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I. Abstract

An experimental proof-of-concept test was conducted to demonstrate reduction of rotor-stator interaction noise through the use of rotor-trailing edge blowing. The velocity deficit from the viscous wake of the rotor blades was reduced by injecting air into the wake from a continuous trailing edge slot. Hollow blades with interior guide vanes create flow channels through which externally supplied air flows from the blade root to the trailing edge. A previous paper documented the substantial tonal reductions of this Trailing Edge Rotor Blowing (TERB) fan. This report documents the broadband characteristics of TERB.

The Active Noise Control Fan (ANCF), located at the NASA Glenn Research Center, was used as the proof-of-concept test bed. Two-component hotwire data behind the rotor, unsteady surface pressures on the stator vane, and farfield directivity acoustic data were acquired at blowing rates of 1.1, 1.5, and 1.8 percent of the total fan mass flow. The results indicate a substantial reduction in the rotor wake turbulent velocity and in the stator vane unsteady surface pressures. Based on the physics of the noise generation, these indirect measurements indicate the prospect of broadband noise reduction. However, since the broadband noise generated by the ANCF is rotor-dominated, any change in the rotor-stator interaction broadband noise levels is barely distinguishable in the farfield measurements.

II. Introduction

The velocity deficit due to the viscous wakes of the rotor blades impinging on the stator vanes is a prime component of rotor-stator interaction noise.[1] This periodic wake disturbance interacts with the stator causing unsteady surface pressures on the stator vane that in turn couple to the duct acoustic modes. The magnitude of the wake deficit correlates to the acoustic levels. It has been demonstrated analytically and experimentally that reducing the harmonic content of the wake will have a substantial effect on reducing the tone component of the fan noise. The wake deficit also contains broadband turbulence that is generally greater than the free-stream levels and therefore is a primary contributor to the broadband rotor-stator interaction noise.

One method to reduce the velocity deficit is to fill the wakes by injecting air into the wakes from a slot in the trailing edge. Prior experiments using rotor trailing edge blowing in a blow-down facility[2] and inlet guide vane trailing edge blowing[3] have shown that filling the wake through trailing edge blowing reduces the harmonic content of the wake. A detailed assessment of the tonal characteristics of the TERB installed on the ANCF, as well as a description of the composite hollow blade assembly, and computational predictions was presented in an earlier paper.[4] This paper assumes the reader has familiarity with reference 4.

It is assumed that the mean wake filling results in lower velocity gradients thereby reducing the turbulence generation mechanism in the wake. The energizing of the wake with the lower-turbulence air can reduce the unsteady surface pressure response of the stator vane. To the extent this unsteady pressure is reduced, the acoustic response will be attenuated.

Blowing rates (defined as mass flow injected into the rotor system divided by the fan mass flow of 125 lb/sec) of 1.1, 1.5, and 1.8 percent at a fan speed of 1800 corrected rpm were tested. The turbulent velocity (measured using a two-component hot-film), the stator vane unsteady surface pressures, and the farfield directivity were acquired and evaluated.

III. Experimental Apparatus

A. ANCF Test Bed

The test was performed on the NASA Glenn 48” Active Noise Control Fan[5] (ANCF) in the fall of 2004. It is located in the Aero-Acoustic Propulsion Laboratory (AAPL) shown in figure 1(a). The ANCF is a ducted fan used to test noise reduction concepts (fig. 1(b)). The four foot diameter fan produces a tip speed of ~425 ft/sec resulting in a mass flow of approximately 125 lb/sec. A 16-bladed rotor in combination with a variable stator vane count and spacing produces the desired rotor-stator interaction modal content at a Blade Passing Frequency (BPF) of approximately 500 Hz along with the harmonics. For the Trailing Edge Rotor Blowing (TERB) test, 14 stator vanes at 1/2-chord spacing were used (nominally 2.5” spacing between the rotor trailing edge and the stator leading edge, at the hub).

B. Trailing Edge Blowing Rotor

The ANCF facility was chosen for this experiment because the relatively low speed allows for a correspondingly simple design. Sixteen composite hollow rotor blades were installed in the ANCF for this experiment. A photograph of the installed blades is shown in figure 2(a).

Figure 2(b) shows a model of the assembled blade with the pressure side skin removed to illustrate the flow passages. Figure 2(c) shows an exploded diagram of the blade components. Each component is fabricated separately. Internal flow channels are created by an internal sintered part along with the airfoil skins. The forward and aft flow channel boundaries are contained in a single component fabricated using laser-sintering techniques. Blade skins are made of graphite/epoxy laminates. The internal geometry is critical in delivering the air to the trailing edge with minimal losses. The hub contained an impeller device that accepted flow from the central drive shaft, turned the flow radial, and delivered it to the fan blade with the proper rotational velocity. The supply air injection through the ANCF drive shaft allowing the air to be introduced without affecting the existing flow as shown in figure 3.

The trailing edge slot created a thick or blunt trailing edge that with no blowing was unsuitable for baseline noise measurements due to vortex shedding. Therefore, a set of inserts that created a sharp trailing edge was installed to more closely model a realistic rotor blade. Although this extended the chord approximately 1/2” (nominal chord, 5”) this effect was ignored and the rotor blades with inserts were defined as the baseline rotor for comparison.

IV. Experimental Methodology and Results

A schematic of the ANCF with measurement locations is shown in figure 4. The baseline case (rotor with trailing edge inserts installed) is compared to the same rotor using three blowing rates: 1.1, 1.5, and 1.8 percent.

A. Hotwire

1. Method

Two component hotwire data (axial and tangential) for the baseline rotor and blowing cases were acquired 1/2 rotor chord behind the rotor at 15 radial positions, at 1800 rpm. Hotwire time histories were acquired synchronous to the shaft rotation at 640 samples-per-revolution for 500 revolutions. The two-component time histories were converted to velocity and flow angle using a two-dimensional fourth-order polynomial curve fit obtained from an off-line calibration in a free jet over the expected experiment velocity and flow angles. This calibration was at a single fixed temperature-the shop air delivery system (~70 °F).

The velocity and flow angle as a function of time were time-domain-averaged over a complete revolution and then further averaged over a single blade passage (40 points). These time histories were then subtracted in blocks aligned to the fan-one-per-rev signal from the original time history to obtain the turbulent velocity, either revolution or passage-averaged.

$$v'(t) = V(t) - \overline{V}(1:40) \quad \text{where}: v'(t) \text{ is the turbulent velocity}$$
$$V(t) \text{ is the total velocity}$$
$$\overline{V}(1:40) \text{ is the velocity averaged over one passage}$$

2. Results

The passage-averaged turbulent velocity is shown in figure 5 for the four cases in contour plot format. Figure 6(a) shows selected radial slices of the turbulent velocity across one blade passage selected to represent the tip area (r = 22"), the mid-span region (r = 18"), and the hub region (r = 12'). These slices illustrate the percentage width of the turbulent wake compared to the passage, and the maximum value of the turbulence or "peak turbulence". In a relative sense, these values indicate the strength of the acoustic response.

Using 1.1 percent blowing, the wake width is nearly the same as compared to the baseline at 32.5 percent for both. The peak turbulence at the tip area is lower (6.8 vs 8.8 fps) when using blowing. In the mid-span the wake is modestly reduced. Near the hub region the wake character is approximately the same as the baseline. Blowing at the 1.5 and 1.8 percent rates reduces the turbulent wake significantly. At the tip region these blowing rates have a reduced wake width of about 25 percent of the rotor passage verse 32.5 percent for baseline wake. The peak depth of the wake is reduced to 4.1 and 5.5 fps respectively, indicating that 1.5 percent is more the effective blowing rate. At the mid-span region the effectiveness of these two blowing rates is approximately equal. The wake width has been reduced but with a slight skewing toward the suction side. The max wake depth is reduced to 4.1/4.4 fps, respectively. In the hub region the wake width is reduced similar amounts with the two blowing rates, but the depth is reduced from 8 to 4.6/3.9 fps indicating that the 1.8 percent rate is more effective in reducing the wake turbulence levels at the hub region.

The distribution of the optimum rate (1.5 percent at the tip, equivalent at mid-span, 1.8 percent at the hub) corresponds very well to the observation that the tip portion of the mean wake is actually over-filled, while the hub span is under-filled (ref. 4). As over-blowing occurs, the velocity gradients in the mean wake increase, resulting in stronger turbulence. An iterated distribution (modifying the slot thickness) would result in a uniform wake modification at a blowing rate between 1.5 and 1.8 percent, which might be more effective at reducing the turbulence.

The turbulent velocity spectra (fig. 6(b)) indicate that lower turbulence is produced up to the 8^{th} fan harmonic (128 shaft orders) when blowing is applied. The spectra confirm the optimum blowing rate to be 1.5 or 1.8 percent depending upon the span location. The reduction in the spectral amplitude over the 1^{st} 3 harmonics (8 to 48 shaft orders), where the highest turbulence levels are produced, is 45 to 55 percent. At the higher frequencies, which have lower turbulent amplitudes, the reduction is 25 to 50 percent.

B. Surface Pressures

1. Method

Unsteady stator vane surface pressures were also acquired for the baseline rotor and 1.8 percent blowing rate. The suction and pressure side of a single stator vane were each instrumented with 30 microphones as detailed in figure 4. The microphones were flush mounted on the surfaces and distributed along three span locations (r/Rtip = 0.49, 0.74, and 0.91) and a radial line at 20 percent chord.

The time histories were acquired synchronous to the shaft rotation at 256 samples-per-revolution for 500 revolutions. A frequency domain averaged FFT with an ensemble length of five revolutions was obtained from the time histories. The shaft-order harmonics, which are bin-centered due to the synchronous sampling technique, were removed from the spectra. The remaining spectra is defined as the broadband content and was integrated for each microphone from 0.5 to 1.5 BPF to give the broadband SPL for the 1^{st} harmonic; from 1.5 to 2.5 BPF to give the broadband SPL for the 2^{nd} harmonic; and from 2.5 to 3.5 BPF to give the broadband SPL for the 3^{rd} harmonic. The integrated SPL levels for individual microphones are then summed to obtain the overall unsteady broadband noise on the vane. Unsteady tonal surface pressures over a stator vane has been shown to have a direct relationship to the tone farfield PWL for this fan,[6] similarly, the broadband stator vane pressures have been shown to have a relationship to the farfield *broadband* levels for a high-speed fan.[7]

2. Results

The suction and pressure surface unsteady broadband pressures of the stator vane are plotted in figures 7 to 9 for the 3 harmonic bands described above. For the 1st harmonic band, figure 7(a) shows that span-wise along the 20 percent chord line the unsteady pressure is reduced 1 to 2 dB on the suction side but only a fraction of a dB along the pressure side. The chord-wise pressure distributions in figure 7(b) show that most of the reduction in the unsteady pressure occurs at the leading edge (10 percent) and the 60 to 85 percent region on the suction side (the relative contribution of a given region to the radiated sound is not known). The reductions in the 2nd harmonic band unsteady pressures (fig. 8) along the vane surfaces, both suction and pressure sides, though the mid-chord region is less affected on the suction side. The 3rd harmonic band (fig. 9) shows a consistent reduction of 2 to 5 dB over both surfaces.

C. Farfield

1. Method

Farfield acoustic data were acquired over the entire range of blowing rates. Thirty microphones were distributed along an arc of 12' radius with approximately 5° increments. Data were acquired at 256 samples per-rev and FFT were obtained by averaging ensemble blocks five revolutions long. The shaft-order harmonics, which are bin-centered due to the synchronous sampling technique, were removed from the spectra. The remaining spectra is defined as the broadband content and was integrated for each microphone from 0.5 to 1.5 BPF to give the broadband SPL for the 1st harmonic; from 1.5 to 2.5 BPF to give the broadband SPL for the 2nd harmonic; and from 2.5 to 3.5 BPF to give the broadband SPL for the 3rd harmonic. The SPL directivity was integrated over the directivity angle subtended by the microphone, assuming constant SPL over the azimuthal angle, to obtain the broadband harmonic PWL.

The ANCF farfield broadband directivity has approximately equal contributions from the rotor and stator; that is the stator vane broadband noise is just distinguishable in the farfield. This makes determination of rotor-stator interaction noise reduction problematic. However, it is instructive to note the characteristics of the broadband farfield acoustics of blowing, with the stators installed.

2. Results

Figure 10 shows the farfield broadband acoustic directivity characteristics of the TERB for the first three harmonic bands. The forward sector is unchanged at the lower rates (1.1 to 1.5 percent). The 1st harmonic band shows modest decreases in the aft sector at 1.1 percent. The 1.8 percent blowing rate shows a 1 dB increase in the PWL for both sectors. For the 2nd and 3rd harmonics the forward sector is essentially unchanged with blowing. The aft sector shows a fraction of a dB decrease in the 2nd, and a 1.0 dB decrease in the 3rd, harmonic bands with blowing.

Figure 11 shows the integrated PWLs for the forward and aft sectors for 6 harmonic bands. This illustrates the negligible overall changes in the forward sector with blowing (except at 1.8 percent). However, the aft quadrant shows clear reductions of 1 to 1.5 dB integrated PWL. Since the fan is aft dominated, this would drive the total reduction. The observed reduction in the aft sector and not the forward sector is probably related to rotor blockage. Any reduction in stator noise is probably not noticeable forward of the rotor.

V. Conclusions

The rotor blades of a low-speed fan were designed to reduce the rotor-stator interaction noise through the use of rotor trailing edge blowing. Composite hollow rotor blades were designed with internal passages to deliver the injected flow at the design pressure and flow rate to fill the wake momentum deficit. Two rotor blade configurations were tested: (ref. 1) the rotor with trailing edge inserts installed (no blowing–baseline) and (ref. 2) blowing through the slotted trailing edge at rates from 1.1, 1.5, and 1.8 percent of the fan mass flow rate. Types of data acquired were: (ref. 1) two-component hotwire downstream of the rotor, (ref. 2) unsteady surface pressures on a stator vane, and (ref. 3) farfield directivity. These data were analyzed for broadband character.

The turbulence level downstream of the rotor was reduced 25 to 50 percent. An average reduction in the broadband SPL integrated over the stator vane of 2 to 3 dB was measured when blowing was applied. These physical quantities are known to be related to the rotor-stator interaction broadband acoustics. Indeed these methods were shown in the prior paper to have a direct connection to the farfield tones reductions obtained with trailing edge blowing. Therefore, it is reasonable to assume the possibility of rotor-stator interaction noise reduction resulting from trailing edge blowing. However, since the ANCF/TERB is rotor noise dominated, reduction in the rotor-stator interaction broadband farfield noise was not strongly apparent. Blowing had essentially no effect on the farfield broadband noise forward sector, due to the rotor-dominated character of the ANCF. The aft sector broadband PWL was reduced 1 to 2 dB.

It is reasonably inferred that applying rotor trailing edge blowing could reduce the broadband rotor-stator interaction noise.

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[6]Sutliff, D.L., Heidelberg, L.J., Envia, E., "Coupling of Low Speed Fan Stator Vane Unsteady pressures to Duct Modes: Measured vs Predicted," NASA/TM—1999–0209050/AIAA–99–1864, May 1999.

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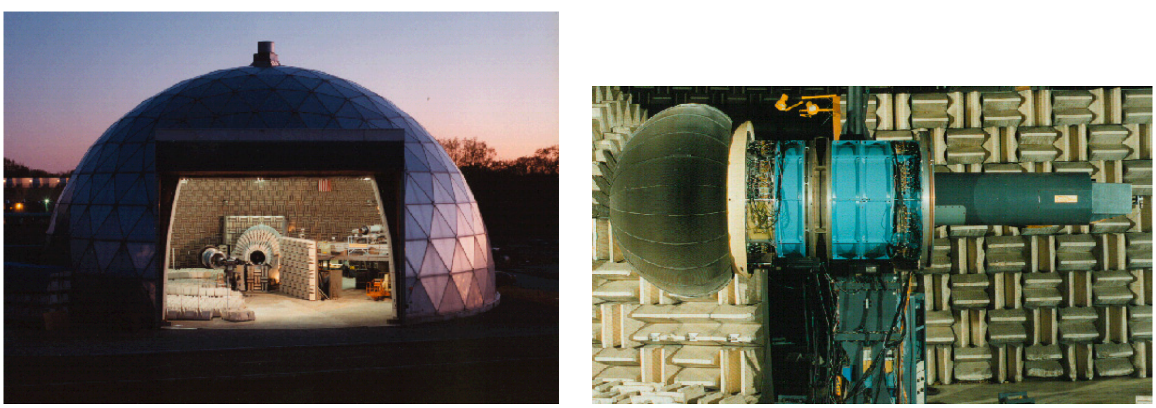
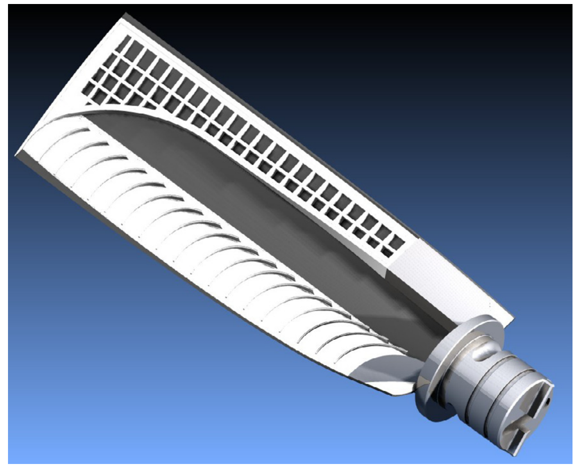


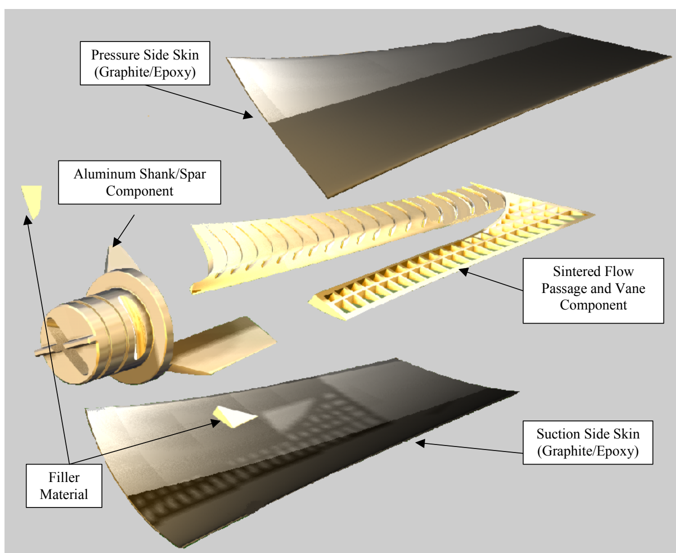
(a) AeroAcoustic Propulsion Laboratory (b) Advanced Noise Control Fan

Figure 1.—AAPL/ANCF test bed.

(a) TERB blade installed on ANCF



(b) TERB hollow fan blade with pressure side skin removed



(c) TERB exploded view showing blade components

Figure 2.—Trailing Edge Rotor Blades.

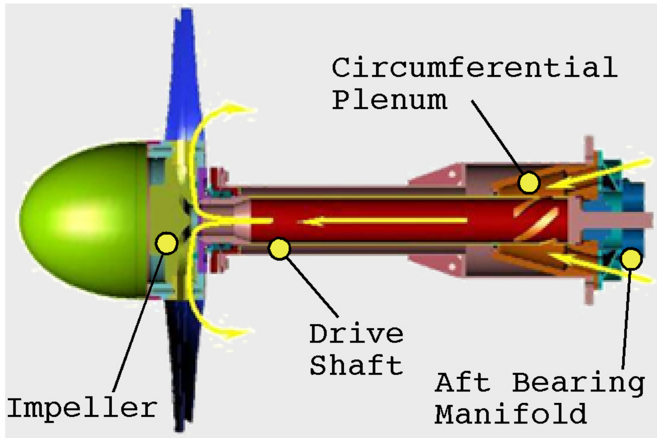


Figure 3.—Schematic of Ancf/Terb illustrating flow path.

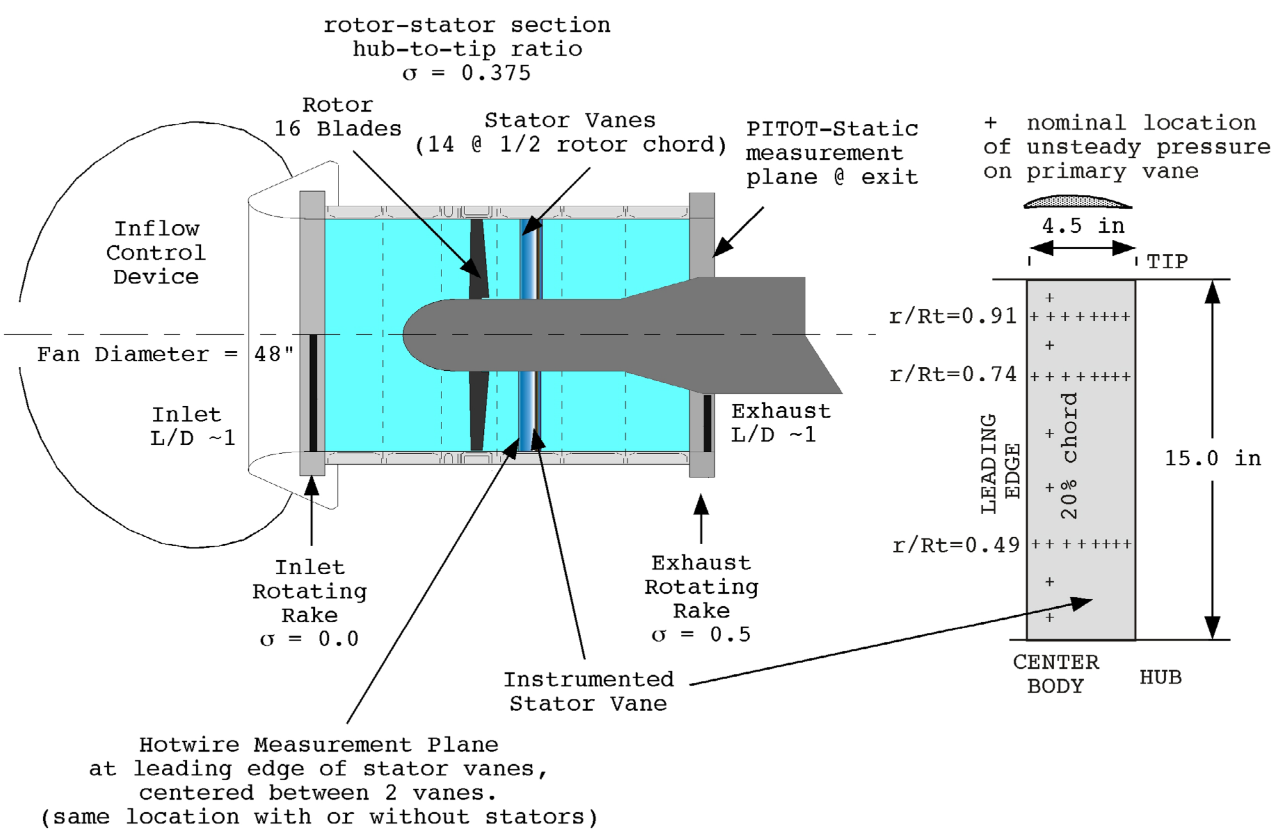


Figure 4.—Schematic of ANCF showing measurement locations.

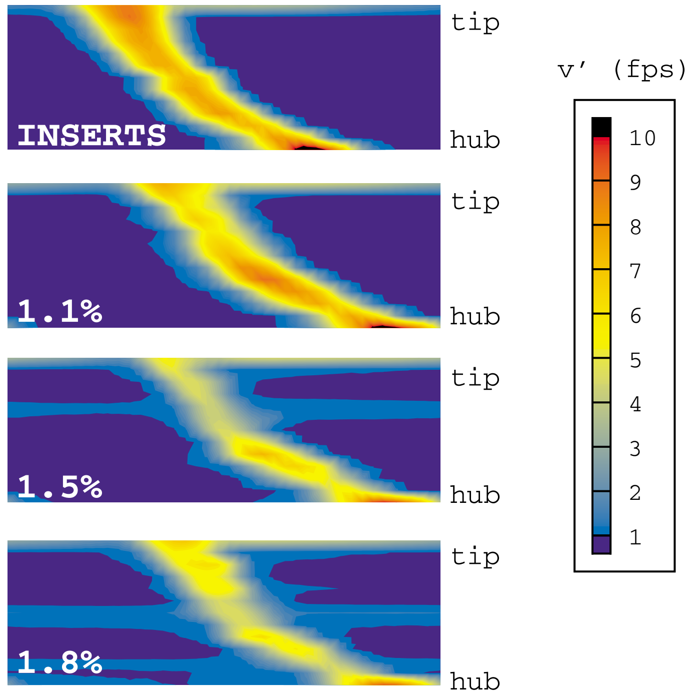


Figure 5.—Contour plots of turbulent velocity behind rotor for several blowing rates.

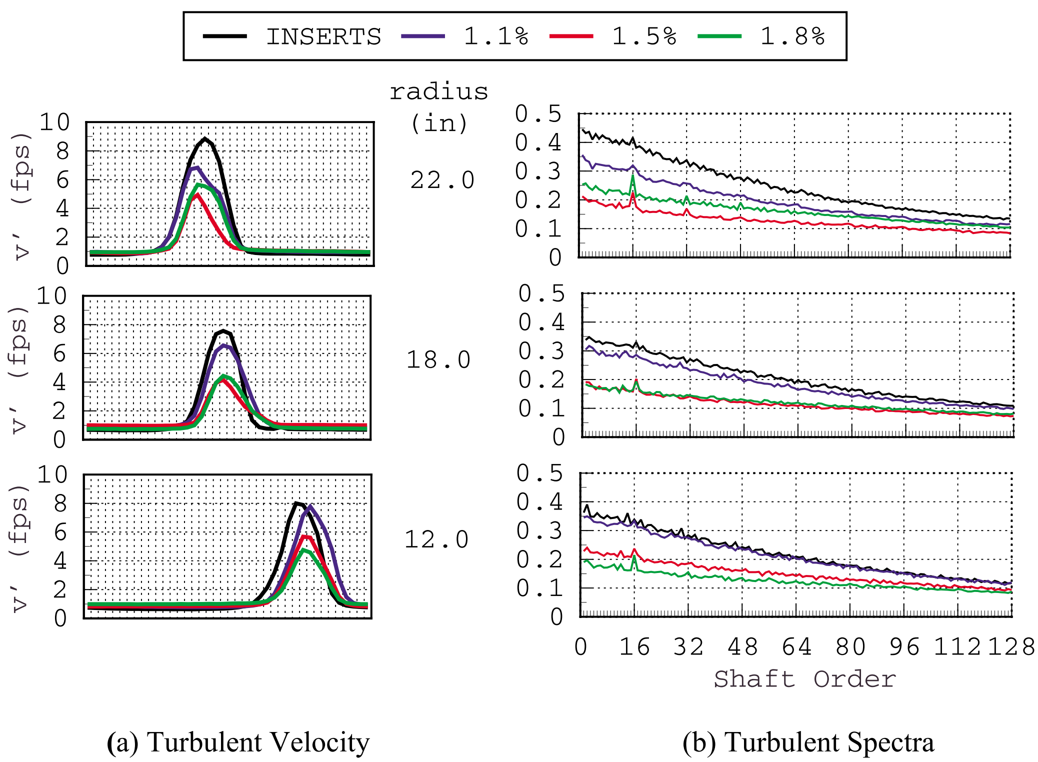
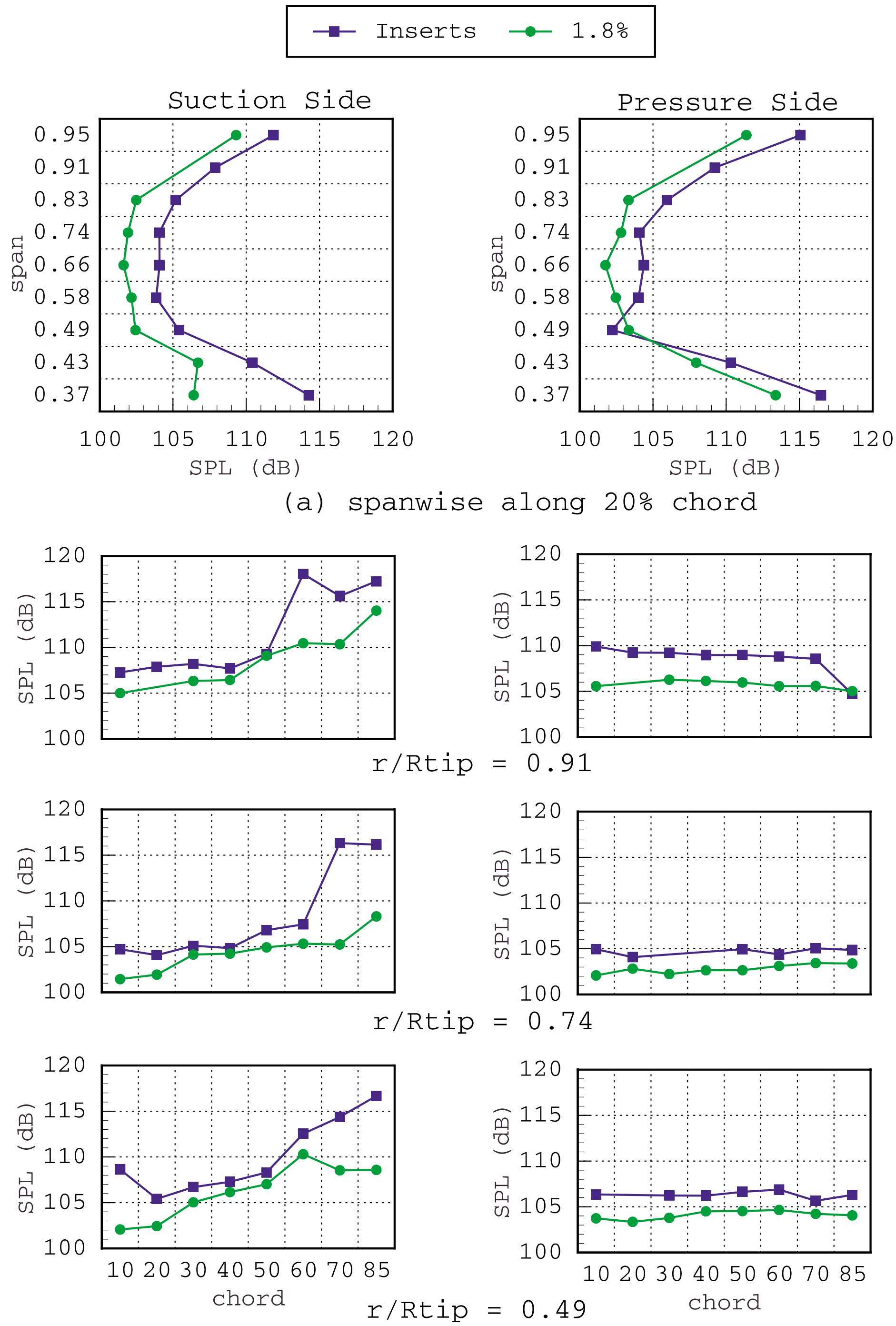


Figure 6.—Radial plots of turbulent velocity and spectra behind rotor for several blowing rates.



(a) spanwise along 20% chord

(b) chordwise at r/Rtip span

Figure 7.—1st harmonic band unsteady stator vane pressures.

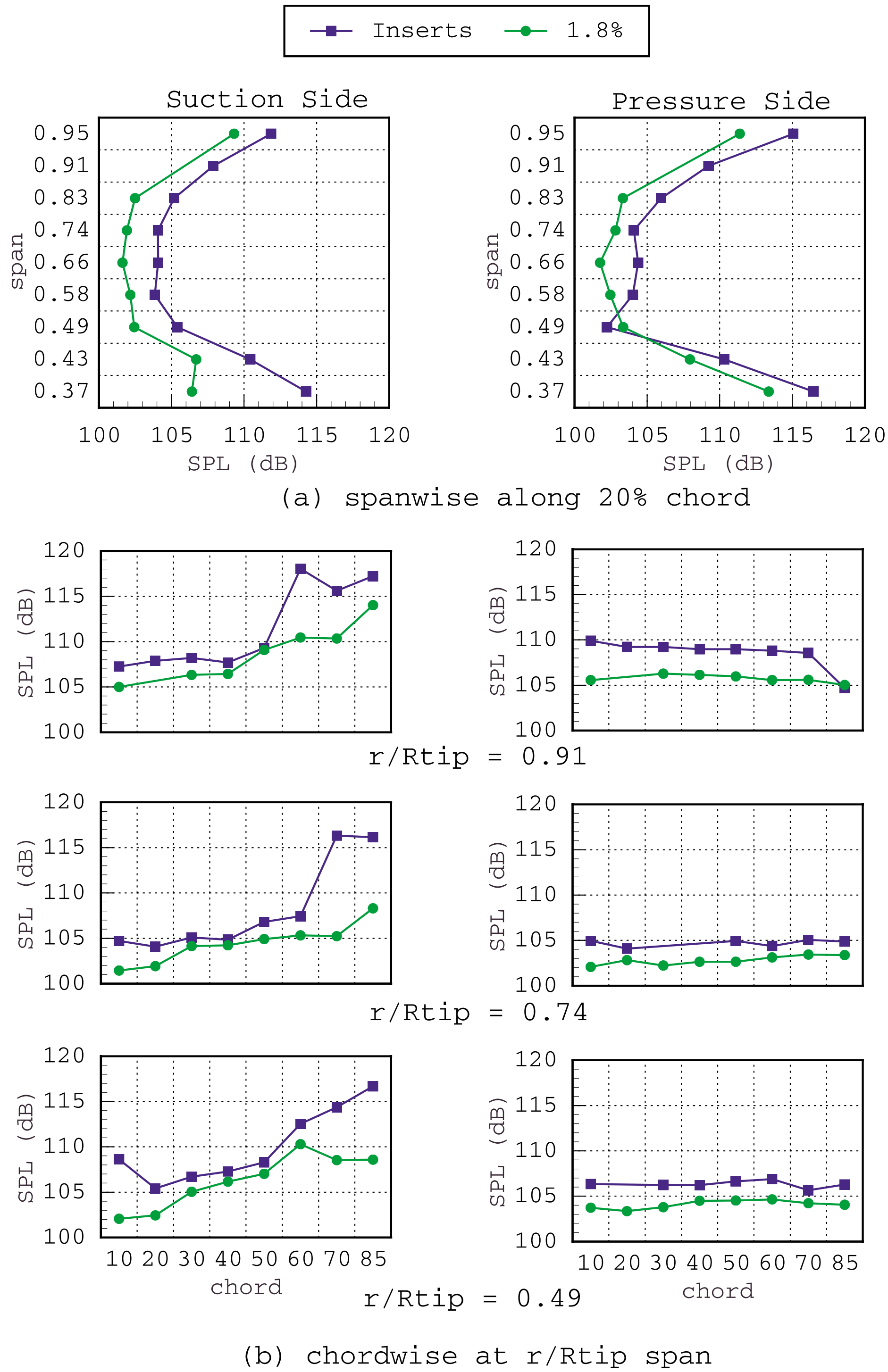


Figure 8.—2nd harmonic band unsteady stator vane pressures.

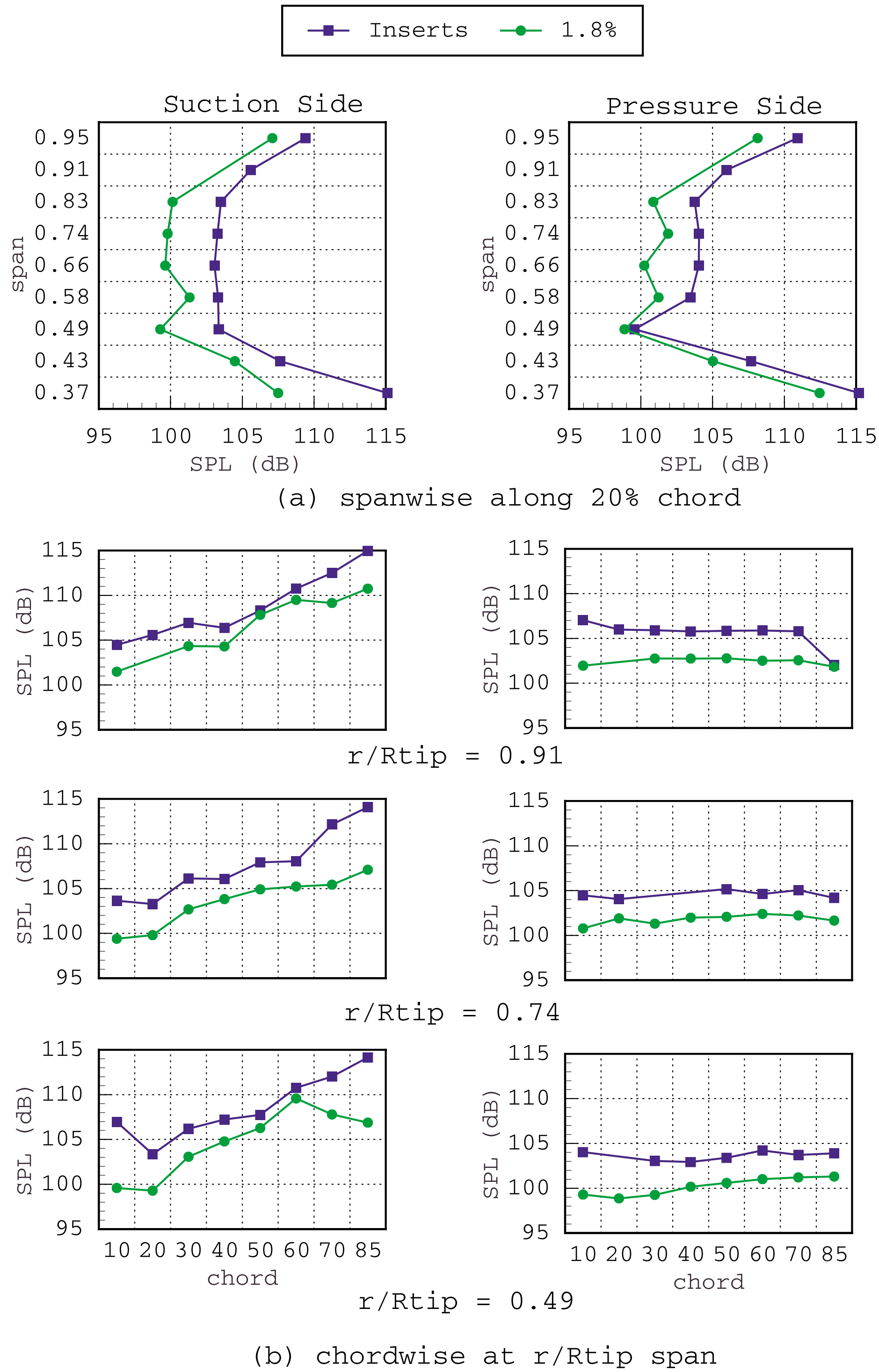


Figure 9.—3rd harmonic band unsteady stator vane pressures.

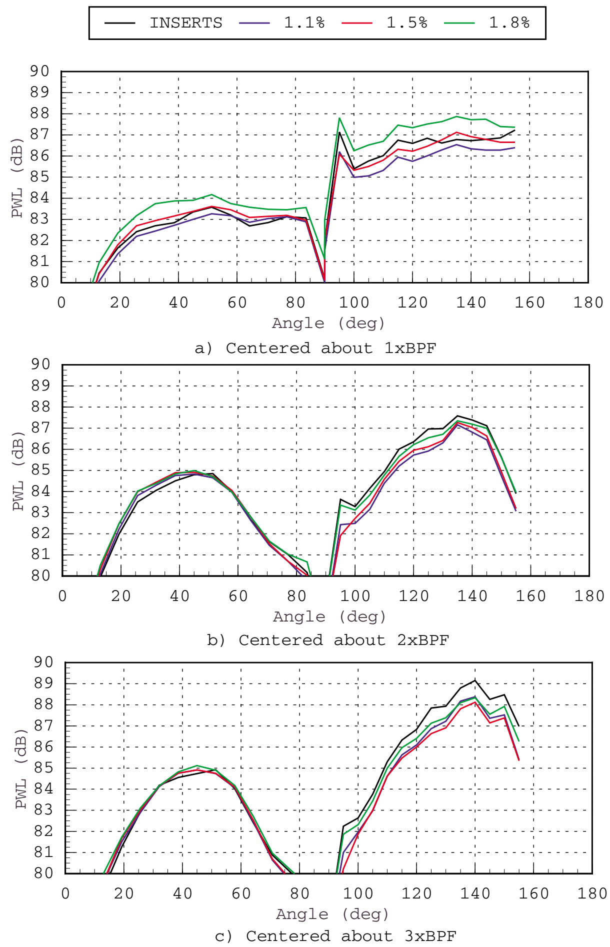


Figure 10.—Effect of blowing rate on farfield broadband directivity.

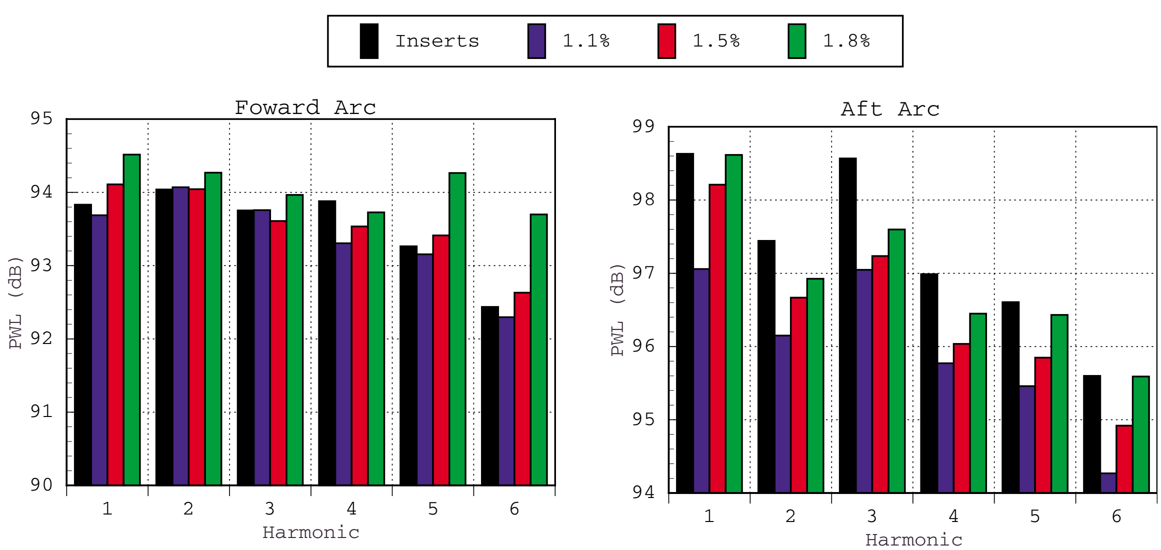


Figure 11.—Effect of blowing rate on farfield PWL.

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13. ABSTRACT *(Maximum 200 words)*

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