JOURNAL OF PROPULSION AND POWER
Vol. 12, No. 5, September–October 1996

Preliminary Assessment of Wake Management Strategies for Reduction of Turbomachinery Fan Noise

I. A. Waitz,* J. M. Brookfield,† J. Sell,† and B. J. Hayden†
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

Preliminary studies of a new approach for reducing rotor–stator interaction noise are presented. The approach centers on removal and/or addition of fluid from the rotor blades to minimize the shed wakes, thereby making the flow into the stator more uniform, and reducing unsteady loading and radiated noise. High bypass ratio fans typical of next-generation gas turbine engine technology were the focus of the work. The results presented include 1) two-dimensional, unsteady numerical simulations of the impact of rotor blade boundary-layer suction on unsteady stator loading and 2) cascade experiments to investigate the effects of various fan blade boundary-layer suction and trailing-edge blowing strategies on both steady and unsteady aspects of the blade wakes. A two-dimensional linearized panel method was used to estimate the reduction in radiated tone noise achievable with these techniques. Results of an analysis of fan blade design requirements and performance impacts for applications of wake management on full-scale engines are also discussed. The principal conclusion of this study is that methods to control the initiation of the fan wake are feasible for application in high-bypass ratio turbomachines. The data presented suggest that greater than 40% reduction of the steady wake velocity deficit and greater than 35% reduction of the unsteady velocity fluctuations in the wake can be achieved by removal of less than 3% of the fan mass flow through blade boundary-layer suction, or through the addition of less than 1% of the fan mass flow through trailing-edge blowing. Reductions in the amplitude of propagating circumferential acoustic modes were estimated for the experimentally obtained wake profiles. Mode amplitudes were reduced approximately 4 dB for boundary-layer suction and from 4 to 11 dB for trailing-edge blowing.

Nomenclature

C_p = pressure coefficient, $(p - p_{\text{inlet}})/[0.5\rho(u_{\text{inlet}})^2]$
c = chord length
EPNdB = effective perceived noise, dB
M = Mach number
p = static pressure
p_T = total pressure
s = blade pitch
U_∞ = freestream velocity
u = time mean velocity
$\bar{u}'$ = magnitude of turbulent velocity fluctuations
x = axial coordinate
θ = momentum thickness
ρ = density

I. Introduction

FAN noise is expected to be the most important community noise source for next-generation subsonic aircraft engine technology. In many situations the radiated noise is dominated by that from unsteady loading on the stator, pylons, and rotor that arises from interaction with both random and periodic gusts from a variety of sources. The most significant sources for these gusts are blade wakes and tip clearance flows. During the last 20 years, progress in reducing fan noise has been evolutionary. Currently available design strategies will be ineffective in meeting the 6-EPNdB engine noise reduction goal established by the NASA Advanced Subsonic Technology Program.

This study focuses on a new approach for reducing fan noise that involves removal and/or addition of fluid through the rotor blades to reduce the blade and tip clearance wakes, thereby making the flow into the stator more uniform. Source control of this nature affects both the time-mean (rotor frame) and unsteady (rotor frame) aspects of the wake, and thus may impact both tonal and broadband radiated noise from fans. In this respect wake management may present an advantage over active control strategies that are being investigated for mitigation of tonal noise.

The objective of the work described in this article is to provide a preliminary assessment of wake management strategies for fan noise reduction. Simplified two-dimensional numerical and experimental models were used to determine the parametric dependence of radiated noise on wake modifications brought about by removal of the blade boundary layer and injection of fluid through the trailing edge of the fan blade. The blade geometry and flow conditions investigated are typical of fan designs for next-generation high bypass ratio gas turbine engines.

This article begins with a discussion of wake structure in gas turbine engines followed by a discussion of strategies for modifying these wakes. The computational and experimental techniques applied in the study are then described. This is followed by results of cascade experiments and two-dimensional unsteady simulations, including predictions of achievable reductions in radiated noise. Finally, fan blade design requirements are discussed.

A. Fan Wake Structure

The fan wakes in high-speed gas turbine engines differ considerably from those associated with two-dimensional, low-speed airfoils. A brief review of fan wake structure is appropriate to emphasize the complex nature of these flows and to set the stage for a discussion of techniques for modifying these wakes.

Rotor–stator wake interaction, as well as unsteady stator loading because of interaction with the endwall flow are clas-

Presented as Paper 95-102 at the AIAA/CEAS 1st Joint Aeroacoustics Conference, Munich, Germany, June 12–15, 1995; received Aug. 10, 1995; revision received March 26, 1996; accepted for publication April 1, 1996.

*Assistant Professor, Department of Aeronautics and Astronautics, Aero-Environmental Research Laboratory. Member AIAA.

†Graduate Student, Department of Aeronautics and Astronautics, Aero-Environmental Research Laboratory.

sically considered as periodic phenomena. However, current understanding of boundary layer and wake behavior in high-speed fans and compressors suggests that these phenomena are, in fact, sources for pressure fluctuations with rich spectral content.

Epstein et al.[1] have described the structure of blade wakes in turbomachinery. The wake structure in high-speed fans is determined by two design characteristics of modern machines: 1) the large variation in spanwise boundary-layer loading that results from the desire for uniform spanwise total pressure rise in a low hub-to-tip ratio geometry and 2) the high degree of unsteadiness driven in large part by the high boundary-layer loading and the shock wave boundary-layer interaction in the supersonic sections of the blading.

The highly unsteady nature of compressor blade wakes is illustrated in Fig. 1 (taken from Ng and Epstein[2]). Here, time-resolved measurements were made just downstream from a transonic compressor rotor. The instantaneous time trace shown in Fig. 1a displays little regular structure in wake spacing, magnitude, or even sign. In Fig. 1b the data were removed from a longer time trace and reassembled to display one particular blade passage each time it rotated by the fixed measurement instrument. It can be seen that only some of the variation in the raw time trace of Fig. 1a can be attributed to geometric differences among blades in the rotor. An ensemble average of the flow over 22 rotor revolutions shown in Fig. 1c finally gives the regular wake-core flow picture classically described.

The source of the wake unsteadiness lies in two phenomena associated with the blade boundary layers: 1) vortex shedding in the wakes and 2) diffuser instabilities.[1] The vortex shedding in the wake is similar to that of a von Kármán vortex street, except that it is quite three dimensional and the shedding frequency is time dependent. The vortex shedding is modulated at low frequencies (~1/10 rotor blade passing) by diffuser-like instabilities within the blade passages. Compressor blading is typically designed using a two-dimensional diffuser criterion to be just at the point where the diffuser pressure recovery drops precipitously, i.e., in the regime of diffuser instability.

Thus the interaction of the actual rotor wake velocity field with a stator will result in both tonal and broadband noise. The importance of reducing broadband noise in addition to tones has been demonstrated in analyses conducted by Hanson and Wagner.[3] Aircraft engine fan noise data was numerically modified to simulate various reductions in either tonal or broadband noise, and then community noise metrics were recalculated with the modified spectra. Complete removal of the tones produced only a 3 EPNdB reduction in the community noise. The analyses suggested that the community noise impact of tonal and broadband noise sources within the fan is of roughly the same magnitude. It is therefore important to consider the effect of wake management techniques on both time-mean and unsteady wake dynamics.

B. Wake Management Strategies

Control of initiation of the wake is sought to minimize the wake deficit and thereby reduce gust amplitude at the inlet to the stator. The two wake management concepts investigated in this study, 1) blade boundary-layer suction and 2) trailing-edge blowing, are shown in Fig. 2. Also shown in Fig. 2 are simplified schematic diagrams of the desired effects of these treatments on the fan wake. Boundary-layer suction and trailing-edge blowing affect the time-mean width, depth, and shape of the wake. Changes in unsteady behavior are brought about by control of the sources for unsteadiness in the wakes, specifically 1) control of unsteady boundary-layer separation and 2)

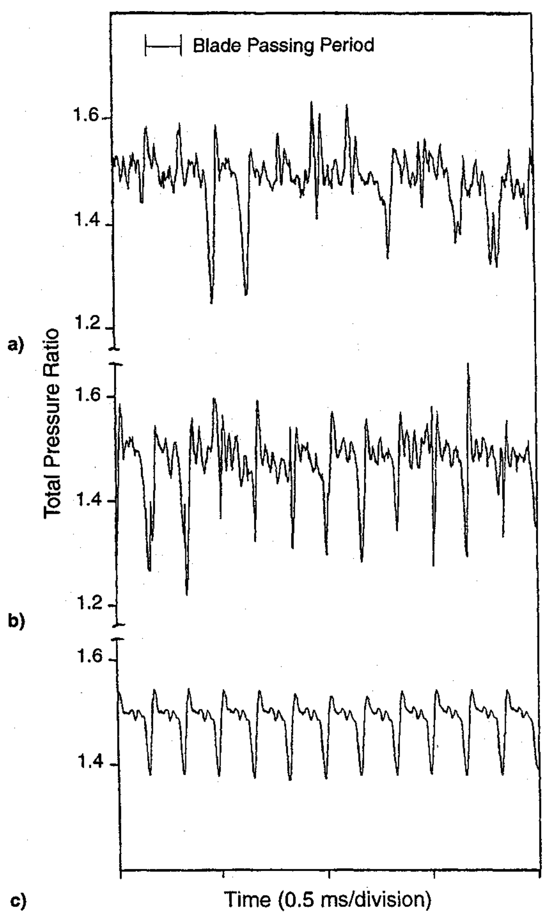

Fig. 1 Transonic compressor rotor exit total pressure near hub: a) instantaneous measurement, b) an individual blade passage as seen once per revolution, and c) an ensemble average of that individual blade passage.[2]

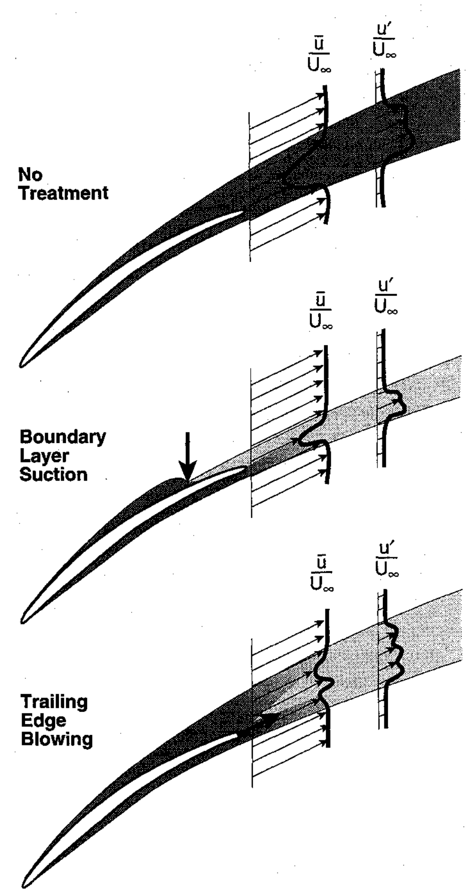

Fig. 2 Schematic diagrams of wake management concepts.

modification of the mean shear profile that influences the frequency and scale of unsteady vortex shedding.

Suction and blowing strategies for wake control have not been investigated previously for fan noise reduction in gas turbine engines because the strategies could not be implemented in practical devices. However, the ideas now merit consideration because of the appreciable size of the individual blades in next-generation gas turbine engines. Indeed some current engines already employ hollow fan blades, with approximately 50% open cross-sectional area, to reduce weight and structural loading. Wake management is also attractive because it can be used during phases of the flight cycle where community noise impact is most significant and then turned off if necessary during cruise.

C. Previous Research

Previous research on controlling wakes behind bodies has been restricted to geometries and flow conditions not representative of a gas turbine engine environment. Experiments[4–6] have shown that trailing-edge blowing from flat plates can be used to eliminate the time-mean wake deficit and to markedly reduce wake unsteadiness. In particular, Naumann's[4] experiments, carried out in water at $Re = 4 \times 10^5$ (based on chord), showed a reduction in a time-mean wake deficit of approximately 90% combined with a reduction in the turbulent velocity fluctuations of greater than 50% for several different trailing-edge blowing configurations. Naumann[4] and Park and Cimbala[6] showed that injection configurations designed to provide more rapid mixing produced more uniform momentumless wake profiles. Leu and Ho[7] used trailing-edge suction to stabilize the wake structure downstream from a flat plate. While the flow conditions and geometries employed in these prior research efforts are different from those in turbomachines, the results suggest that significant control of both time-mean and unsteady wake phenomena is possible. An objective of the present effort is to study methods for controlling the wake in conditions more representative of gas turbine engine fan applications.

In addition, Succi[8] has investigated the use of blowing and suction on propeller and helicopter rotor blades, not for reduction of rotor–stator interaction noise, but for the reduction of both thickness and steady loading noise associated with the rotor. He has predicted that significant reductions in noise radiated from a rotor may result from specific spanwise distributions of suction and blowing. It is possible that certain suction and blowing strategies designed to reduce rotor–stator interaction noise could either increase or decrease rotor noise. The additional rotor noise associated with wake management strategies was evaluated by modeling the mass and momentum addition with simple acoustic sources. For the subsonic tip speeds of interest, the rotor tone noise was found to be small compared to the rotor–stator interaction tone noise. Therefore, the impacts of wake management on rotor noise were not addressed further in the current study.

II. Computational and Experimental Methods

This section begins with a description of the particular fan geometry examined in this study (Sec. II.A), followed by a discussion of the experimental and numerical techniques used. Section II.B describes two-dimensional unsteady simulations of rotor–stator interaction. Two-dimensional linear cascade analysis of the radiated acoustics for both numerically and experimentally obtained blade wakes is discussed in Sec. II.C. In Sec. II.D the experimental cascade testing of wake management strategies is described.

A. Description of the Test Geometry

The experiments and computations were performed on a high-bypass-ratio fan design typical of some next-generation engine concepts. The design employs 16 rotor blades and 40 stator blades. Midspan sections of the fan and stator blades were used as a basis for the two-dimensional numerical and experimental models. The blade coordinates were taken from a 0.56-m-diam model-scale geometry. The blade incidence angles, inflow Mach number, and relative speed were set at values representative of takeoff conditions, where the community noise impact of these fans is of the most concern. The takeoff conditions at midspan are summarized in Table 1. For this design all circumferential acoustic modes at the blade passage frequency (BPF) are cut off at the conditions tested. The primary propagating modes are listed in Table 2.

Table 1 Test fan flow conditions at midspan in relative frame

Fan design parameters	Inlet	Exit
Mach number	0.74	0.52
Flow angle	39.8 deg	58.9 deg
Incidence	11 deg	
Chord	0.097 m	

Table 2 Propagating circumferential acoustic modes for the test fan

Frequency	Circumferential mode order
BPF	None
2 × BPF	$m = -8$
3 × BPF	$m = 8$
	$m = -32$
4 × BPF	$m = 24$
	$m = -16$
	$m = -56$

B. Two-Dimensional, Unsteady Modeling

Two-dimensional unsteady modeling was used 1) to parameterize the effects of varying wake width and depth on unsteady stator loading, and 2) to investigate the effects of blade-boundary layer suction on unsteady stator loading. For the applications of interest, the rotor–stator spacing is large enough that potential flow interaction effects between the rotor and the stator can be neglected. This allowed the boundary-layer suction on the rotor and the impact on the stator to be considered in a two-part analysis. The first part, a steady, viscous calculation on the rotor, was performed using MISES,[9] a two-dimensional cascade code. The second part, an unsteady, thin shear-layer Navier–Stokes calculation on the stator was performed using UNSFLO.[10] Descriptions of these computational models follow.

MISES is a viscous, multiple-blade, cascade code that was modified to model boundary-layer suction, and then used to calculate boundary-layer and wake characteristics. The code uses a Newton solution method to solve the steady, two-dimensional Euler equations for the outer flow. Boundary layers and wakes are modeled and described with integral equations that are coupled to the inviscid flow (the grid for the inviscid flow region is displaced from the blade by the displacement thickness of the boundary layer). Reference 9 includes a validation of the code with comparisons of blade pressure distributions, displacement thickness, momentum thickness, and boundary-layer shape parameter calculations to experimental data. A one-seventh-power law velocity profile was assumed for the turbulent portion of the boundary layer and a Falkner–Skan profile for the laminar region, with the transition point calculated using the e^n method. A cosine velocity profile was assumed in the wake downstream from the blade.

Boundary-layer suction was modeled by decrementing the momentum and displacement thicknesses of the boundary layer at a given location along the airfoil chord. The reduction of these parameters was performed by removing a fraction of the bottom of a one-seventh-power law velocity profile, and recalculating the momentum thickness, displacement thickness, and shape factor for the remaining (top) portion of the profile.[11] These values were then used to reinitiate the boundary layer downstream from the suction location.

The unsteady loading calculations on the stator were performed using UNSFLO,[10] a two-dimensional thin shear-layer, Navier–Stokes cascade solver. UNSFLO employs a hybrid Euler/Navier–Stokes scheme, with the Euler algorithm used in inviscid regions and the Navier–Stokes algorithm used in viscous regions. Manwaring and Wisler[12] validated the code for predicting gust response in compressors and turbines through comparison with experimental data. Gaussian wake distributions in the rotor reference frame were converted to stator coordinates and specified at the inlet plane of the stator. The wake deficit, wake width, rotor–stator pitch ratio, and flow angles were also specified.

C. Estimating Acoustic Radiation

Estimation of the magnitude of the radiated tone noise for propagating duct acoustic modes associated with the rotor–stator interaction was completed using LINSUB, a two-dimensional, linearized panel method written by Smith.[13] The code utilizes flat plate airfoils with zero mean loading and sinusoidal inlet wakes. Both up and downstream propagating acoustic waves are calculated as is the downstream convected vorticity wave shed from the stator blades because of the unsteady loading. The code has been used extensively throughout the aircraft engine industry (e.g., Hanson[14]). Flow conditions were established by setting the flow angle, Mach number, and rotor–stator pitch ratio. Experimentally and numerically obtained wake profiles were transformed into the stator reference frame and decomposed into spatial harmonics. LINSUB was then used to calculate the pressure amplitudes of the radiated acoustic waves. The acoustic modes radiated in the two-dimensional cascade model corresponded to the circumferential mode orders in the three-dimensional annular geometry.

D. Cascade Experiments

As discussed previously, the feasibility of using suction and blowing strategies to control wakes shed by a flat plate has been demonstrated.[4–6] However, this prior research has neglected essential features of the gas turbine environment. In particular, realistic fan blade geometries have not been tested, and the previous experiments have been carried out at zero incidence, not the higher loading encountered in turbomachinery. Further, cascade effects introduce normal and axial pressure gradients that are not modeled by single plate experiments. All of these effects are important for producing unsteady wake phenomena such as that shown in Fig. 1a. To assess the feasibility of using suction and blowing to reduce fan noise, and in particular the impact on broadband noise sources, a cascade facility was designed to test fan blade geometries under conditions more representative of those found in turbomachinery.

A schematic diagram of the experimental facility is shown in Fig. 3. Measurements of time-mean and unsteady wake velocity components were made downstream from a cascade consisting of three of the test fan blades (midspan geometry). The incidence and loading were set to match the takeoff conditions listed in Table 1, with an inlet-to-exit pressure rise coefficient of $C_p = 0.45$. The chord of the blades was 0.25 m and the span was 0.3 m. The Reynolds number based on chord was maintained above 3×10^5; this is sufficient to simulate the turbulent blade boundary layers and wakes that are present at full-scale conditions.[15] One of the blades was instrumented with 20 static pressure taps on each of the suction and pressure surfaces. The experimentally measured local surface pressure coefficients were compared to results of a numerical simulation obtained using the MISES code described in Sec. II.B. The measured and calculated pressure coefficients compared within 5% at all points along the chord. With the exception of three-dimensional effects, the blade boundary layer and wake development in the cascade facility are expected to be representative of the test fan at midspan.

The wake management strategies investigated include boundary-layer suction and blowing at the trailing edge of the blade. A schematic diagram of the blade used to test these concepts is shown in Fig. 4. The suction was performed through spanwise slots 2.5 mm wide (chordwise) by 12.5 mm long, separated along the span by 3 mm. The slots were located at chordwise positions $x/c = 0.5$ and 0.8. Suction was applied at rates corresponding to reduction of the local boundary-layer momentum thickness of 50 and 70%, based on estimates of the boundary-layer thickness calculated using MISES. The suction mass flows for these two cases corresponded to removal of 1.5 and 2.2% of the fan throughflow. The nonuniformity of suction mass flow rate along the span was less than ±10%. Trailing-edge blowing was performed through an array of 1.5-mm i.d. tubes with a center-to-center spacing of 3 mm. The tubes were aligned along the mean camber line at the trailing edge. Blowing was performed at rates corresponding to addition of 25, 75, and 90% of the natural wake momentum deficit. The mass flows for these cases corresponded to the addition of 0.7, 0.8, and 0.9% of the fan throughflow, respectively.

Measurements of the wake were taken using a single hot-wire anemometer probe. Sampling was carried out at 25 KHz and frequencies above 10 KHz were filtered. Unsteady flow was resolved below 10 KHz, corresponding to a Strouhal number of 1.4 based on the blade trailing-edge thickness of 2.5 mm and the freestream velocity of 18 m/s. Thus the time response of the hot-wire anemometer was sufficient to resolve the dominant turbulent structures in the wake. The error in the velocity measurements obtained with the hot wire was less than ±1%.

Measurements were made at midspan height in the cascade at 0, 0.5, 1.5, and 2.5 chord lengths downstream from the blade trailing edge. The probe was traversed along a line parallel to the exit plane of the cascade. Since the axial pressure gradients downstream from fans are typically near zero, the area of the downstream duct in which the wakes were measured was ad-

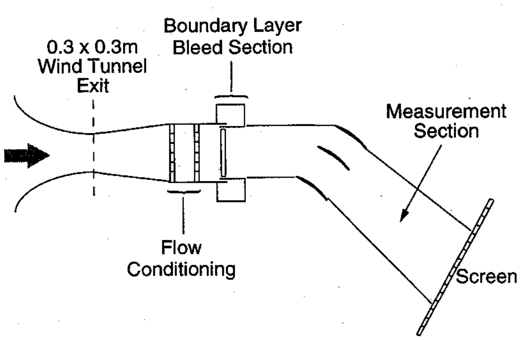

Fig. 3 Schematic diagram of the cascade test facility.

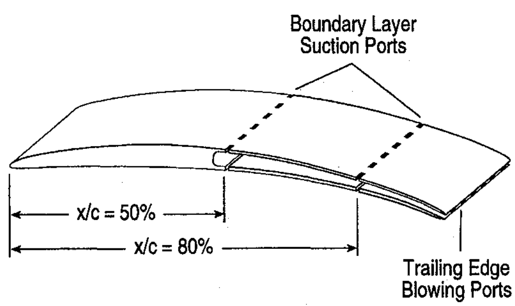

Fig. 4 Schematic diagram of wake management test blade.

justed so that the streamwise pressure change was maintained at less than 1.5% of the dynamic head.

III. Results

Discussion of the results is divided into four sections. Section III.A contains results of a numerical parameterization of the effect of wake modifications on unsteady stator loading and radiated tone noise. This is followed by numerical analysis of the effects of boundary-layer suction on wake development and unsteady loading in Sec. III.B. Experimental results are then presented in Sec. III.C to show the effects of both boundary-layer suction and trailing-edge blowing on steady and unsteady wake characteristics; estimates of the impact on radiated noise are included. In Sec. III.D blade design criteria for wake management strategies are addressed.

A. Numerical Parameterization of Effects of Wake Modifications

As a first step in evaluating wake management techniques, calculations were performed to determine the sensitivity of unsteady stator loading and radiated tone noise to specified modifications of the wake. Gaussian wake distributions in the rotor reference frame, of given width and depth, were specified at the inlet plane of the stator. The 16/40 rotor–stator pitch ratio of the test geometry and the flow conditions shown in Table 1 were used. UNSFLO was used to parameterize the effects of varying wake width and deficit on unsteady forces on the stator blade. The effects on radiated acoustic modes were determined using LINSUB.

The wake deficit was varied over a range of 0–30% of the freestream velocity while holding the wake width constant at 100% of the rotor pitch. Wake deficits between 5–15% are typical of fan rotor–stator spacings of technological interest. Over this range the unsteady stator loading harmonics, in multiples of BPF were approximately proportional to the wake deficit. This result is in accord with linear theory that applies for wakes that are small perturbations to the mean flow. Thus, if a particular spatial harmonic of the wake was reduced by 50%, one would expect a reduction of roughly 6 dB in any associated propagating acoustic modes.

Similar calculations were performed holding the wake deficit constant at 10% while varying the wake width over a range of 10–160% of the rotor pitch. Reducing the wake width had two effects, both of which were, in general, deleterious. First, for wake widths greater than one rotor pitch, the wake edges begin to merge together as shown in Fig. 5. The wake merging results in a reduction of the effective deficit seen by the stator row, as the freestream velocity is reduced. For fan rotor–stator axial spacings of 1.5–2 fan chord lengths, as are typical of current technology engines, the wakes are merged. Thus reducing the width of wakes so that they are no longer merged can effectively increase the stator loading and associated tone noise.

The second effect of changing the wake width is a result of changes in the harmonic content of the gust field that is incident on the stator. Many fan geometries are designed so that acoustic modes associated with the first wake harmonic (BPF) are cut off over most of the engine operating envelope. Therefore, the acoustic modes of greatest concern are associated with the 2 × BPF, 3 × BPF, etc., spatial harmonics of the wake. For a constant wake centerline velocity deficit (i.e., the same maximum change in incidence angle), these harmonics are increased when the wake width is decreased. Indeed for Gaussian wakes, each spatial mode number n peaks at a wake width of approximately $1/n$ times the rotor pitch. It is thus advantageous for the wake width to be approximately equal to the rotor pitch to maximize the amplitude of the BPF harmonic with respect to higher-order harmonics.

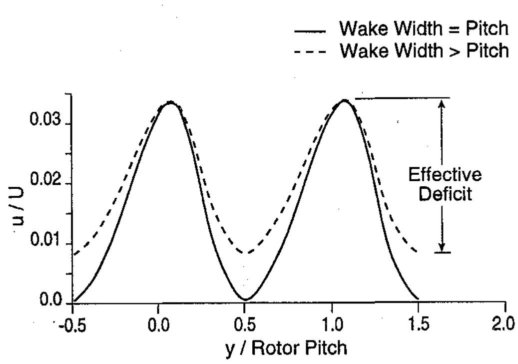

Fig. 5 Wake merging.

Table 3 Radiated acoustic mode amplitudes for changing wake width

Mode	Mode amplitudes in decibel: upstream and (downstream)[a]			
	0.25	0.5	0.75	1.0
2 × BPF,	5.5	8.1	5.8	0
$m = -8$	(5.5)	(8.1)	(5.8)	(0)
3 × BPF,	6.4	4.7	−4.8	−19.4
$m = 8$	(−21.3)	(−23.0)	(−32.5)	(−47.1)
3 × BPF,	1.5	−0.1	−9.6	−24.2
$m = -32$	(−2.5)	(−4.2)	(−13.7)	(−28.3)
4 × BPF,	2.5	−4.8	−26.3	−42.2
$m = 24$	(−9.8)	(−17.1)	(−38.6)	(−54.7)
4 × BPF,	−16.2	−23.5	−45.0	−61.1
$m = -16$	(−7.8)	(−15.1)	(−36.6)	(−52.7)
4 × BPF,	4.9	−2.5	−23.9	−40.0
$m = -56$	(−5.7)	(−13.0)	(−34.5)	(−50.6)

[a]All referenced to $m = -8$, 2 × BPF upstream and (downstream), respectively, for wake width = rotor pitch (wake width in fraction pitch).

Examples of the changes in amplitude of radiated acoustic modes with varying wake width are shown in Table 3. The results were obtained using LINSUB. The mode amplitudes upstream and downstream from the stator are shown referenced to the $m = -8$, 2 × BPF upstream and downstream amplitudes, respectively, for a wake width-to-pitch ratio of 1. (For reference, for the $m = -8$, 2 × BPF mode, the downstream amplitude is 15.9 dB greater than the upstream amplitude.) The sensitivity of the higher-order modes to wake width is significant. For example, for the 2 × BPF mode, a decrease in wake deficit of 50% would be nullified if it were accompanied by a decrease in wake width from 100% of rotor pitch to 75% of rotor pitch. Thus, a general goal for wake management is to strive for shallow but wide wakes to minimize the propagating tone noise.

B. Numerical Analysis of the Effects of Boundary Layer Suction on the Test Geometry

Numerical analyses of the effects of fan blade boundary-layer suction on wake development and unsteady stator loading were performed using MISES and UNSFLO as described in Sec. II.B. (Trailing-edge blowing was less tractable to model numerically using the computational techniques employed in this study and was therefore only evaluated experimentally.) Cases with boundary-layer suction on the rotor at 50, 80, and 90% chord location, with 0, 25, 50, and 75% of the local boundary-layer momentum thickness removed were examined at rotor–stator spacings of 2 and 3 rotor chord lengths. Boundary-layer removal was implemented on the suction side of the rotor blade only. The suction side boundary layer was approximately 5 times thicker than the pressure side boundary layer for the conditions investigated in this study. The suction side boundary layer was thus the dominant contributor to the momentum deficit in the wake.

Figures 6 and 7 show the effect of varying amounts of boundary-layer suction on the depth and width of the wake at two and three chord lengths downstream from the trailing edge. The wake width was reduced by 21% and the velocity deficit was reduced by approximately 40% at a position of two chord lengths downstream from the fan blade trailing edge. Changes in the wake deficit and width with suction were limited by two effects: 1) the presence of the pressure side boundary layer and 2) finite trailing-edge thickness. For the blade with no treatment the displacement thickness of the suction side boundary layer was 1.3% of chord, whereas the pressure side boundary-layer displacement thickness was 0.25% chord. For this 0.56-m model-scale geometry the trailing-edge thickness was 1.3% chord, equal to the suction side boundary-layer displacement thickness. For many production-scale blades, the trailing-edge thickness is a smaller fraction of the chord length, on the order of 0.1–0.5% chord. Thus, while the wake reductions estimated for the test geometry are relatively small, a larger impact of boundary-layer suction may be expected for full-scale applications.

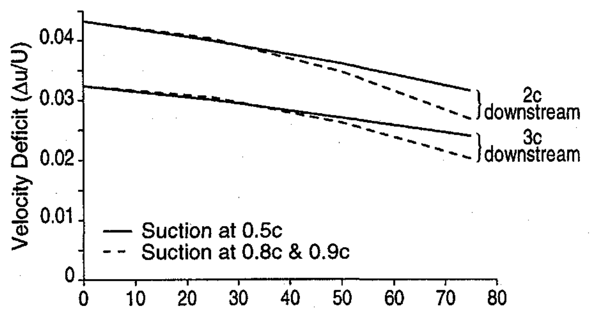

Fig. 6 Test fan wake velocity deficit vs percent boundary-layer momentum thickness removed.

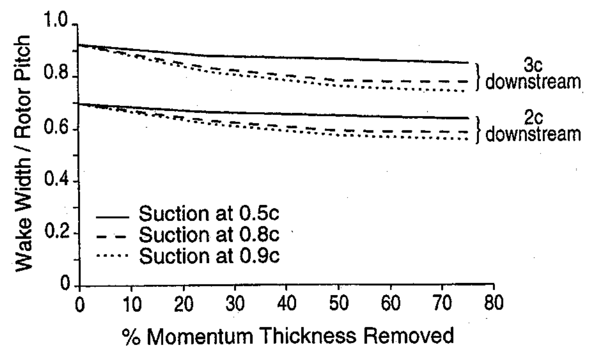

Fig. 7 Test fan wake width vs percent boundary-layer momentum thickness removed.

The changes in unsteady stator loading for the modified wakes were obtained using UNSFLO. For compact sources, the unsteady loading is directly related to the amplitude of the radiated acoustic modes. For the baseline case with no suction, the wakes spread larger than the rotor pitch, merging and effectively reducing the velocity deficit. Thus for cases with small amounts of suction (e.g., 25%), the increase in effective deficit because of the unmerging of the wakes outweighed the decrease in deficit because of boundary-layer removal, so that the unsteady loading was increased approximately 5%. For larger suction levels, unsteady loading reductions were demonstrated. The largest reduction in total loading for the test fan geometry was approximately 25%. This corresponded to 75% suction at 80% chord. If the treatment were to be applied uniformly along the span of a fan blade, this condition would correspond to removal of approximately 3.5% of the fan through flow.

The case displaying the maximum reduction in unsteady loading, however, did not correspond to the largest reduction in radiated tone noise. Using LINSUB, it was estimated that for the case of maximum loading reduction there was no change in radiated tone noise. The null result was because of competition between the increased higher harmonic content from the decreased wake width and the reduction in velocity deficit. For the test fan studied, the largest reduction in radiated noise with boundary-layer suction (3 dB for the strongest propagating mode) was estimated to occur for 100% boundary-layer removal at a 50–60% chord location. As shown in Figs. 6 and 7, this case results in relatively large changes in wake deficit for small changes in wake width. Further, only half the total mass flow is required to be removed down the blade for suction at 50% chord compared to suction at 90% chord.

The previous simulations capture only the changes in time-mean wake structure brought about by boundary-layer suction and do not address the changes in unsteady character of the wake or the effects of trailing-edge blowing. These topics were investigated using experimental cascade tests, which are discussed in Sec. III.C.

C. Experimental Cascade Testing of Boundary-Layer Suction and Trailing-Edge Blowing

Cascade experiments were carried out for blade boundary-layer suction and trailing-edge blowing to elucidate the effects of these treatments on both steady and unsteady wake characteristics. The takeoff flow conditions and blade incidence

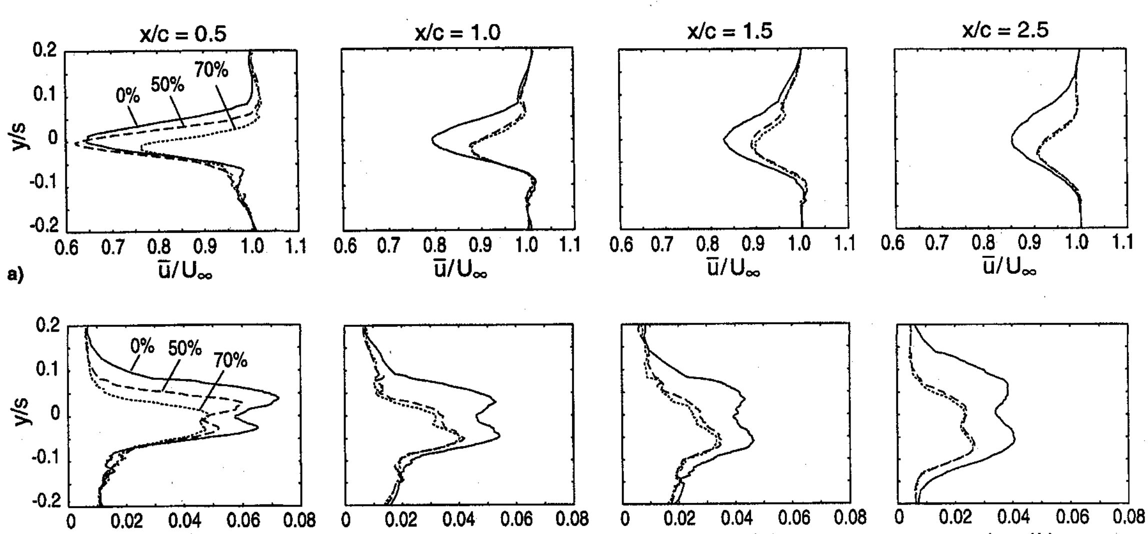

Fig. 8 Wake profiles for boundary-layer suction at 80% chord. Curves are shown for various percentage reductions in the boundary-layer momentum thickness $\Delta\theta_{b.l.}$: a) mean velocity and b) velocity fluctuations.

angles summarized in Table 1 were used. The reduction in tone noise associated with the wake management treatments was estimated by using the experimentally obtained time-mean wake signatures as input to LINSUB.

1. Boundary-Layer Suction

Boundary-layer suction was applied on the suction side of the blade at 50 and 80% chord for suction mass flow rates corresponding to 50 and 70% reduction of the local boundary-layer momentum thickness. The variation in mean velocity deficit with suction at 80% chord is shown in Fig. 8a as a function of distance downstream from the trailing edge of the fan blade. The narrowing of the wake from the suction side ($y/s > 0$) where the boundary layer was removed is evident. Note that the wake was changed little in going from 50 to 70% boundary-layer momentum thickness removal. For the case of 70% momentum thickness reduction the peak wake deficit was reduced 40% at 1.5 chords downstream from the blade. The reduction in width for this case was approximately 15%. The reductions in width and deficit are in accord with the numerical simulations presented in Sec. III.B. However, the overall shape of the wakes differs from those of the numerical simulations that were, in general, shallower and wider, suggesting that the turbulent viscosity was not modeled accurately.

Table 4 Radiated acoustic mode amplitudes for experimental wake management profiles at x/c = 1.5

	Mode amplitudes in decibel: upstream and (downstream)[a]		
Mode	Baseline	Boundary-layer suction, $\Delta\theta_{b.l.} = 70\%$	Trailing-edge blowing, $1 - \theta/\theta_0 = 0.9$
2 × BPF,	0	−4.4	−11.4
$m = -8$	(0)	(−4.4)	(−11.4)
3 × BPF,	−0.6	−5.1	−7.7
$m = 8$	(−28.3)	(−32.7)	(−35.3)
3 × BPF,	−5.5	−9.9	−12.5
$m = -32$	(−9.5)	(−13.9)	(−16.5)
4 × BPF,	−6.0	−9.9	−10.7
$m = 24$	(−18.3)	(−22.1)	(−23.0)
4 × BPF,	−24.7	−28.5	−29.3
$m = -16$	(−16.3)	(−20.1)	(−21.0)
4 × BPF,	−3.7	−7.5	−8.3
$m = -56$	(−14.2)	(−18.1)	(−18.9)

[a]All referenced to baseline $m = -8$, 2 × BPF upstream and (downstream), respectively.

The change in unsteady wake behavior with suction at 80% chord is shown in Fig. 8b, where the rms of the velocity fluctuations in the wake is plotted at several locations downstream from the trailing edge. Note the two peaks in turbulent fluctuations that are characteristic of the vortex shedding described by Epstein et al.[1] The peaks correspond roughly to the location of maximum shear in the mean velocity profiles as expected. At 1.5 chords downstream, the turbulent velocity fluctuations were reduced approximately 35% for the case of maximum suction. Since there were not significant changes in the turbulence spectrum, this reduction would correspond to approximately a 3.7 dB reduction in the component of broadband noise associated with the wake turbulence.

For the condition of 70% reduction in boundary-layer momentum thickness, the time–mean wake signature at 1.5 chord lengths downstream from the trailing edge was converted to the stator coordinate frame and used as an initial condition in LINSUB. Recall that for this geometry the 1 × BPF acoustic mode is cutoff, and so it is only the higher spatial harmonics of the wake (2 × BPF and higher) that influence radiated tone noise. The upstream and downstream amplitudes of the propagating acoustic modes were compared to those obtained for the baseline wake profile measured experimentally. (For the baseline $m = -8$, 2 × BPF mode, the downstream amplitude is 15.9 dB greater than the upstream amplitude.) The results of this analysis are shown in Table 4. For the case with boundary-layer suction, the amplitude of the strongest propagating mode ($m = -8$, 2 × BPF, downstream) is reduced by 4.4 dB. Higher-order propagating modes show similar reductions in amplitude. If the treatment were to be applied uniformly along the span of a fan blade, this condition would correspond to removal of approximately 2.2% of the fan through flow.

2. Trailing-Edge Blowing

Experiments employing trailing-edge blowing were conducted for mass flow rates corresponding to addition of 25, 75, and 90% of the natural wake momentum deficit. The variation in mean velocity defect for these cases is shown in Fig. 9a as a function of distance downstream from the trailing edge of the fan blade. The filling of the pressure side ($y/s < 0$) of the wake deficit may be because of the alignment of the injection ports with the mean camber line, which differs from the direction that the flow leaves the blade by a deviation angle of approximately 6 deg. The maximum reduction in steady wake amplitude shown is approximately 50% at x/c = 1.5. Blowing strategies that produce better mixing may give more uniform reductions of the

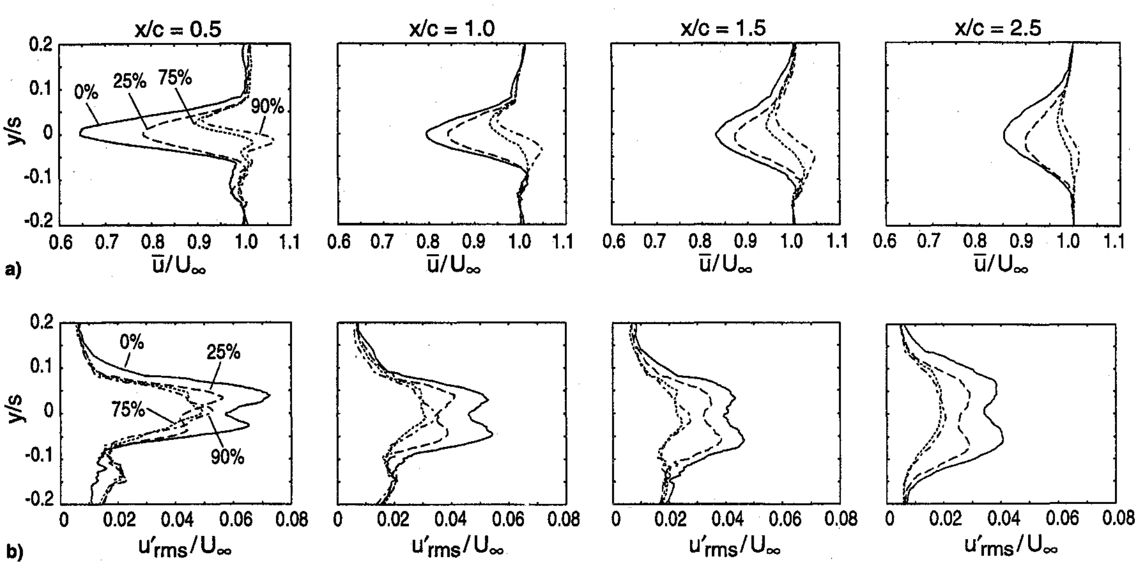

Fig. 9 Wake profiles for trailing-edge blowing. Curves are shown for various percentage reductions in the wake momentum thickness $1 - \theta/\theta_0$: a) mean velocity and b) velocity fluctuations.

wake deficit as demonstrated by Naumann[4] and Park and Cimbala.[6] In particular, for certain trailing-edge geometries, reductions in steady wake amplitudes greater than 90% have been demonstrated downstream from flat plates.[4]

The change in unsteady wake character is shown in Fig. 9b, where the rms of the velocity fluctuations in the wake is plotted at several locations downstream from the trailing edge. The maximum reduction in wake velocity fluctuations is approximately 50% at $x/c = 1.5$ for the case of 90% filling of the natural wake momentum deficit. Again, since there was little change in the turbulence spectrum, this result implies a reduction of 6 dB in the component of broadband noise associated with the wake turbulence.

For the addition of 90% of the wake momentum deficit, the time–mean wake signatures at 1.5 chord lengths downstream from the trailing edge were converted to the stator coordinate frame and used as input to LINSUB. The upstream and downstream amplitudes of the propagating acoustic modes were compared to those obtained for the baseline wake profile measured experimentally (again, the downstream reference amplitude is greater than the upstream reference amplitude by 15.9 dB). The results of this analysis are shown in Table 4. For trailing-edge blowing the amplitude of the strongest propagating mode ($m = -8$, $2 \times$ BPF, downstream) is reduced by 11.4 dB. Other propagating modes show reductions in amplitudes of 5–10 dB. If the treatment were to be applied uniformly along the span of a fan blade, the addition of 90% of the natural wake momentum deficit would correspond to the addition of approximately 0.9% of the fan throughflow for this particular blowing geometry.

IV. Analysis of Fan Blade Design Requirements

An analysis was performed to determine the requirements for internal fan blade passages to allow the removal or addition of sufficient mass flow to perform the treatments described previously. The flow internal to the blades was modeled as a one-dimensional viscous flow in a variable area, rotating channel with heat transfer at the walls. The conservation equations were integrated radially to determine the hub pressure required to obtain a specified flow rate in the passage for a given blade and passage geometry, and operating condition. The viscous and heat transfer terms were approximated using relations given by White.[16]

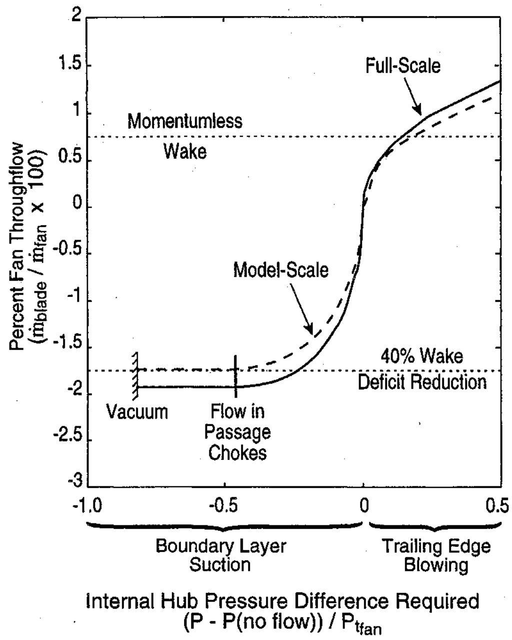

Fig. 10 Suction and blowing performance for sample blade design.

The analysis was performed for a three-dimensional blade design for which the midspan conditions are given in Table 1. The calculations were carried out both for the 0.56-m-diam model-scale blade and for a full-scale blade (there is roughly a factor of 6 difference in scale). The analysis was conducted assuming a maximum suction passage open area of 50% of the total blade area at each spanwise location, and uniform percentage reduction in the boundary-layer momentum thickness at each spanwise location. An open area of 30% of the total blade area and uniform spanwise reduction in the wake momentum deficit was assumed for trailing-edge blowing. These percentages of open area are similar to what is present in the hollow fan blades currently used in some gas turbine engines, and thus are feasible to implement from a structural design perspective.

Figure 10 shows solutions for boundary-layer suction and trailing-edge blowing for the 0.56-m model-scale and full-scale blades. The solutions are dependent on the blade passage geometry and the configuration for the suction and blowing ports. Thus, while the results are representative, they are not general. For the 0.56-m fan model all relevant nondimensional external flow parameters were matched to full-scale conditions with the exception of the size of the fan. The only difference between the solutions for the model-scale and the full-scale blades is the viscous forces within the blade passages. The full-scale case behaves essentially inviscidly; viscous forces limit the flow rate only at model scale.

The nonsymmetry of the curves for suction and blowing shown in Fig. 10 is caused by the effects of rotation and different passage geometries for the two cases. The maximum passage mass flow for either suction or blowing is obtained when the fluid chokes in the passage. The choking typically occurs at the hub for suction and at the tip for blowing. The suction is limited to an amount of mass removal that will allow approximately a 40% reduction in wake deficit based on the simulations shown in Sec. III.B. This corresponds to removing approximately 2% of the fan throughflow.

Trailing-edge blowing in general is a more attractive strategy to implement. Note that the hub pressure required for blowing would allow air to be bled from the early stages of the core compressor. In addition, for trailing-edge blowing less mass flow and passage flow area are required to gain considerably better deficit reduction. This is because of the following two effects:

1) Deficit reduction with boundary-layer suction is limited by finite trailing-edge thickness; deficit reduction with trailing-edge blowing is not.

2) The radial pressure gradient set up by the blade rotation accelerates the flow moving outward radially, but impedes the removal of air to the hub as required for boundary-layer suction.

V. Summary and Conclusions

Preliminary studies of a new approach for reducing rotor–stator interaction noise were presented. The approach centers on the removal and/or addition of fluid from the rotor blades to minimize the shed wakes, thereby making the flow into the stator more uniform and reducing unsteady loading and radiated noise. Two-dimensional numerical and experimental models were used to determine the parametric dependence of radiated noise on wake modifications brought about by suction surface boundary-layer removal and the injection of fluid through the trailing edge of the fan blade. The blade geometry and flow conditions investigated are typical of fan designs for next-generation high bypass ratio gas turbine engines.

The principal conclusion of this study is that methods to control the initiation of the fan wake are feasible for application in high-bypass ratio turbomachines. The results presented suggest that reductions in amplitude of the strongest tonal harmonics of greater than 10 dB are achievable, as are reductions of approximately 6 dB in the component of broadband noise associated with wake turbulence.

1) A numerical parameterization of the effects of wake width and depth on unsteady stator loading and amplitudes of radiated acoustic modes was presented. For typical fan designs the BPF acoustic modes are nonpropagating. Noise is minimized by reducing 2 × BPF and higher spatial harmonics of the wake. For Gaussian wake profiles, this is best achieved by maintaining the wake width approximately equal to the rotor pitch while reducing the peak deficit.

2) Numerical simulations were used to show the relative importance of the blade suction and pressure side boundary layers, and the trailing-edge thickness on wake development. For the test fan geometry, the trailing-edge thickness was approximately equal to the suction surface boundary-layer displacement thickness. With 75% reduction in suction side boundary-layer momentum thickness, the reduction in the time-mean wake width and deficit was limited to 21 and 40%, respectively.

3) Cascade testing of a representative fan geometry with trailing-edge blowing showed reductions in the time-mean wake deficit of 50% and reductions in the rms of the turbulent velocity fluctuations of 50% at 1.5 chord lengths downstream from the trailing edge. The amount of mass addition corresponded to 0.9% of the fan throughflow. The reduction in amplitude of the strongest propagating circumferential acoustic mode for this case was estimated to be 11.4 dB. Other propagating modes were reduced between 5–10 dB. The reduction in turbulent velocity fluctuations would correspond to a 6-dB reduction in the component of broadband noise associated with wake turbulence.

4) Cascade testing of a representative fan geometry was also carried out with suction surface boundary-layer removal at 80% chord at a mass flow rate corresponding to removal of 2.2% of the fan throughflow. The boundary-layer suction produced a reduction in the mean velocity deficit of 40% and a reduction in the rms of the turbulent velocity fluctuations of 35%. The reduction in amplitude of the strongest propagating circumferential acoustic mode for this case was estimated to be 4.4 dB. The reduction in the component of broadband noise associated with wake turbulence would be approximately 3.7 dB.

5) Analysis of internal flow requirements for suction and blowing passages in fan blades showed that the primary limitation for mass flow rate for both suction and blowing is choking in the internal passages. For a representative engine fan geometry choking limited the amount of mass removal through boundary-layer suction to an amount that would allow reduction of the wake deficit by 40% if applied uniformly along the span. Trailing-edge blowing is relatively easier to implement. Blowing at a rate corresponding to 0.75% of the fan throughflow can be used to produce momentumless wakes along the span. The pressure differential required at the hub to produce this flow is 0.15 times the fan throughflow total pressure.

Additional research is required to optimize the mass addition and removal geometries to produce more uniform wake profiles as suggested by the research of Naumann[4] and Park and Cimbala.[6] Further, to accurately evaluate the radiated noise it is important to consider the three-dimensional acoustic mode structure. The effects of spanwise distributions of wake management should be studied in the context of coupling to radial acoustic modes.

There are several flow characteristics that were not captured by the two-dimensional numerical and experimental models employed in the current study. In particular, in low hub-to-tip ratio fans the wake is not radially uniform in width/pitch or deficit, and it is skewed circumferentially and stretched because of the swirl downstream from the rotor. Also, the presence of swirl between the blade rows produces different cutoff conditions between the blade rows compared to upstream or downstream, and the blades are not perfectly uniform in geometry or spacing; both of these effects tend to enrich the harmonic content of the radiated tone noise.

Acknowledgments

This work was supported by NASA Grant NAG1-1512. The ongoing interaction with D. B. Hanson of Pratt and Whitney has provided the authors invaluable guidance in many of the technical aspects of gas turbine noise, and we thank Pratt and Whitney for providing the geometry for the fan used in this study. K. U. Ingard provided an unparalleled level of insight into the physics of fan acoustics, and discussions with A. H. Epstein and M. Durali brought many of the difficult problems of working in rotating machinery to light. The help of M. Drela and M. B. Giles in applying their codes was appreciated, as was the technical support of M. Bathe, V. Dubrowski, J. Letendre, and D. Lopez. The guidance, interest, and support of the Technical Monitor C. H. Gerhold, and D. G. Stephens of NASA Langley Research Center enabled the research effort, and are very much appreciated.

References

[1]Epstein, A. H., Gertz, J. B., Chen, P. R., and Giles, M. B., "Vortex Shedding in High-Speed Compressor Blade Wakes," *Journal of Propulsion and Power*, Vol. 4, No. 3, 1988, pp. 236–244.

[2]Ng, W. G., and Epstein, A. H., "Unsteady Losses in Transonic Compressors," *Journal of Engineering for Power*, Vol. 107, April 1985, pp. 345–353.

[3]Hanson, D. B., and Wagner, B., personal communication, Pratt and Whitney, United Technologies, 1995.

[4]Naumann, R. G., "Control of the Wake from a Simulated Blade by Trailing-Edge Blowing," M.S. Thesis, Lehigh Univ., Bethlehem, PA, 1992.

[5]Corcoran, T. E., "Control of the Wake from a Simulated Blade by Trailing-Edge Blowing," M.S. Thesis, Lehigh Univ., Bethlehem, PA, 1992.

[6]Park, W. J., and Cimbala, J. M., "The Effect of Jet Injection Geometry on Two-Dimensional Momentumless Wakes," *Journal of Fluid Mechanics*, Vol. 224, March 1991, pp. 29–47.

[7]Leu, T.-S., and Ho, C.-M., "Free Shear Layer Control and Its Application to Fan Noise," AIAA Paper 93-3242, July 1993.

[8]Succi, G. P., "System and Method for Suppressing Noise Produced by Rotors," U.S. Patent 5217349, 1993.

[9]Drela, M., "Two-Dimensional Transonic Aerodynamic Design and Analysis Using the Euler Equations," Massachusetts Inst. of Technology, Gas Turbine Lab. Rept. 187, Cambridge, MA, 1986.

[10]Giles, M. B., "UNSFLO: A Numerical Method for the Calculation of Unsteady Flow in Turbomachinery," Massachusetts Inst. of Technology, Gas Turbine Lab. Rept. 205, Cambridge, MA, 1991.

[11]Hayden, B. J., "Two-Dimensional Analysis of Rotor Suction and the Impact on Rotor-Stator Interaction Noise," M.S. Thesis, Dept. of Aeronautics and Astronautics, Massachusetts Inst. of Technology, Cambridge, MA, 1994.

[12]Manwaring, S. R., and Wisler, D. C., "Unsteady Aerodynamics and Gust Response in Compressors and Turbines," American Society of Mechanical Engineers 37th International Gas Turbine and Aeroengine Congress and Exposition, Cologne, Germany, 1992.

[13]Smith, S. N., "Discrete Frequency Sound Generation in Axial Flow Turbomachines," Aeronautical Research Council R&M 3709, March 1972.

[14]Hanson, D. B., "Coupled 2-Dimensional Cascade Theory for Noise and Unsteady Aerodynamics of Blade Row Interaction in Turbofans, Volume 1—Theory Development and Parametric Studies," NASA CR 4506, Jan. 1994.

[15]Cumpsty, N. A., *Compressor Aerodynamics*, Wiley, New York, 1989.

[16]White, F. M., *Viscous Fluid Flow*, McGraw–Hill, New York, 1974.