDGK.v2 embodies an extension of the original theory. By representing the Fourier coefficients of the axial distortion velocity profile in a more general form, tone sound power level estimates can be generated when the obstructions in the fan inlet duct are placed in circumferentially asymmetric locations. GDGK.v2 calculations for the circumferentially asymmetric inlet duct obstructions were compared well against data from the 2007 ANCF inlet distortion experiments. Results indicated that calculated sound power levels were sensitive to the accuracy of the modeled wake.

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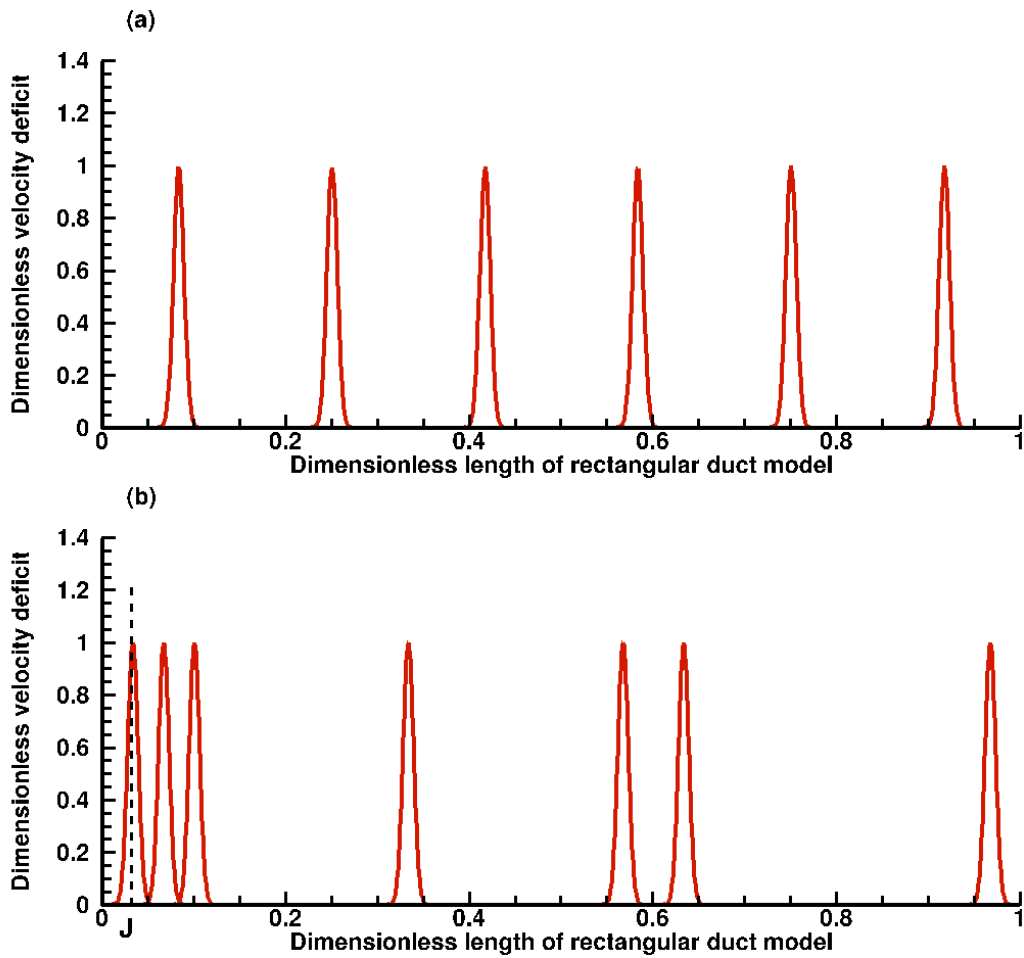


Figure 1.—Notional Gaussian functions used to model wakes from circumferentially (a) symmetric and (b) asymmetric arrangements of upstream struts or vanes that can distort the flow entering a fan. The center location for the wakes depicted in (b) are represented in Equation (15) and (16) by variable J_j .

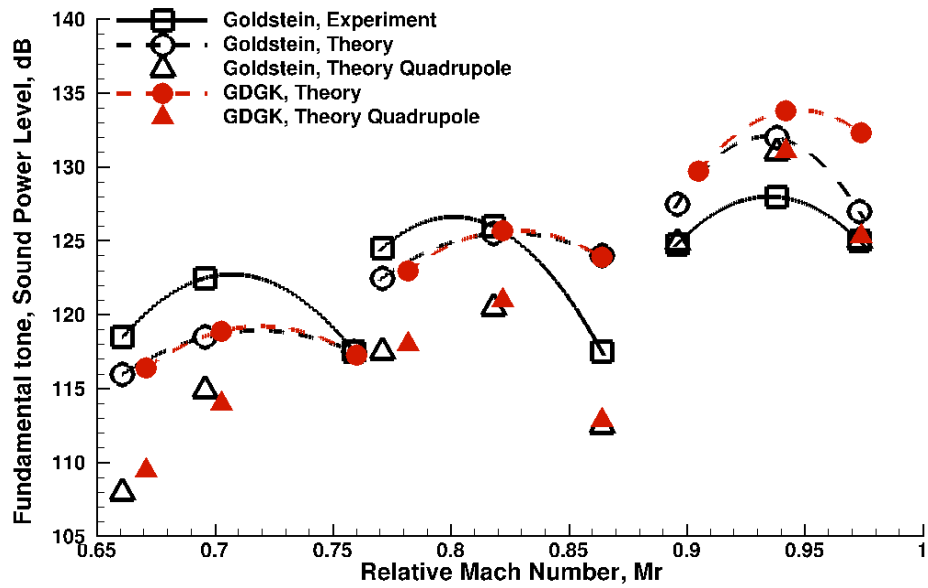


Figure 2.—Predicted and measured sound power levels of the fundamental tone of a 51-cm model fan. Predictions from the GDGK codes are compared to predictions and experimental data originally published by Goldstein et al., Reference 1. Calculated results from GDGK.v1 and GDGK.v2 were identical.

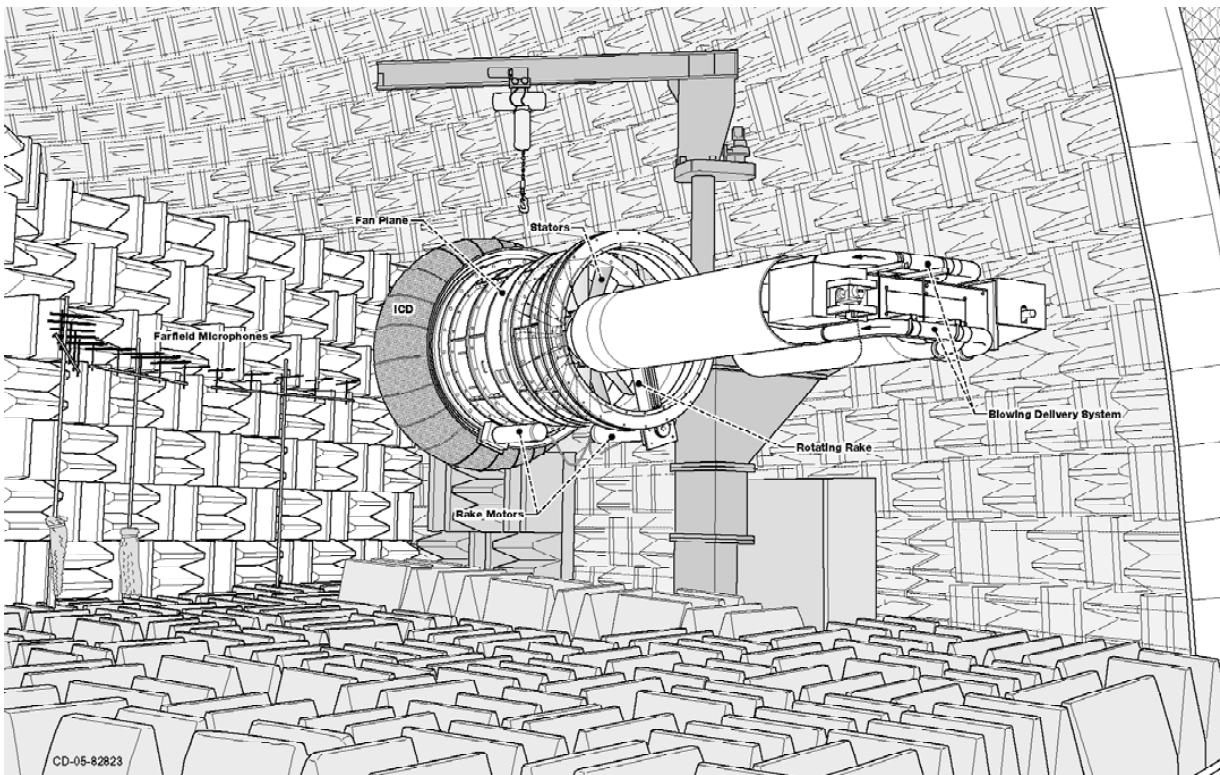


Figure 3.—The Advanced Noise Control Fan in the NASA Glenn AeroAcoustic Propulsion Lab.

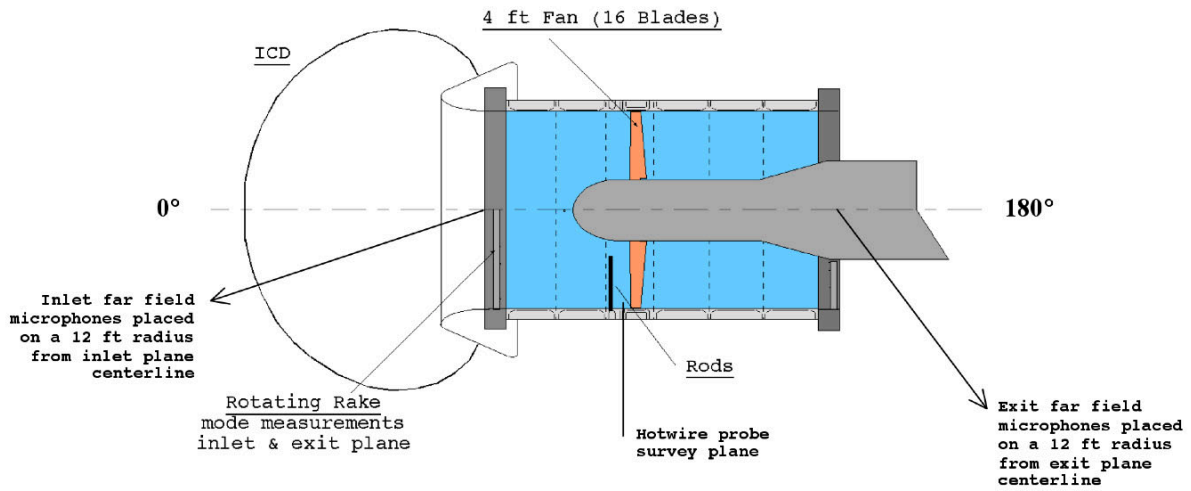


Figure 4.—Cross-sectional diagram of Advanced Noise Control Fan for the inlet distortion tests.

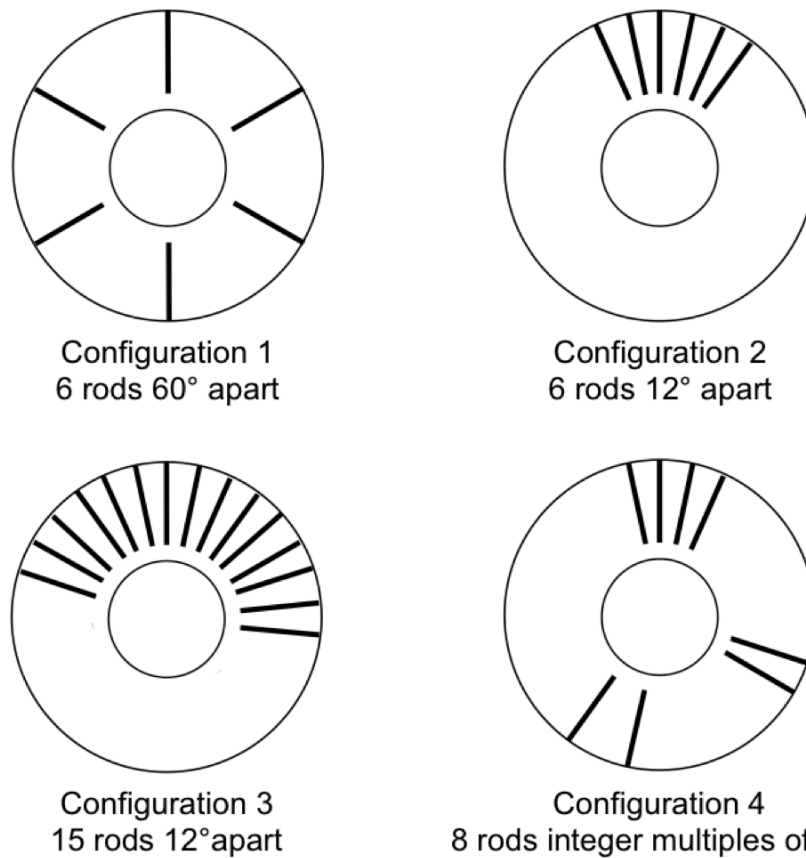


Figure 5.—Circumferential locations of inlet distortion rods tested in 2007 in the ANCF at NASA Glenn.

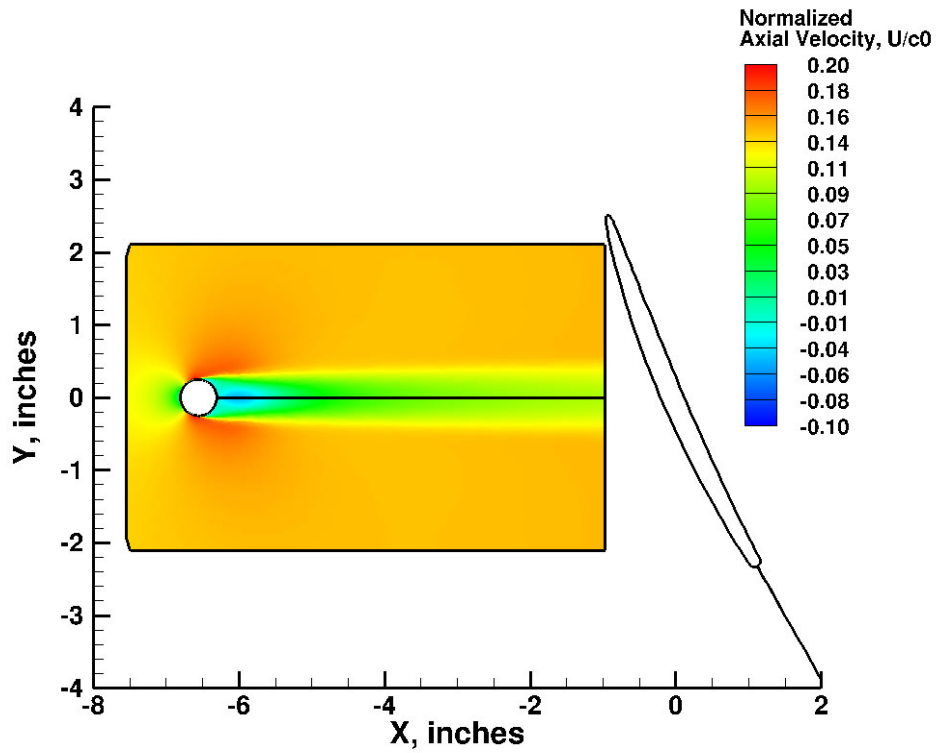


Figure 6.—Contours of normalized axial velocity, U/c_0 , in the wake of a cylindrical rod from TSWIFT, a computational fluid dynamics solver.

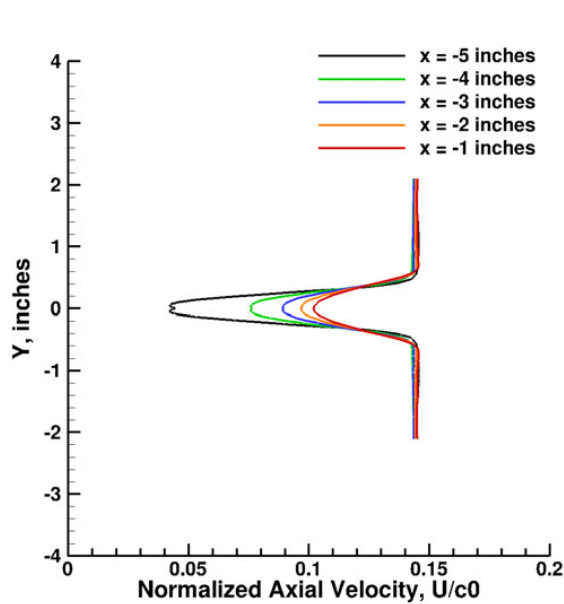


Figure 7.—Predicted wakes at five axial locations at radius $R = 0.5906$ m (23.25 in) and a rotor speed of 2000 rpm.

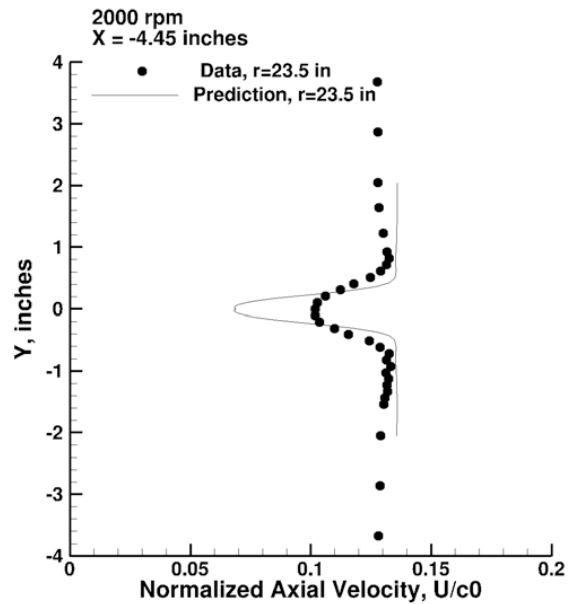


Figure 8.—Predicted and measured wake at radius $R = 0.597$ m (23.50 in) and axial location $X = -0.113$ m (-4.45 in).

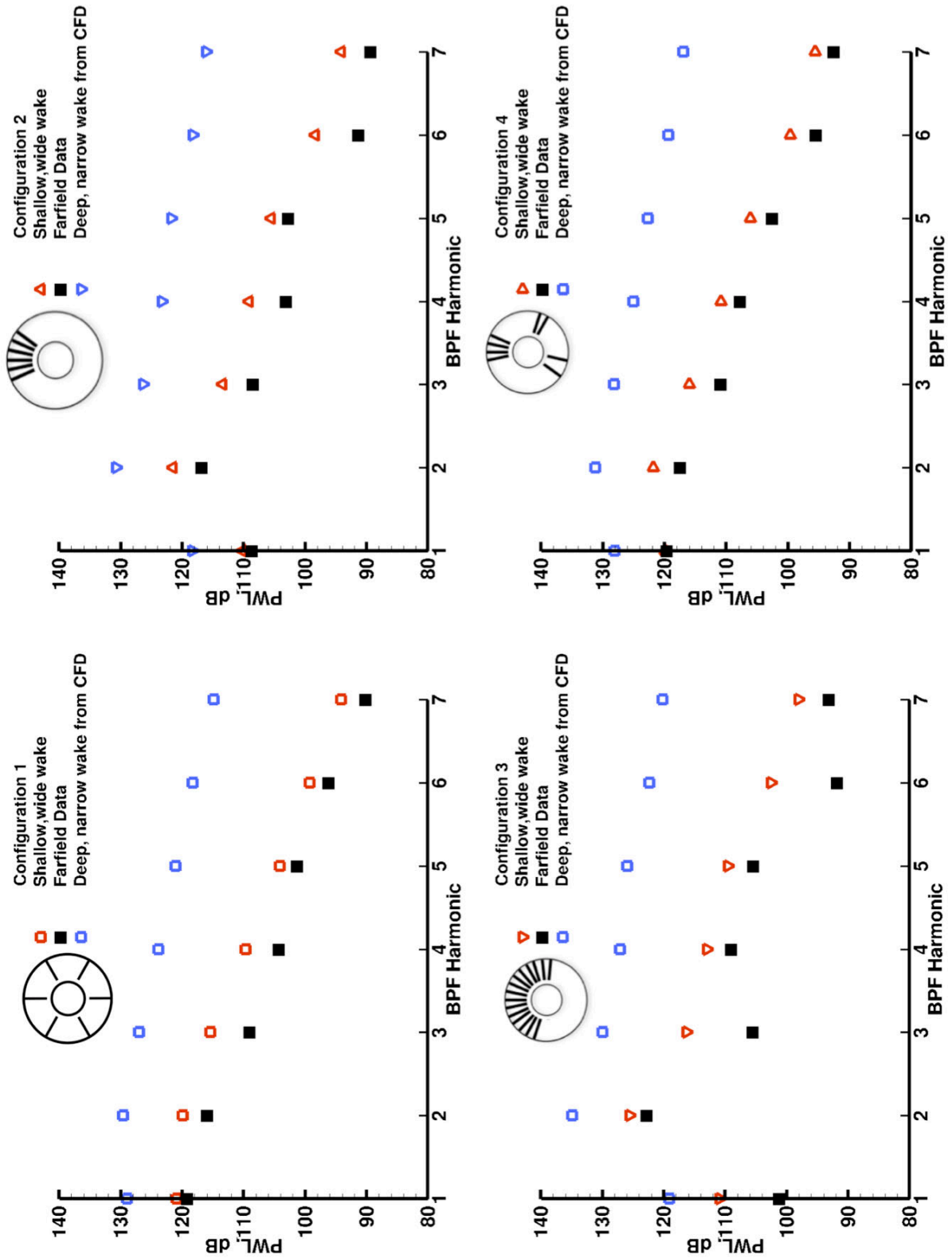


Figure 9.—Calculations of the sound power levels of the blade passing frequency harmonics from the GDGK.v2 code compared with measured far field sound power levels in the inlet region of the NASA Glenn Advanced Noise Control Fan (ANCF), 2000 rpm.

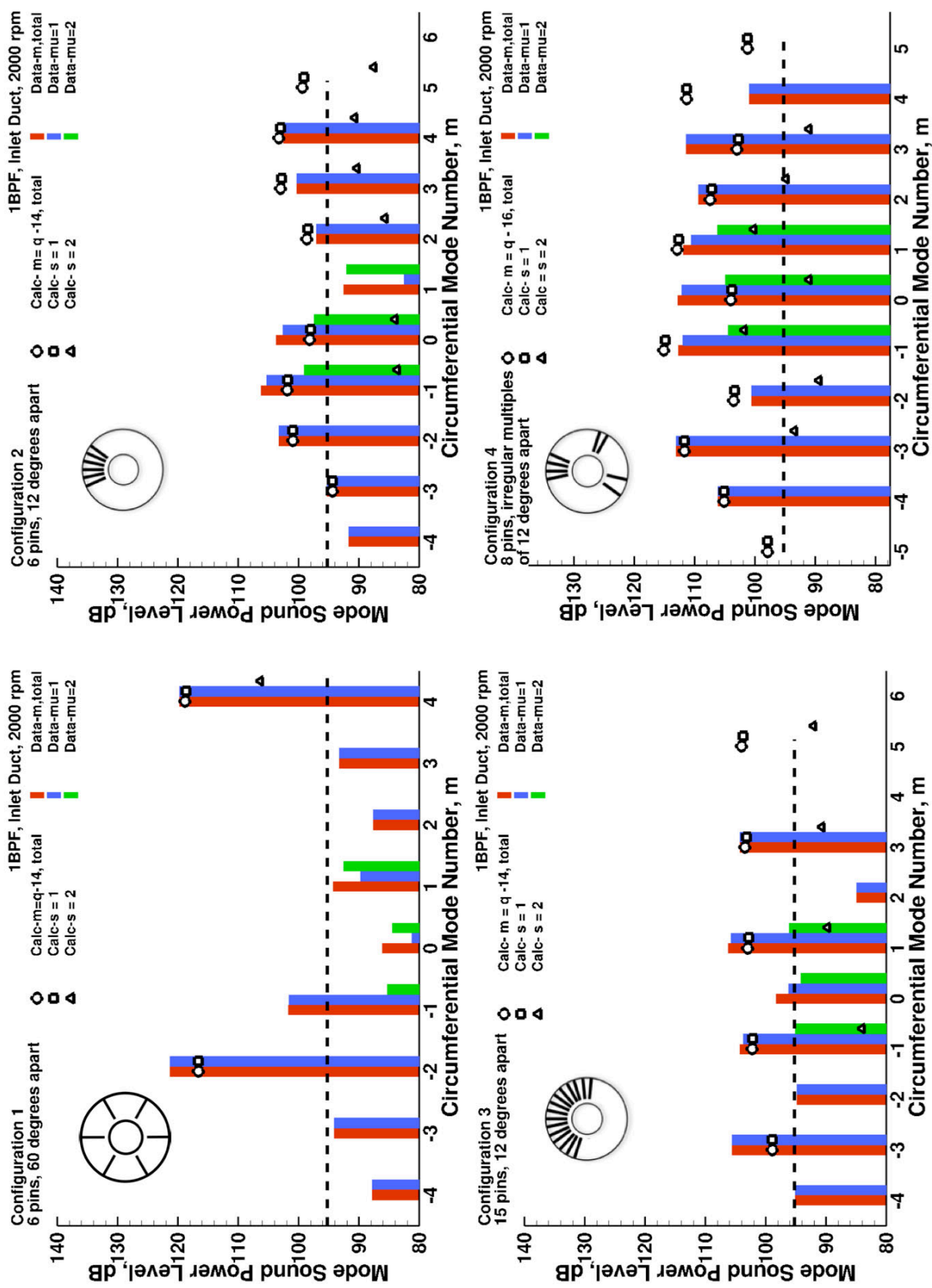
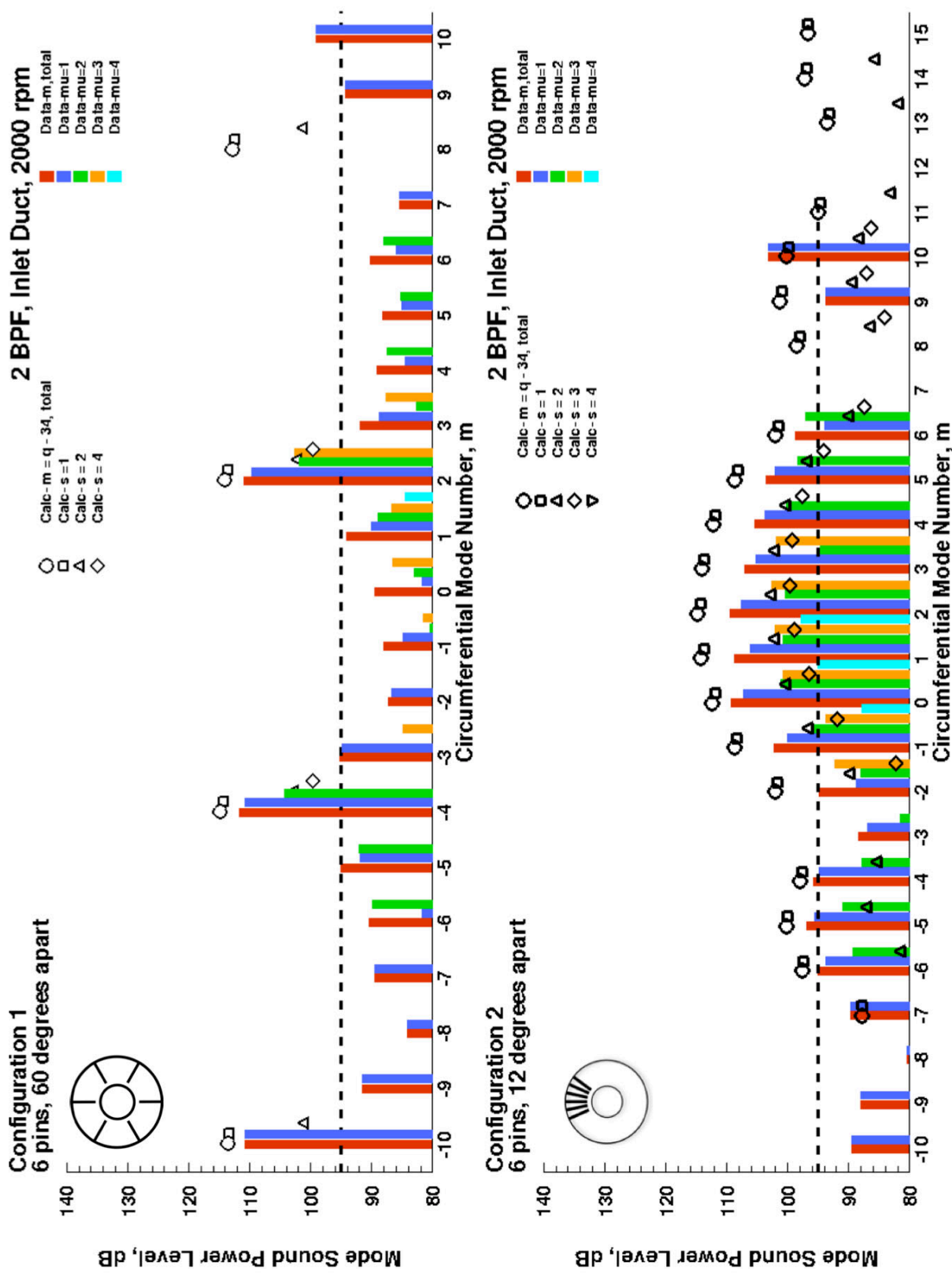


Figure 10.—Calculated ($P_{1,q,s}$) and measured ($P_{1,m,t}$) in-duct circumferential and radial sound power levels for the inlet duct, 1 BPF, 2000 rpm. Horizontal dashed line indicates noise floor for the data set. Measurements were obtained with the ANCF Rotating Rake.



(a) (b)

Figure 11.—Calculated ($P_{2,q,s}$) and measured ($P_{2,m}$) in-duct circumferential and radial sound power levels for the inlet duct, 2 BPF, 2000 rpm. Horizontal dashed line indicates noise floor for the data set. Measurements were obtained with the ANCF Rotating Rake.

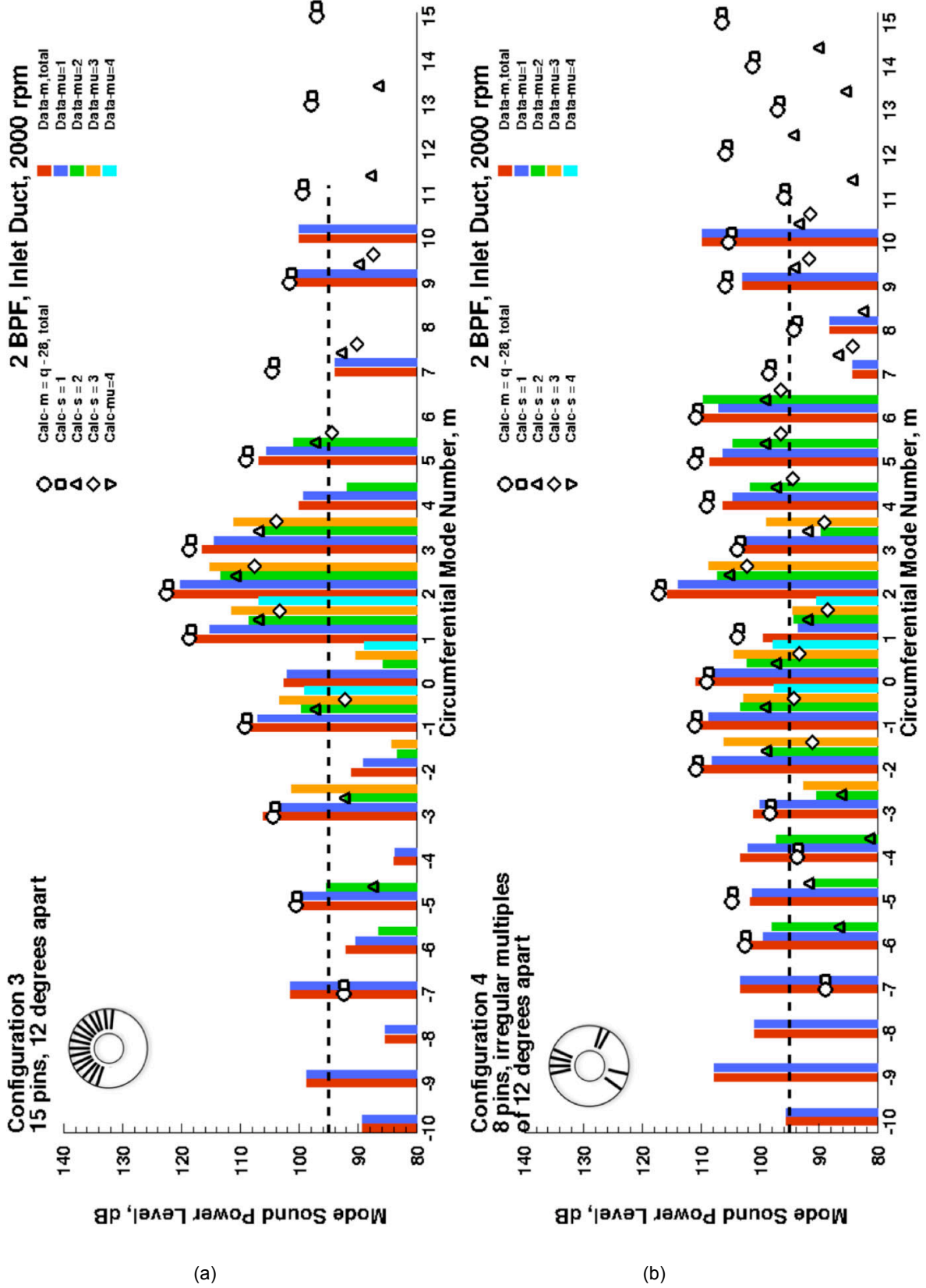


Figure 12.—Calculated ($P_{2,q,s}$) and measured ($P_{2,m,\mu}$) in-duct circumferential and radial sound power levels for the inlet duct, 2 BPF, 2000 rpm. Horizontal dashed line indicates noise floor for the data set. Measurements were obtained with the ANCF Rotating Rake.

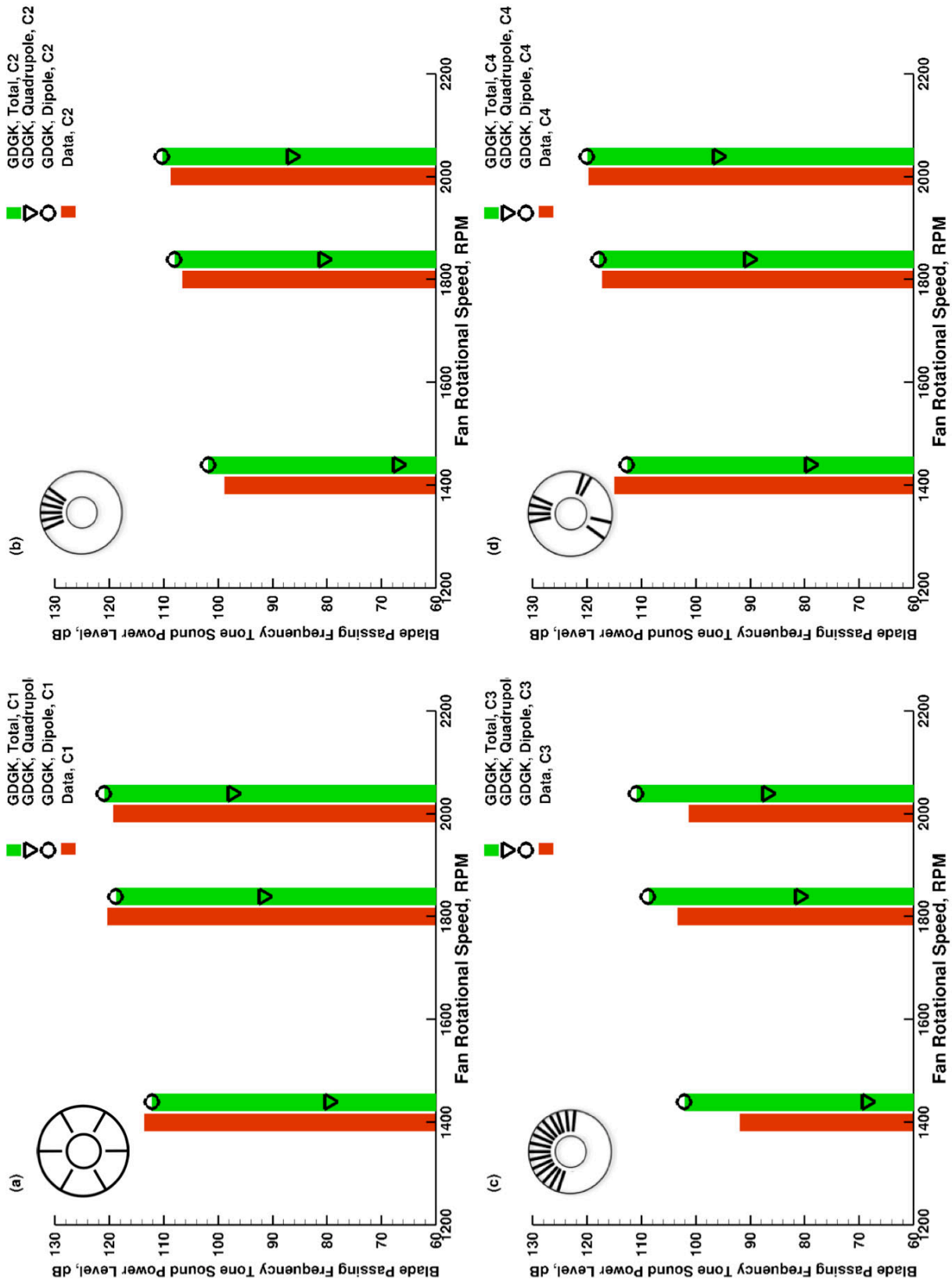


Figure 13.—Calculated (P_1) and measured (P_1) fundamental tone sound power levels for the inlet region. Symbols represent the sound power levels of the dipole and quadrupole term, while the green bars represent the sound power levels calculated by combining both the quadrupole and dipole terms. Measurements were obtained from the far field microphone array in the inlet region of the ANCF.

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14. ABSTRACT 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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