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Trailing-Edge Blowing for Reduction of Turbomachinery Fan Noise

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A new technique for reducing rotor wake–stator interaction noise was investigated. The approach involves injecting air from near the trailing edge of the rotating fan blades to fill in the mass/momentum deficit of the rotor wakes. Results are presented from experiments on a $\frac{1}{6}$th-scale high-bypass-ratio fan stage with blades incorporating internal passages for trailing-edge blowing. Two different spanwise blowing distributions are discussed; for each, the mass flow injected from the trailing edge was less than 2% of the fan throughflow. Time-mean and turbulent profiles of the rotor-relative Mach number are presented, along with stator unsteady loading measurements. Significant filling of the time-mean wake profile was achieved with reductions in the first three blade-passing frequency harmonic amplitudes of up to 85% at 1.5 chord downstream of the rotor. In addition, stator measurements showed reductions in the stator unsteady loading of up to 10 dB. The results demonstrate that trailing-edge blowing is effective for reducing the rotor wakes and their mean harmonic amplitudes. Therefore, with appropriate blade design, significant noise reductions are possible while maintaining rotor–stator spacing; alternately, the rotor–stator spacing may be significantly reduced while maintaining similar radiated noise levels.

Nomenclature

c = rotor chord length
M = Mach number
M_r = Mach number relative to rotor frame
$\bar{M}_r$ = time-mean relative Mach number
$M'_{r_{rms}}$ = root mean square of unsteady relative Mach number
$\dot{m}$ = trailing-edge blowing mass flow (% of fan throughflow)
P_t = total pressure
x = axial distance

I. Introduction

AIRCRAFT community noise is an important environmental concern, and with the demand for air travel growing at approximately 5% per year, noise restrictions on next-generation aircraft engines are expected to become more stringent. Of the various aircraft noise sources at takeoff, fan rotor–stator interaction is among the most significant contributors to the overall perceived noise for aircraft powered by turbofan engines. Noise is generated by the interaction between the unsteady flow exiting the fan rotor and the downstream stator blades. Reductions in the noise generated in the fan stage have been obtained over the last 30 years through appropriate choice of rotor–stator blade count, increasing rotor–stator axial spacing, and acoustic treatment, among other methods.[1] However, these techniques are not expected to produce the additional noise reductions necessary to meet future regulations.

The research described in this paper focuses on a new technique for reducing rotor–stator interaction noise. The technique is based on injecting air from the trailing edge of the rotor blades; thus filling in the mass/momentum deficit of the wake. By filling in the wake, the magnitude of variations in the mean velocity profile can be significantly reduced, and through modification of the mean shear, the wake turbulence can be reduced. The former is a source of tonal noise, whereas the latter is responsible for generating broadband noise.

This paper begins with a brief overview of fan-noise generation mechanisms and previous research on trailing-edge blowing. The experimental facility used for the study is then described, followed by discussion of the trailing-edge blowing blade design. Flowfield measurements are then presented for experiments on a $\frac{1}{6}$th-scale fan stage, both with and without injection from the trailing edge. Reductions in the relative Mach number mean wake profiles and their harmonic content are shown. In addition, the relative Mach number turbulence intensity, stator unsteady loading, and duct wall acoustic amplitudes are presented.

II. Previous Research

Wakes shed from high-speed fan rotors are three dimensional and unsteady. The unsteadiness in the flowfield exiting the rotor can be decomposed into two parts: 1) unsteadiness periodic on the blade-passing period, and 2) fluctuations that are not periodic on the blade-passing period. The first of these, the mean wake profile, is obtained by ensemble averaging the flowfield over the rotor blade-passing period. This mean profile results in unsteady pressure perturbations on the stator blade, at multiples of rotor blade-passing frequency (BPF), which lead to tonal noise.[2] The fluctuations in the flowfield that are not periodic on the blade-passing period may arise because of blade-to-blade differences or turbulence. The latter is a dominant broadband noise source. For typical engines, the level of turbulence in the wake is roughly equal to the mean velocity deficit in the wake. The resulting tonal and broadband noise both make important contributions to the overall perceived noise level.

Fan wakes typically display spanwise variations in both their mean and unsteady flow properties. These three-dimensional characteristics result in radial variations in the amplitude of unsteady pressure loading on the stator blades. In addition, the spanwise distribution of work imparted on the flow by the rotor typically results in radial variation of the circumferential transport of the wake as it is convected downstream. The resultant skewing of the wake[3] often results in several wakes impacting a stator blade at any given time, causing spanwise variations in the phase of the stator unsteady pressure perturbations. The radial phase and amplitude variations determine which radial modes dominate when the stator surface pressure fluctuations are coupled to the duct acoustic modes.

Initial trailing-edge blowing experiments reported in the literature[4,5] concentrated primarily on stationary flat plate or unloaded airfoils. These experiments demonstrated that the mean wake profiles and turbulent fluctuations can be significantly reduced through trailing-edge mass injection. To more closely represent trailing-edge blowing on a fan blade, the midspan airfoil of a high-bypass ratio turbofan was used by Sell[6] in a cascade experiment. Streamwise

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Table 1 Estimated acoustic mode amplitude reductions at $x/c = 1.5$ for experimental cascade trailing-edge blowing[6]

	Δ Mode amplitudes, dB		
Mode	$-25\%\ \dot{m}$	$\theta = 0$	$+25\%\ \dot{m}$
2 × BPF, $m = -8$	−8.0	−24.4	−3.9
3 × BPF, $m = 8, -32$	−8.1	−18.6	−2.6
4 × BPF, $m = 24, -16, -56$	−8.3	−13.2	+0.8
Broadband noise	−6.6	−7.0	−0.9

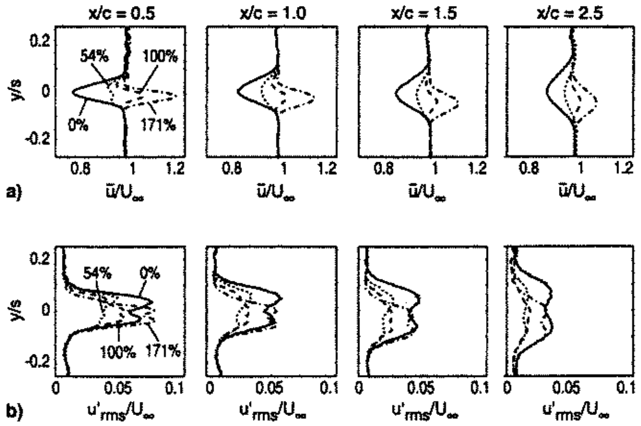

Fig. 1 Wake profiles for cascade trailing-edge blowing at the deviation angle. Curves are shown for various percentage injections of wake momentum deficit[6]: a) mean velocity and b) velocity fluctuations.

velocity measurements were taken with a single-element hot wire at several locations downstream.

Sell tried several different trailing-edge blowing configurations. The most effective configuration was one that injected air from the suction surface of the airfoil at ~91% chord. The injection was aligned with the deviation angle of the freestream flow and resulted in the best overall reductions in the mean deficit and turbulence intensity in the wake. The results for this configuration are shown in Fig. 1. The wake profiles are shown at four locations downstream of the airfoil ($x/c = 0.5$, 1.0, 1.5, and 2.5, where c is the airfoil chord). The mean profiles are shown in Fig. 1a, and the unsteady fluctuations are shown in Fig. 1b. In addition to the baseline wake with no blowing, three blowing rates are shown, corresponding to the mass flow that results in a momentumless wake (~1.1% of the throughflow), and cases with 25% more and 25% less mass flow. The estimated uncertainty in the measured velocity was 1%.

For these cascade experiments, trailing-edge blowing that produced a momentumless wake resulted in reductions in both the mean velocity deficit and the peak turbulence intensity of ~60% at $x/c = 1.5$. Because each tone of the rotor wake–stator interaction noise is generated by its corresponding harmonic of the mean wake profile, the wake mean profiles in Fig. 1a (at 1.5 chord) were decomposed and the resulting amplitudes were compared with the baseline no-blowing wake. If the pressure perturbations on the stator blade are assumed to be approximately linear with inlet velocity perturbation, then the noise generated from the stator will be roughly linear with the wake harmonic amplitudes. In this manner, the noise reduction for the propagating circumferential modes can be estimated using the wake harmonic amplitudes. These estimates are shown in Table 1. Reductions of 13–24 dB are calculated for the momentumless wake blowing. Note that even with only 75% of the momentumless wake mass flow, reductions of ~8 dB are estimated. In addition, because the spectral content of the turbulence in the wake remained approximately constant independent of mass addition, the broadband noise reduction can be estimated in the same manner as the tonal noise reduction. For injection that results in a momentumless wake, the corresponding reduction in broadband noise associated with the wake would be approximately 7 dB.

Sell's results[6] suggest that, with appropriate blade design, significant noise reductions may be obtained. However, the cascade experiments do not address the many difficulties inherent in applying trailing-edge blowing in a high-bypass-ratio turbofan where the three-dimensional character of the geometry, flowfield, and acoustic mode structure can significantly complicate the problem. The primary objective of the work discussed in this paper was to address these challenges by applying trailing-edge blowing on a representative next-generation fan stage.

III. Experimental Facility and Methods

The fan stage used for the testing has a mass-averaged pressure ratio (total to static) of 1.2, a tip Mach number of 0.8, an inlet Mach number of 0.45, and a tip diameter of 0.56 m. The rotor has 16 wide-chord fan blades, and the stator row has 40 blades. The hub-to-tip ratio is 0.5, and the rotor and stator are separated by about 1.7 rotor midspan axial chord lengths. A drawing of the test section is shown in Fig. 2. The trailing-edge blowing mass flow was initiated from a plenum located outside of the tunnel. The blowing flow was then brought across the fan annulus downstream of a choke plate, which served as a throttle for the fan throughflow, using eight equally spaced tubes. Eight passages were provided within the hub to bring the blowing flow to a plenum on the back side of the rotor disk. A face seal was used to limit leakage from this plenum into the fan annulus to less than 0.03% of the throughflow. The blowing flow passed from the plenum to holes in the disk that joined with the bottom of the blade internal passages.

Instrumentation ports for flowfield measurements were located ~0.5 chord upstream of the rotor, and 0.1, 0.5, 1.0, and 1.5 chord downstream of the rotor. Flowfield measurements were made with a probe utilizing four flush-mounted Kulite pressure transducers with vacuum reference and water cooling. A schematic of the probe is shown in Fig. 3a. The pressure transducers are oriented 45 deg apart, with one facing the main flow, two at ±45 deg in the tangential direction, and one at 45 deg in the radial direction. This distribution allows the determination of total and static pressure and tangential and radial flow angles, giving the components of the Mach number vector. The size of the probe is ~5% of the fan pitch. The probe was calibrated in a steady-flow facility and yielded measurements of the various Mach number components with an uncertainty of ~1%.

Duct microphone pairs were placed $\frac{1}{16}$th of the circumference apart in the outer casing at 1.0 chord upstream and downstream of both blade rows for acoustic measurements. In addition to the acoustic and flowfield measurements, unsteady stator surface pressure measurements were made with a stator blade, which is shown in Fig. 3b. The blade was instrumented with 13 flush-mounted, Kulite pressure transducers (seven on the suction side and six on the pressure side).

The fan stage was tested in a transient facility first described by Kerrebrock.[7] The rotor was accelerated to full speed in a vacuum, and then a fast-acting valve was opened, initiating the gas flow. With correct matching of the rotor inertia and the initial supply gas pressure, the nondimensional flow characteristics, such as flow angles and Mach numbers, are held constant within 2% for ~80 ms. This corresponds to ~200 rotor flow-through times, and

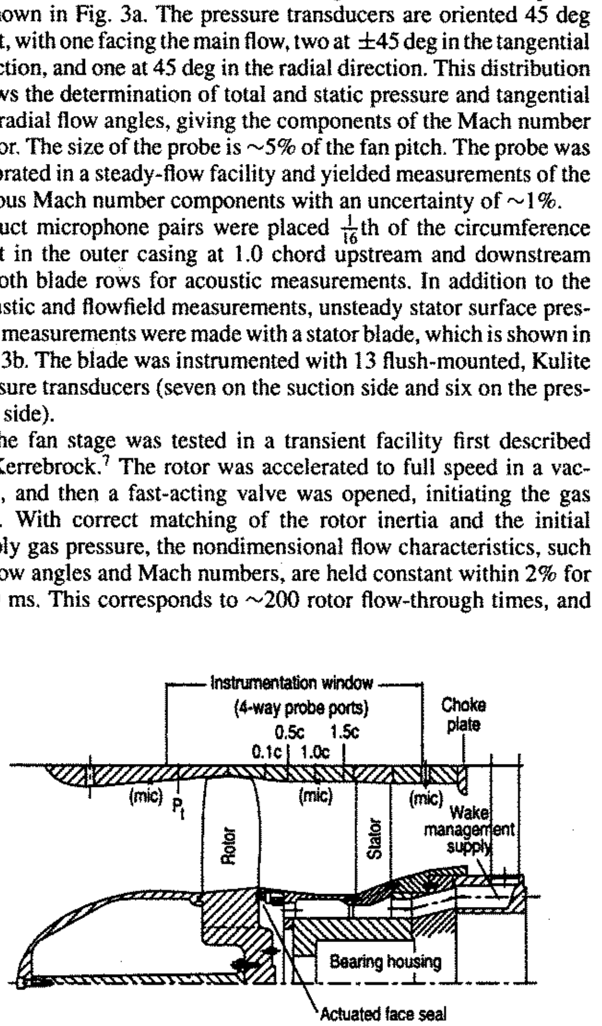

Fig. 2 Schematic of test section layout for fan stage trailing-edge blowing experiments.

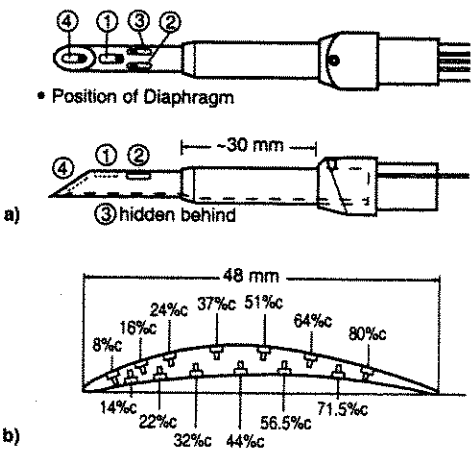

Fig. 3 Schematics of instrumentation: a) four-way probe and b) instrumented stator blade.

so steady-state flow phenomena related to passage length scales are accurately represented. In many cases, multiple runs were averaged together to decrease the uncertainty in the results. More detailed discussions of the experimental facility and methods were presented by Brookfield.[8]

IV. Blade Design

The primary functional requirement for the trailing-edge blowing blades was to reduce the wake harmonics and turbulent unsteadiness entering the stator row for mitigation of rotor wake–stator interaction noise. Further, it was desired that this be done without significant changes to the external blade shapes employed in a typical high-bypass ratio fan.

It was shown in Sec. II that trailing-edge mass injection at the deviation angle on a loaded two-dimensional airfoil resulted in substantial reductions in the mean wake harmonics and turbulence intensity. Designing injection for maximum noise suppression in a fan stage, however, is a more difficult task due to the three-dimensional nature of both the flowfield and the resulting acoustic modes. For example, it is possible to increase the radiated noise by changing the radial structure of the wake, even while reducing the wake deficits along various portions of the span. To minimize this possibility, a design objective was to provide the appropriate radial distribution of injection such that a momentumless wake was achieved along the entire span. This strategy would ideally result in radially uniform reduction of the wake harmonics and no change to the radial coupling; i.e., all radial acoustic modes for a given circumferential mode would be decreased uniformly. In addition, to enable future testing directed at developing a better understanding of the complicated three-dimensional flow and acoustic mode structure, the spanwise injection distribution was designed to be adjustable. This flexibility was desired because it is possible that maximum noise reduction may be obtained with considerably less total mass flow if only certain sections of the wake, e.g., the tip, are important to the overall radiated noise.

The trailing-edge blowing fan blades used the outside airfoil shape provided by an engine manufacturer, but included internal passages. A perspective view of a blade is shown in Fig. 4. Five internal passages that include turning vanes are shown. The internal passages terminate at discrete orifices near the trailing edge. A void is included in the leading-edge tip region for stress relief. Cross sections of the fan blade at the hub and midspan are also shown in Fig. 4. The blades were made by machining two blade halves and then brazing the pieces together. A photograph of the finished blades mounted in the disk is shown in Fig. 5. Further details of the blade design procedure are described next.

The internal passages were designed using a numerical code to evaluate the flow in the rotating channels within the blade. This simplified model approximated the flow as a one-dimensional, rotating, viscous flow through a channel with area variation and heat

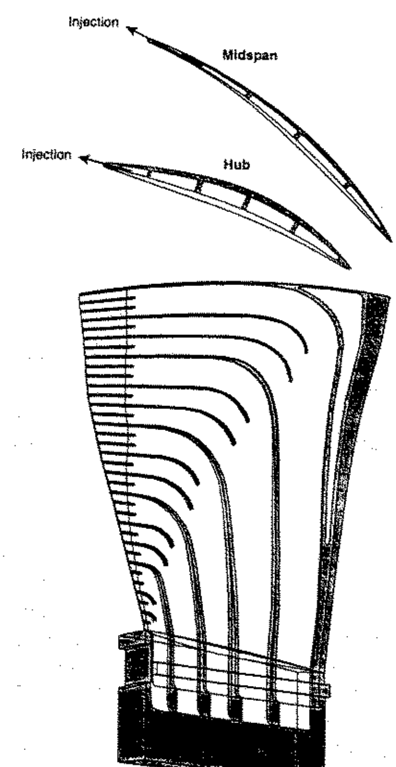

Fig. 4 Schematic of trailing-edge blowing fan blade: perspective view and hub and midspan cross sections.

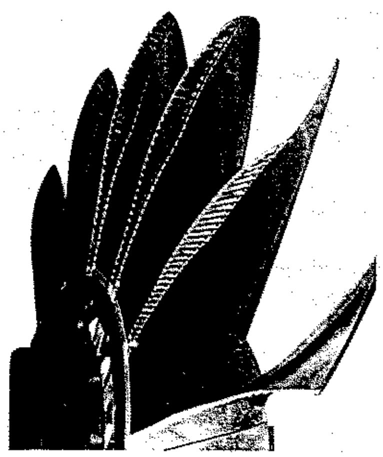

Fig. 5 Trailing-edge blowing rotor.

transfer to the walls. Total pressure loss estimates due to flow through sudden area changes and around corners were made using empirical data.[9] This design procedure was described in more detail by Waitz, et al.[10] and was verified using three-dimensional Navier–Stokes simulations.

The number of passages used in the blade was a function of the spanwise distribution of blowing required, as well as the structural constraints. To achieve a spanwise momentumless wake, the mass flow and total pressure required near the tip were 1.6–1.8 times that required near the hub. Measurements behind a rotor with solid blades (discussed in Sec. V.A) and numerical computations provided the distribution required for the blowing. Because of the large variation in blowing mass flow and total pressure required along the span, five passages were used. Throttle plates were placed at the base of the blades to provide the necessary flow conditions at the inlet to each passage. The plates also allow for independent throttling of the flow in each passage for future experiments.

The internal blade passages included turning vanes to help direct the flow into the chordwise direction and provide structural support to the blade skin. Stresses were kept well below the material yield stress, and surface deflections due to the pressure differential across the blade skins were kept below 1% of the local blade thickness. Discrete blowing orifices were used to provide torsional strength, as well as to increase the mixing of the wake. The orifices opened from the suction surface of the blade at approximately the deviation angle and continued back to the trailing edge, creating a scalloped suction surface. This was done to allow the blowing fluid to expand from sonic exit conditions, to increase mixing with the suction surface boundary layer, and to decrease the effective trailing-edge thickness.

The internal passages comprised the middle 50% of the blade thickness, with each blade skin being 25% of the original blade thickness. It would be possible to further increase the open area of the blade with additional design tools, but it was desired to keep the structural characteristics of the hollow blade as close to those of the solid blade as possible. This was done so that significant changes in blade untwist, natural frequencies, etc., were not encountered. Finite element analysis of a preliminary blade design suggested that the difference in untwist between a blade with internal passages and a solid blade would be less than 2 deg at the tip.

V. Results

The results of the experimental evaluation of the fan stage with trailing-edge blowing will be presented in several sections. First, the performance of the trailing-edge blowing rotor with no injection will be compared with the performance of a rotor with solid blades. Second, measurements with the rotor incorporating trailing-edge blowing with two different spanwise injection distributions will be presented. Relative Mach number mean profiles $\bar{M}_r$ and their harmonic content will be shown for these hollow blades, both with and without blowing. The turbulent fluctuations in relative Mach number $M'_{r_{rms}}$ will also be shown. Then, stator unsteady loading measurements will be presented. Finally, duct acoustic measurements at the outer casing wall downstream of the stator will be discussed.

A. Trailing-Edge Blowing Rotor, No Injection

Wake measurements were taken downstream of a solid-bladed rotor, both to facilitate the design of the trailing-edge blowing blades and to evaluate changes in the no-injection characteristics of the trailing-edge blowing blades. This comparison was done to ensure that the trailing-edge blowing rotor was representative of a typical fan stage.

The performance of the trailing-edge blowing blades without mass injection did not differ significantly from that of the solid blades. The average Mach numbers downstream of the two rotors were within 4%, the wake deficits were within 7%, and the total pressure ratio across the two rotors was within 1%, except near the tip where the wake deficit of the trailing-edge blowing rotor was about 11% higher and the total pressure ratio was about 2% lower than that of the rotor with solid blades. These differences may be the result of small differences in untwist characteristics and exterior shape between the solid and hollow blades. A more detailed discussion of this comparison can be found in Ref. 8.

B. Spanwise Injection Distributions

The trailing-edge blowing blades were designed to inject fluid such that a momentumless wake was created along the entire span of the fan exit flowfield. This was done to ensure that all of the harmonics of the wake perturbations would be uniformly decreased over the entire flowfield and that no changes to the radial coupling would occur. With the initial throttle plates installed in the rotor, uniform wake reduction was not achieved. While injection resulted in only moderate wake smoothing near the hub, substantial reduction of the wake mean profiles was achieved in the outer half of the span. A momentumless wake was generated at ~80% span and the tip was overblown. The distribution of momentum addition is shown in Fig. 6. The injection mass flow for this tip-weighted configuration was ~1.9% of the fan throughflow. After the testing was completed for the tip-weighted configuration, the throttle plates were removed, resulting in the midspan-weighted distribution also shown in Fig. 6. Results from both distributions will be discussed in the following sections.

Table 2 Tip-weighted injection at 1.5c fraction of no-blowing amplitude

Span, %	BPF	2 × BPF	3 × BPF	4 × BPF
25	0.75	1.00	2.03	0.79
50	0.71	0.52	0.56	0.56
75	0.32	0.24	0.55	1.05
87.5	0.21	0.66	0.55	1.59

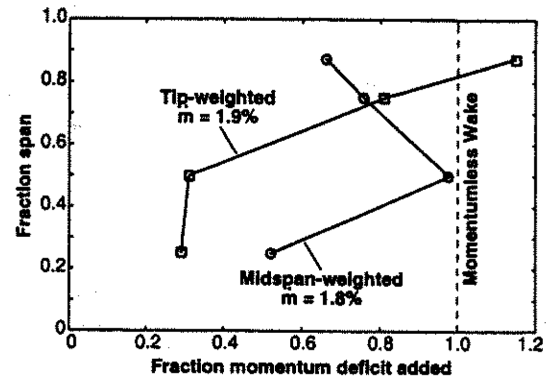

Fig. 6 Spanwise distributions of trailing-edge blowing.

C. Wake Profiles with Tip-Weighted Injection

Wake measurements are first presented for 0.1 chord, just downstream of the rotor trailing edge. The ensemble-averaged, relative Mach number mean profiles, harmonics, and turbulence intensities at 25, 50, 75 and 87.5% span are shown in Figs. 7a–7d, respectively, for the tip-weighted injection case. In all plots shown, the solid line corresponds to the case without blowing and the dashed line corresponds to the case with blowing. In addition, all data are presented with 95% confidence intervals. At all spanwise positions, the wakes are seen to be significantly smoothed; reductions of both time-mean deficits (rotor frame) and turbulent fluctuations in the wake are apparent. Note, the decrease in the pitch-averaged relative Mach number with blowing was caused by the increased mass flow, and, thus, decreased inlet axial Mach number. From these plots, it can be seen that the wake was underfilled near the hub, but overfilled near the tip.

In addition to measurements at 0.1 chord, tests were completed at 1.5 chord for the tip-weighted injection case. The wake characteristics at this location are of more direct relevance to noise generation because of the close proximity to the stator. Ensemble-averaged, time-mean profiles of relative Mach number at 25, 50, 75, and 87.5% span, 1.5 chord, are shown in Figs. 8a–8d, respectively, with and without blowing. Also shown in Figs. 8a–8d are the harmonic content of the mean relative Mach number profile and the turbulence intensity of relative Mach number. The wake harmonic amplitudes for the tip-weighted injection configuration are tabulated as a fraction of the amplitudes with no injection in Table 2.

At 25% span, the BPF harmonic amplitude of the flow is decreased by ~25%. The higher harmonic amplitudes and turbulence intensity are essentially unchanged. At 50% span, shown in Fig. 8b, the blowing results in a wake with ~30% reduction in momentum deficit, and a reduction in the wake harmonic amplitudes of ~30% for BPF, 50% for 2 × BPF, and 45% for 3 × BPF. Changes in the turbulence level, however, are not discernible within the 95% confidence intervals.

The 75% span location, presented in Fig. 8c, shows significant smoothing of the wake with the mean deficit decreased by ~60%. The wake harmonic amplitudes are also substantially decreased, with BPF reduced by 70%, 2 × BPF reduced by 75%, and 3 × BPF reduced by 45%. The turbulence level across the pitch has been nearly reduced to the level of the no-blowing freestream value, a decrease in the peak value of ~25%. The trailing-edge blowing results in a nearly momentumless wake at this location.

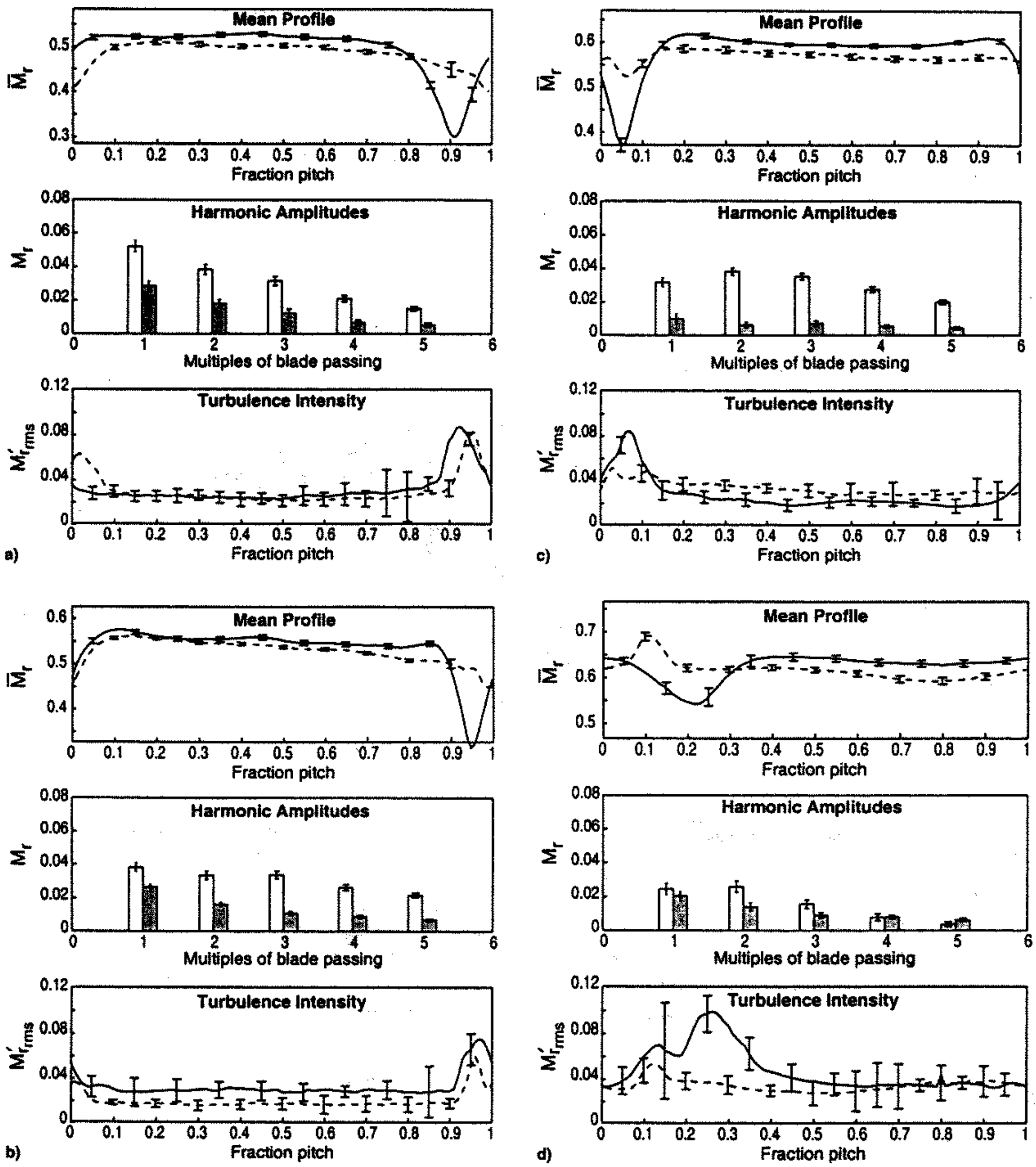

Fig. 7 Wake behavior with and without blowing at 0.1 chord downstream of the rotor trailing edge for tip-weighted injection. The solid curves correspond to no injection and the dashed curves (and shaded bars) correspond to injection of 1.9% of the fan throughflow. a) 25%, b) 50%, c) 75%, and d) 87.5% span.

Near the tip of the blade at 87.5% span, the wake is much wider than below 80% span due to the high skewing of the wake in the tip region. This results in increased mixing of the wake as it evolves downstream and a much wider and shallower wake when measured circumferentially.[3] In this region the wake is slightly overfilled by injection with a reduction of the BPF harmonic amplitude of ~80% and a $2\times$ BPF reduction of about 35%, as seen in Fig. 8d. Because the wake is primarily composed of the BPF harmonic near the tip, the higher harmonics are not greatly reduced by the trailing-edge blowing in this region. The peak unsteadiness is reduced by about 15%, but the average level is approximately the same as the no-blowing configuration.

Comparing the results of Fig. 8 with those of Fig. 7, the wake BPF and $2\times$ BPF harmonics at 0.1 chord with injection (shaded bars in Fig. 7) are seen to be close to and often smaller than the no-blowing wake harmonics at 1.5 chord (open bars in Fig. 8). This would indicate that with injection, the rotor–stator spacing could possibly be reduced without increasing the radiated noise relative to the baseline fan stage. However, the effects of wake skew, i.e., radial coupling, must be taken into account when considering such modifications.

Note also that the circumferential skew of the wake can be observed in Fig. 8 by examining the pitchwise location of the wake centerline at different spanwise locations. The wake profiles presented show considerable skew of the wake at 1.5 chord, and, thus, the stator pressure fluctuations will have corresponding spanwise phase variations. The skew impacts the coupling of the acoustic modes, and, consequently, the dominant modes produced. As mentioned earlier, this indicates that wake management must be done with care; blowing in a manner that changes the radial distribution of amplitude and/or phase can increase the overall radiated noise, even if the originally dominant mode amplitude is decreased.

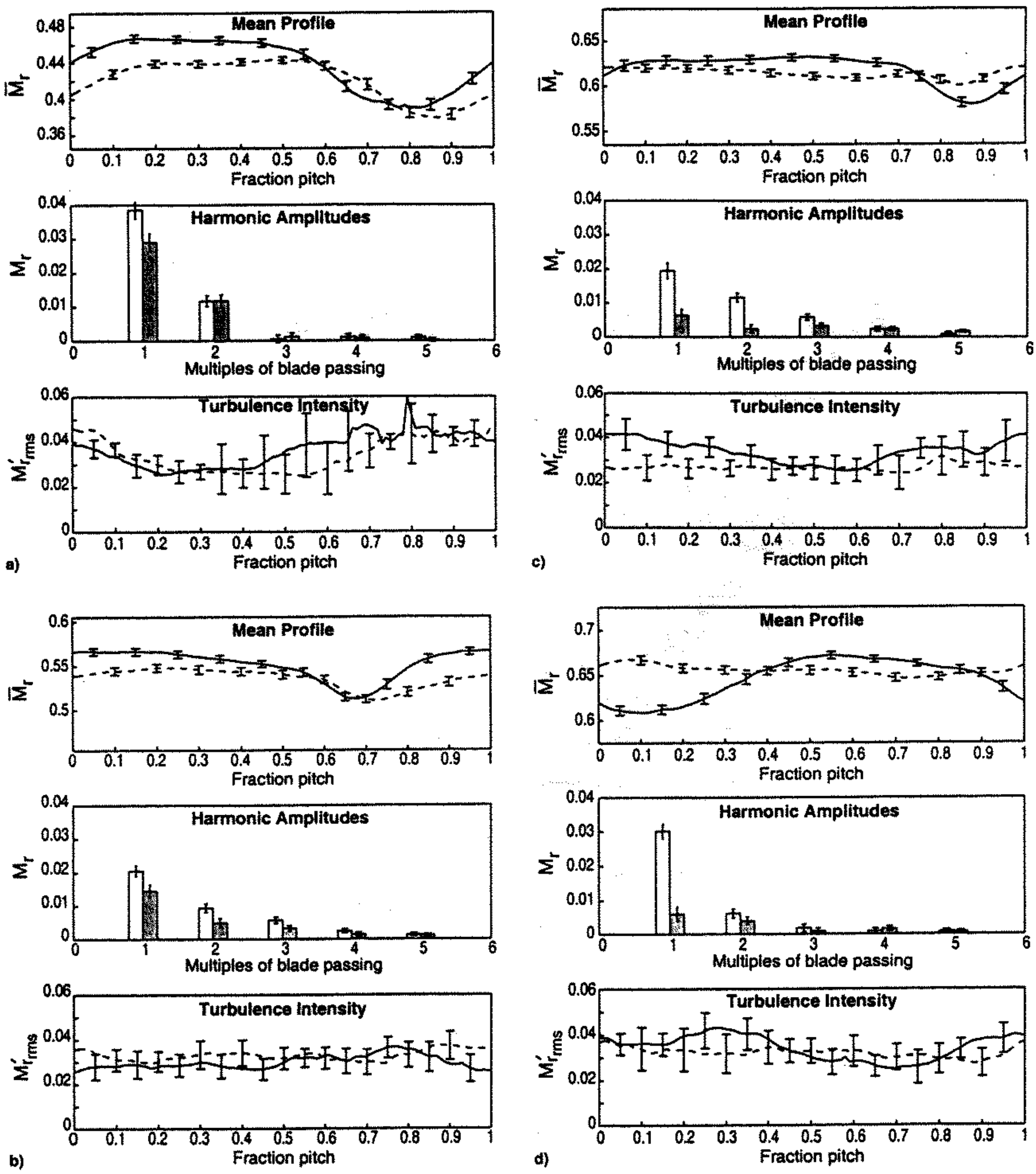

Fig. 8 Wake behavior with and without blowing at 1.5 chords downstream of the rotor trailing edge for tip-weighted injection. The solid curves correspond to no injection and the dashed curves (and shaded bars) correspond to injection of 1.9% of the fan throughflow. a) 25%, b) 50%, c) 75%, and d) 87.5% span.

The phase of the first four harmonics of the wakes at 25, 50, 75, and 87.5% span, 1.5 chord are shown in Fig. 9 with and without tip-weighted injection. The phases change significantly when injection is applied. For example, the 2 × BPF harmonics have ~330 deg of phase variation from 50 to 87.5% span with no injection, but only 80 deg with injection. The combination of radial variation in harmonic amplitude reduction and phase shift with injection will cause changes in the radial coupling of the wake–stator interaction and the acoustic modes.

D. Midspan-Weighted Injection

In this section, measurements taken at 1.5 chords are presented for the case with a midspan-weighted injection distribution. The results are only summarized here because the general flow features are similar to those for the tip-weighted injection; a more detailed presentation is contained in Ref. 8. The mass flow rate was 1.8% of the fan throughflow. For this case, the wake harmonic amplitudes are tabulated in Table 3 as a fraction of the no-injection amplitudes. The reductions at 50% span (nearly momentumless wake) are seen to be ~85% for the BPF and 2 × BPF harmonics. The wake phase angles (for the midspan-weighted injection) are shown in Fig. 10. In this case, the phase of the BPF harmonic is almost unchanged with blowing. However, a small jet component in the wake at 50% span resulted in a shift of 180 deg for the 2 × BPF harmonic. Together with the measurements for the tip-weighted configuration, the results imply that if the injection distribution is tuned to obtain a momentumless wake along the entire span, the wake harmonic

Table 3 Midspan-weighted injection at 1.5c fraction of no-blowing amplitude

Span, %	BPF	2 × BPF	3 × BPF	4 × BPF
25	0.55	0.72	5.33	1.20
50	0.16	0.15	0.38	0.56
75	0.32	0.30	0.57	1.14
87.5	0.38	0.65	1.63	0.97

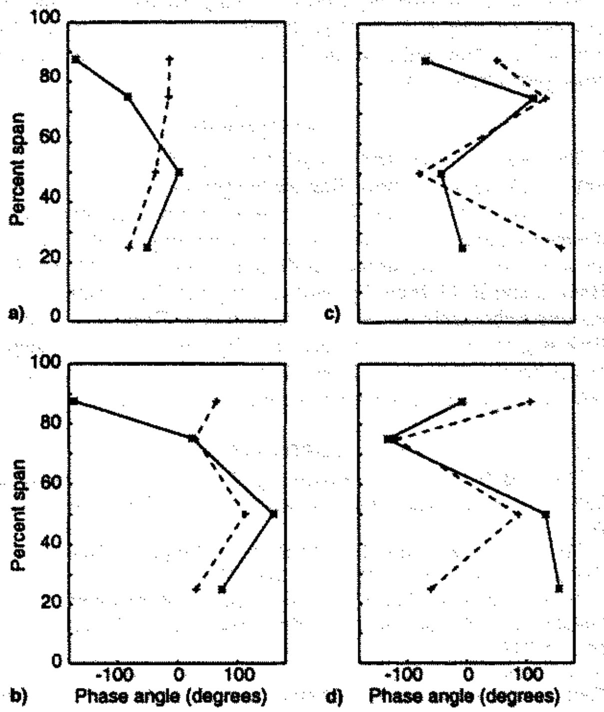

Fig. 9 Phase of relative Mach number BPF harmonics at 1.5 chord for tip-weighted injection. ——, no injection; and – – –, injection of 1.9% of the fan throughflow: a) BPF, b) 2 × BPF, c) 3 × BPF, and d) 4 × BPF.

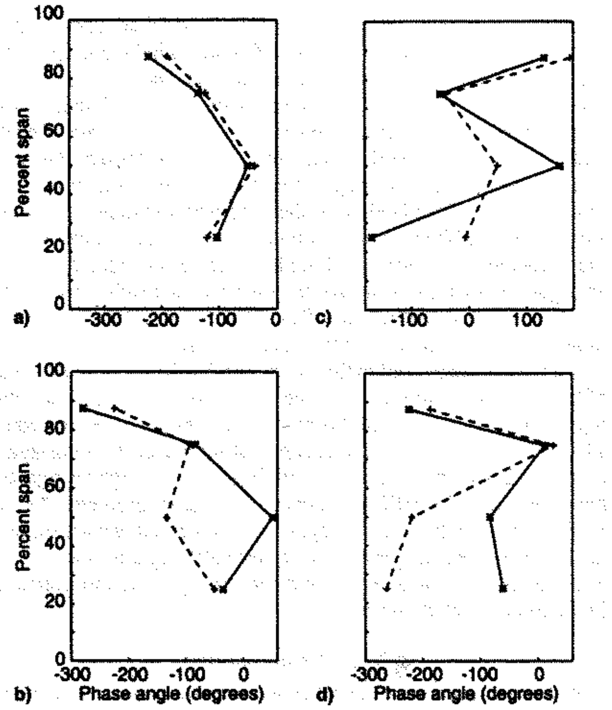

Fig. 10 Phase of relative Mach number BPF harmonics at 1.5 chord for midspan-weighted injection. ——, no injection; and – – –, injection of 1.8% of the fan throughflow: a) BPF, b) 2 × BPF, c) 3 × BPF, and d) 4 × BPF.

amplitudes can be significantly reduced in the entire flowfield. Further, overblowing specific spanwise regions allows the potential for tailoring the wake harmonic amplitude and phase distribution to achieve maximum noise reduction.

E. Stator Unsteady Loading

While characteristics of the wakes are indicative of the effects of trailing-edge blowing, changes in the unsteady aerodynamic loading on the stator are more directly related to the noise. Stator unsteady pressure measurements were taken on both the suction and pressure surfaces of the blade and the harmonics of the pressure difference across the stator blade were calculated. The amplitude of the BPF harmonic of the stator unsteady loading is shown in Fig. 11 with and without tip-weighted injection. The higher harmonics are not shown because the uncertainty was large relative to the amplitude of the changes in loading (due to insufficient data for averaging). The unsteady loading is seen to increase at 50% span with injection, but is decreased at 75 and 87.5% span. At 87.5% span, the stator loading is reduced up to 10 dB, which corresponds to about 70% of the change seen in the wake BPF harmonic amplitude at 87.5% span, 1.5 chord. The lack of direct correspondence between changes in the wake harmonic amplitudes (shown in Fig. 8 and Table 2) and changes in the stator unsteady pressure fields may be due to the strong three dimensionality of the wake–stator interaction as suggested by the radial variations in the wake phase angles as shown in Fig. 9. This suggests that traditional two-dimensional strip theory may not accurately capture changes in stator unsteady loading and acoustics due to trailing-edge blowing.

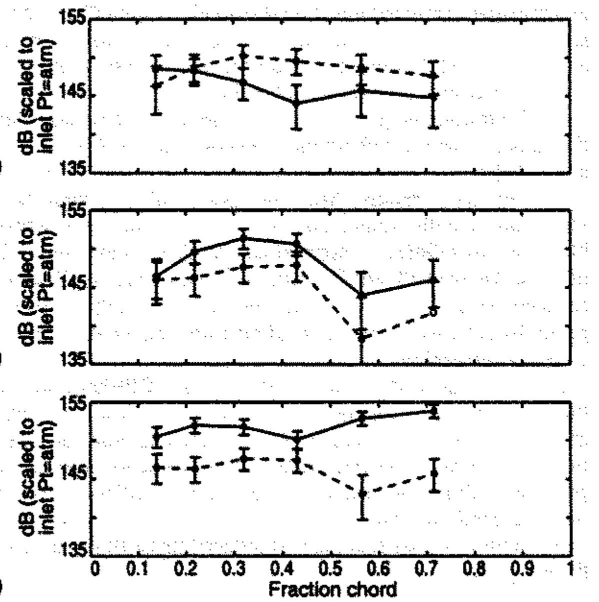

Fig. 11 Stator unsteady loading (BPF harmonic) for tip-weighted injection. ——, no injection; and – – –, injection for 1.9% of fan throughflow: a) 50%, b) 75%, and c) 87.5% span.

F. Duct Acoustic Measurements

Although detailed acoustic measurements are difficult to obtain in the facility used for these experiments, the acoustic amplitudes at the wall were measured to obtain a qualitative assessment of the effects of injection on the duct acoustics.

The duct acoustic modes were measured by pairs of microphones, which were separated by $\frac{1}{16}$th of the casing circumference, and located in the outer shroud approximately one midspan rotor chord upstream and downstream of the rotor, and approximately one stator chord upstream and downstream of the stator row, as shown in Fig. 2.

These measurements provide the amplitude of the acoustic modes at the wall and are thus a combination of all the radial modes present in the system. Blowing that achieves a spanwise momentumless wake and uniform reduction of the wake harmonics will ideally reduce all radial modes uniformly. The wall measurements would then correctly capture the reduction in the overall duct acoustics. The radial modes will not be uniformly reduced; however, if the radial structure of the flowfield is altered, the wall measurements then reflect a different combination of the radial modes present. Therefore, for the cases presented, the radial mode structure is expected to change as suggested by Figs. 9 and 10, and the acoustic results cannot be interpreted unequivocally. Regardless, these measurements give some indication of the changes in the duct acoustics.

For the fan stage used in this study, the 2 × BPF tone downstream of the stator is the dominant source of tonal noise. With tip-weighted injection, the amplitude of this mode at the shroud wall was reduced 11 dB. There were smaller changes observed in the midstage region and upstream of the rotor. With midspan-weighted injection, however, the 2–4 × BPF tones in the midstage region were reduced ~10 dB, with only small changes upstream and downstream of the fan stage. These changes may be caused solely by a shift in the radial acoustic mode content and are not necessarily related to a reduction in the total radiated power.

VI. Conclusions

A new technique for the reduction of rotor wake–stator interaction noise was tested on a next-generation fan stage. Internal passages were employed in the fan blade for injection of fluid into the wake through orifices in the blade suction surface near the trailing edge. Measurements were obtained downstream of a rotor with solid blades and a rotor with blades that contained internal passages to enable trailing-edge blowing. The blowing mass flow rate was less than 2% of the fan throughflow. Results from both tip-weighted and midspan-weighted injection distributions were discussed. Data showing reductions in both the time mean wake profiles in the relative frame and the unsteady stator loading were presented.

Specific results include the following:

1) The trailing-edge blowing rotor did not have substantially reduced performance without blowing compared with the rotor with solid blades.

2) Time-mean relative Mach number profiles through the wake were substantially smoothed. For spanwise locations where the blowing was tailored to approximately fill the momentum deficit of the wake, the BPF and 2 × BPF wake harmonic amplitudes were reduced 70–85%. The wake harmonics higher than 3 × BPF were generally close to the level of random unsteadiness; thus, reductions were not discernible.

3) Wake relative Mach number BPF and 2 × BPF harmonic amplitudes at 0.1 chord with injection were near or below the amplitudes at 1.5 chord without injection. These results demonstrate that with injection, considerable reduction of the rotor–stator spacing may be possible with no increase in the radiated acoustics relative to the baseline configuration.

4) Stator unsteady loading was reduced up to 10 dB at BPF with tip-weighted injection.

The results of these first-of-a-kind experiments with trailing-edge blowing on a fan stage rotor show that significant smoothing of the downstream wakes is possible. Wake harmonics can be reduced by up to 85%, and reduction in radiated tonal noise of greater than 10 dB may be possible. Further, significant control of the radial phase variation of the wake harmonic amplitudes can be obtained through overblowing the wake in various regions.

Future testing will first focus on obtaining more uniform spanwise wake reductions so that the wake harmonics can be reduced in the entire flowfield without changing the radial coupling of the acoustic modes. Later, blowing along only certain portions of the blade will be used as a diagnostic tool to better understand the complex three-dimensional flow and acoustic fields, and to provide data to assess noise prediction tools.

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