Journal of Sound and Vibration (2000) **235**(2), 235–245
doi:10.1006/jsvi.2000.2922, available online at http://www.idealibrary.com on IDEAL®

REDUCTION OF UNSTEADY STATOR–ROTOR INTERACTION USING TRAILING EDGE BLOWING

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(*Received* 28 *June* 1999, *and in final form* 4 *January* 2000)

An aeroacoustic investigation was performed to assess the effects of adding mass flow at the trailing edges of stators upstream of an aircraft engine simulator. By using trailing edge blowing to minimize the shed wakes of the stators, the flow into the rotor was made more uniform, hence reducing the unsteady stator–rotor interaction. In these experiments, a reduced number of stators (four) was used in a 1/14 scale model inlet which was coupled to a 4·1 in (10·4 cm) turbofan engine simulator. Steady state measurements of the aerodynamic flow field and acoustic far field were made in order to evaluate the aeroacoustic performance at three simulator speeds: 30k, 50k, and 70k r.p.m. The lowest test speed (30k r.p.m.) showed a noise reduction as large as 8·9 dB in the blade passing tone. At 50k and 70k r.p.m., the reduction in blade passing tone was 5·5 and 2·6 dB respectively. In addition, trailing edge blowing reduced the overall sound pressure level in every case. Aerodynamic measurements showed that fan face distortion was significantly reduced due to trailing edge blowing. The addition of trailing edge blowing from the four upstream stators did not change the operating point of the fan, and the mass flow added by the blowing was less than 1% of the fan mass flow rate. The results of these experiments clearly demonstrate that blowing from the trailing edges of the stators is effective in reducing unsteady stator–rotor interaction and the subsequent forward radiated noise.

1. INTRODUCTION

Decreasing the environmental impact of aircraft engines is an important design criteria. A major aspect of an aircraft engine's environmental impact is the airport community noise. Densely populated areas are frequently exposed to excessive noise when engines are loudest and when aircraft are closest to the ground. The two most prominent sources of noise from jet engines are forward-radiated fan noise and jet exhaust noise [1].

A primary generating mechanism of forward-radiated fan noise is stator–rotor interaction. The three most common types of interactions are rotor blades chopping through the wakes of upstream stators, wakes from rotor blades impinging on downstream stators, and the pressure fields of the rotors reflecting off nearby objects. This research efforts focuses on the first generating mechanism, where the rotor blades cut through the wakes from upstream stators. This study investigates the noise reduction possible by reducing the unsteady interaction between the stators and rotors by adding mass flow at the

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trailing edges of the upstream stators. In this experiment, a reduced number of upstream stators (four total) was used, all with no turning angle. The results from this testing will be used to focus a future study involving an increased stator count.

The amount of published material in the open literature regarding the aeroacoustic effects of wake management using trailing edge blowing is somewhat limited. Several experiments were performed to examine the effectiveness of different wake management strategies, and one experiment utilized results of wake management tests to make acoustic predictions [2]. To the author's knowledge, this is the first published work to describe actual acoustic measurements resulting from wake management in a realistic turbomachinery environment.

1.1. PREVIOUS RESEARCH IN TRAILING EDGE BLOWING

Park and Cimbala [3], Meyer and Cimbala [4], Corcoran [5], and Naumann [6] demonstrated that trailing edge blowing can significantly reduce time-mean wake deficits and unsteadiness downstream from a flat plate. Corcoran [5] and Naumann [6] experimented with several blowing techniques and configurations in a closed-circuit water channel. They both found that trailing edge blowing is effective in attenuating the mean wake deficit from the edge of a flat plate. In addition, Corcoran [5] showed that trailing edge blowing reduces Reynolds stress, vorticity, and velocity fluctuations within one chord length downstream. They also noted that the fluid characteristics of re-energized wakes are highly dependent upon the method that was used to generate them. Naumann [6] examined several different configurations for trailing edge blowing, including a continuous slit at the trailing edge, a set of discrete jets, and a set of discrete jets with vortex generators. Naumann's work showed that of these configurations discrete jets provide the best results. Furthermore, he went on to show that vortex generators enhance downstream mixing of the trailing edge blowing air and the wake.

Waitz *et al.* [2] used trailing edge blowing along with boundary layer suction on an actual rotor blade in an effort to minimize the shed wake. His study used two-dimensional numerical and experimental models to determine how wake modification effects radiated noise. The magnitude of the radiated noise was estimated using LINSUB, a two-dimensional, linearized panel method. Using the experimental and numerical wake profiles, LINSUB was then used to calculate the amplitudes of the radiated acoustic waves. These experiments were performed in a wind tunnel facility using a stationary rotor blade with a chord of 9·8 in (25 cm) and span of 11·8 in (30 cm). Trailing edge blowing was accomplished using 0·06 in (1·5 mm) internal diameter tubes center spaced at 0·12 in (3 mm). Waitz *et al.* [2] concluded that wake management is feasible for high-bypass turbomachinery. Acoustic predictions based on the aerodynamic data suggest that the strongest tonal harmonics can be reduced by more than 10 dB. Trailing edge blowing reduced the time mean wake deficit by 50% and the turbulent velocity fluctuations by 45% at a downstream distance of 1·5 chord lengths. The amount of air added through the trailing edge blowing was less than 1% of the overall fan mass flow.

All of the works previously discussed were geared toward applying wake management to stator–rotor interaction. However, it is important to note that there is a separate noise-generating mechanism at work, noise from the rotor only. A common example of this noise is that radiated from helicopter rotor and propeller-driven aircraft. Succi [7] examined techniques to suppress the noise associated with the rotor only. By carefully applying blowing and suction strategies along the span of the rotor, he predicted that significant rotor noise attenuation was achievable. Waitz *et al.* [2] cited that many of the blowing and suction strategies designed to suppress noise from stator–rotor interaction could either increase or decrease the noise which is associated with the rotor only. However, they went on to conclude that for high-bypass turbofans any additional rotor noise resulting from wake management was small when compared with stator–rotor interaction noise.

2. EXPERIMENTAL TECHNIQUES

This section describes the inlet, stator with trailing edge blowing, turbofan simulator, and test set-up which utilized the Virginia Tech Anechoic Chamber in the Vibration and Acoustics Laboratory. These same facilities and equipment have been used in the past by Nuckolls and Ng [8].

2.1. INLET AND UPSTREAM STRATORS

Figure 1 shows the inlet geometry used for this work. The inlet geometry was based on a combination of subsonic and supersonic designs, so that the experimental results would be applicable to a wider range of inlet types. This inlet was equipped with a geometrically simple centerbody and four stators. In order to reduce boundary layer effects, the inlet was shorter than a typical supersonic inlet. The bellmouth on the inlet was necessary to prevent lip separation during the static testing. In previous work, Miller and Ng [9] observed large regions of flow separation originating from a sharp cowl lip.

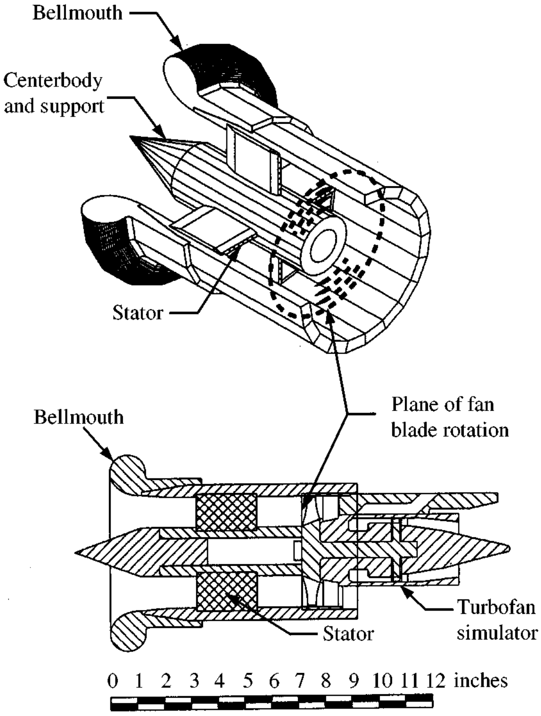


Figure 1. Inlet geometry.

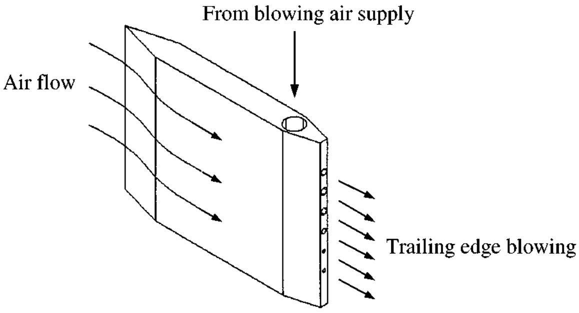


Figure 2. Geometry of the staor.

The geometry of the stators is shown in Figure 2. These stators had zero turning angle, and were positioned with the trailing edge 0·75 chord lengths (based on stator chord) upstream of the turbofan simulator fan face. The axial distance between the stators and fan face was chosen to be representative of a high-speed civil transport-type inlet. The blowing air was supplied externally from a pressure regulated plenum. The size and spacing of the trailing edge blowing holes was critical to provide uniform spanwise re-energizing of the stators' wakes. The goal in designing a trailing edge configuration was to produce a uniform blowing profile from the tip to the hub. A secondary consideration was that the hole configuration be designed to use a minimal amount of blowing air. In order to achieve the most uniform spanwise profile possible, a series of bench tests are initiated to aid in the design of the geometry of the blowing holes at the stator trailing edge. Results [10] show that six equally spaced holes with non-uniform hole diameter along the span provided the best configuration (Figure 2). Blowing holes with smaller diameter are used near the hub to account for the non-uniform pressure inside the supply air plenum of the blade.

2.2. TURBOFAN SIMULATOR

The noise source used in this experiment was a Tech development Model 460 turbofan simulator. This simulator functions like a fan in a high-bypass ratio engine. Figure 1 shows the simulator mated to the inlet. The simulator was powered by high-pressure air exhausting through a single-stage turbine. The turbine turns a single-stage fan which draws air into the simulator from the ambient atmosphere. The turbine and fan air streams are mixed downstream of the simulator exit. The 4·1 in diameter fan was made up of 18 fan blades and 26 outlet guide vanes (OGV). The Model 460 has a design speed of 80 000 r.p.m., and was capable of producing total pressure ratio of 1·6 with a mass flow of 2·72 lb m/s (1·23 kg/s). For these experiments, the simulator was tested at 30 000, 50 000, and 70 000 r.p.m.

2.3. TEST CONFIGURATION

All testing was performed in the Virginia Tech Anechoic Chamber facility. All experiments conducted were static tests. The chamber working space dimensions are 13·1 × 8·9 × 6·6 ft. This space is surrounded by sound-absorbing wedges made of industrial fiberglass. This facility is considered anechoic for frequencies above 200 Hz with an ambient noise level of approximately 30 dB. This ambient noise level is considerably lower than the noise levels of interest measured during testing. The turbofan simulator was mounted 4 ft above the ground level to prevent the ingestion of ground vortex.

2.4. AERODYNAMIC MEASUREMENTS

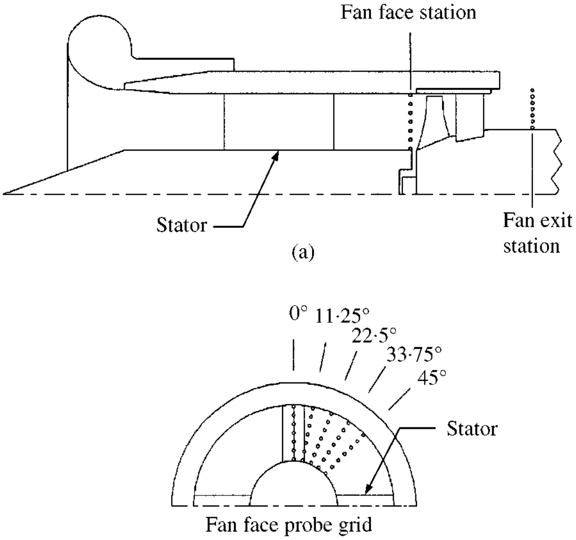
The acoustic performance of an aircraft engine inlet is closely linked to its aerodynamic behavior. In order to correlate the change in acoustic performance with a corresponding change in flow distortion, it was essential to document the aerodynamic performance of the inlet with and without trailing edge blowing. Steady state measurements of static and total pressure were taken to completely map the fan face and downstream wakes from the stators.

A 0·0625 in (1·6 mm) diameter Pitot-static probe was used to measure the static and total pressures in order to calculate Mach number. In addition, a 0·125 in (3·2 mm) diameter Kiel probe was used to make measurements of total pressure.

Aerodynamic measurements were made at three axial stations: behind the stators, at the fan face, and at the fan exit (see Figure 3). Radial traverses were made in order to map out the entire fan face, which was at a downstream distance of 75% of the stator chord length from the trailing edges of the stators. The traverses at the fan face were radial traverses from the tip to hub, with each traverse comprised of seven data points. Nuckolls and Ng [8] showed that the flows at the fan face and fan exit stations were axisymmetric. Therefore, radial traverses were made at only five circumferential locations. These five circumferential locations were at equally spaced angles between 0 and 45° (see Figure 3). In addition to radial traverses, measurements were also taken to survey the profiles of the stator wake near the tip and near midspan downstream of the stator.

2.5. ACOUSTIC MEASUREMENTS

Acoustic measurements were taken at 12 points along a circular arc ranging from 0 to 110° at a horizontal distance of 48 in (1·22 m) from the cowl lip of the inlet. The microphone



(a)

(b)

Figure 3. Aerodynamic measurement location: (a) side view; (b) front view.

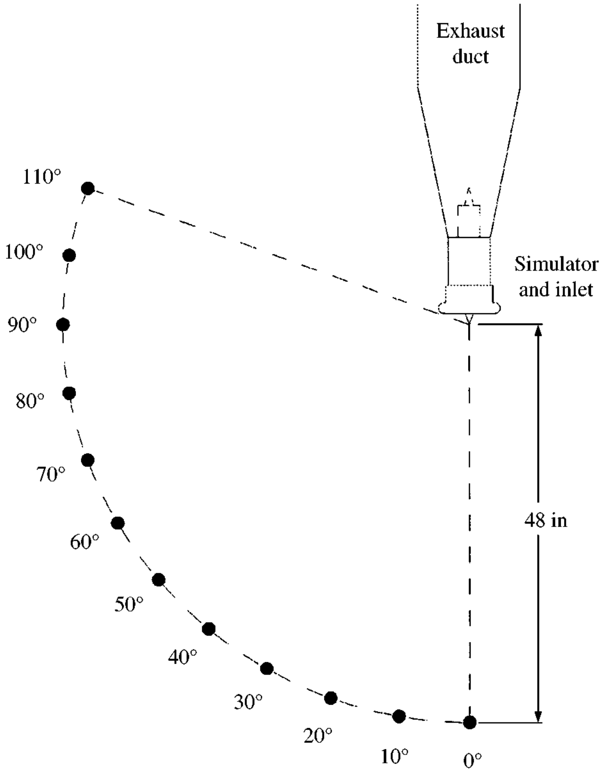


Figure 4. Acoustic measurement locations; ●, microphone locations.

was elevated 48 in (1·22 m) from the floor for all measurements. Figure 4 illustrates the acoustic measurement locations.

A Bruel and Kjaer Model 4136 condenser microphone was used for all acoustic measurements. The microphone has a 0·25 in (6·4 mm) diameter diaphragm which provided linear response up to 30 000 Hz. A Bruel and Kjaer Model 2030 spectrum analyzer was then used to process the signal from the microphone. The signal analyzer produced a narrow band frequency spectrum from 0 to 25 600 Hz with a bandwidth of 32 Hz. From each of these spectrums, the sound pressure level of the blade passing frequency (BPF) and the overall sound pressure level (OASPL) were obtained. The overall sound pressure level is the summation of the sound pressure levels for the frequencies from 0 to 25 600 Hz. To account for the variation inherent to these acoustic measurements, 20 spectra were linearly averaged to produce one measurement for a given position, configuration, and speed. Next, five of these measurements were taken and averaged to yield the sound pressure level for a particular position. In total, the sound pressure level was measured 100 times and averaged to yield each data point.

2.6. TEST MATRIX

These experiments were conducted at three different simulator speeds: 30 000, 50 000 and 70 000 r.p.m. Each of these speeds was tested with and without blowing. For 30 000 and 50 000 r.p.m. cases both aerodynamic and acoustic data were taken. At 70 000 r.p.m. only acoustic data were taken.

3. RESULTS AND DISCUSSION

3.1. AERODYNAMIC RESULTS

Flow distortion at the fan face is a significant contributor to fan noise. The use of wake management in this research to re-energize the stators' wakes will reduce the flow distortion at the fan face. Figure 5 compares the Mach number contours with and without blowing at 30 000 r.p.m. It can be seen from Figure 5 that a significant portion of each stator wake is removed with the use of trailing edge blowing. Similar results are obtained for 50 000 r.p.m. A distortion parameter, based on the Aerospace Recommended Practice (ARP 1420) by the Society of Automotive Engineers, was calculated to give the overall circumferential distortion at the fan face. Results show that the circumferential distortion parameters for both 30 000 and 50 000 r.p.m. were reduced by about 30% when blowing was used for wake filling [10].

Probe traverse data taken perpendicular to the stators provide the most insight as to how the trailing edge blowing affects the stator wakes. Figure 6 shows the total pressure profiles behind the stators with the simulator running at 30 000 r.p.m. These traverses were

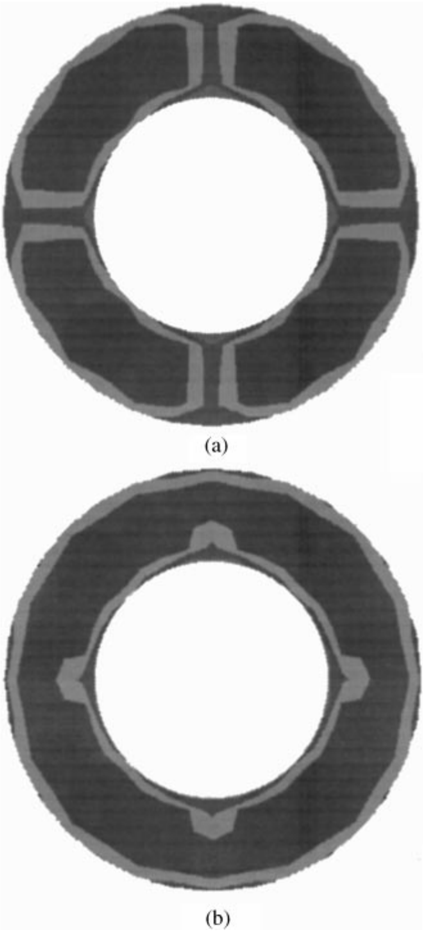


Figure 5. Mach number contour plots: (a) without blowing, (b) with blowing: ■ 0·150; ■ 0·140; ■ 0·130; ■ 0·120; ■ 0·110.

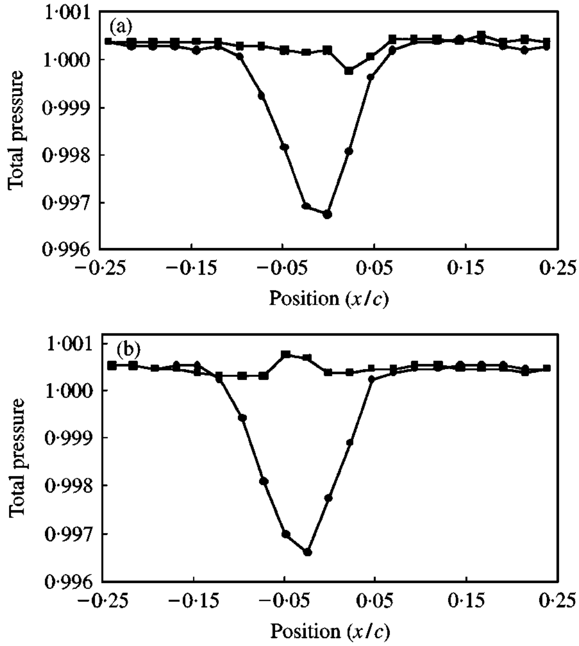


Figure 6. Total pressure profiles behind stator: (a) tip station, (b) midspan station; ●, without blowing; ■, with blowing.

measured at 25 (near tip) and 50% span. Note that the use of trailing edge blowing is very successful in wake filling. The blowing pressure was chosen so that optimal wake filling is achieved, with minimum over-shoot that may cause undesirable effects.

Noise from a fan is a function of blade loading. In order to draw any conclusions about whether trailing edge blowing from the stators reduced the radiated noise, it is necessary to determine the effect of the blowing on the fan operating point. Total pressure measurements were made at the fan exit in order to determine the total pressure ratio for the fan. Results show that within experimental uncertainty, using trailing edge blowing did not alter the fan operating point. This should not come as a surprise, since it was estimated that only less than 1% of mass flow through the turbofan simulator is added due to the trailing edge blowing.

3.2. ACOUSTIC RESULTS

A sample acoustic spectrum comparing the effect of trailing edge blowing with the baseline of no blowing is shown in Figure 7. The spectrum was taken with the simulator running at 30 000 r.p.m. and the microphone was located at the 90° position. As is common among fans with subsonic blade tip velocities, the blade passing tone dominates the spectra at 9 kHz. The first harmonic of the blade passing frequency is also prominent at 18 kHz. As expected, trailing edge blowing reduced the blade passing tone SPL, as well as the first harmonic. The use of trailing edge blowing had little effect on the broadband noise.

The key results of the experiment are presented in the directivity plots. Figure 8 shows the effects of trailing edge blowing on the radiated tone and overall sound pressure level at 30 000 r.p.m. Note the significant reduction of the tone SPL at some locations. There was a maximum reduction of 8·9 dB in the tone SPL at the 80° location. Between 30 and 90°

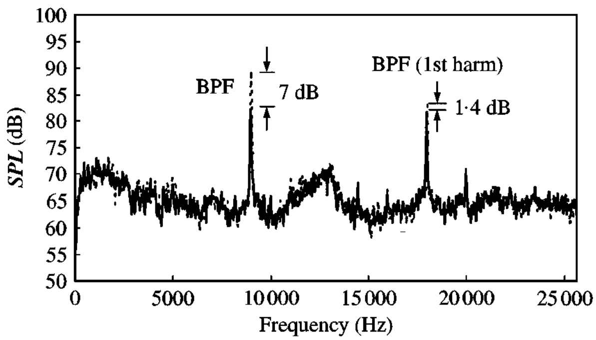


Figure 7. Sample acoustic spectrum at 30k r.p.m.: - - -, without blowing; ——, with blowing.

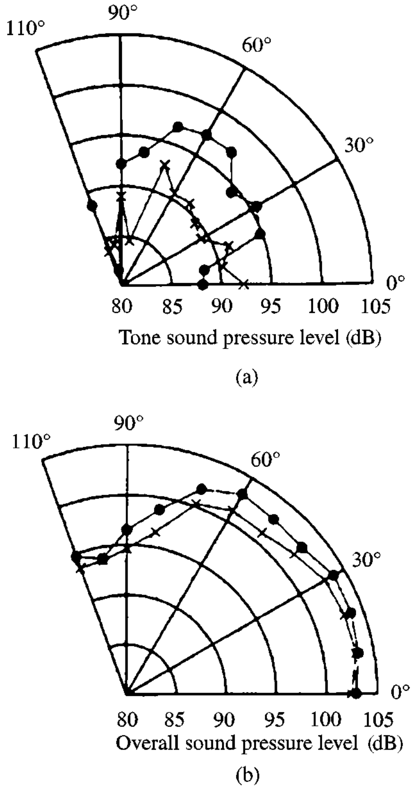


Figure 8. Directivity plots for 30k r.p.m.: (a) tone sound pressure level, (b) overall sound pressure level; ●, without blowing; ×, with blowing.

position, the average reduction was 6·2 dB in tone. There was a small increase in tone at the 0° angular position. The reason for this is not yet known at this point. On average, the overall SPL was reduced by approximately 1 dB for all angular position, with as much as 2 dB reduction between 50 and 90°.

At 50 000 r.p.m., the average reduction in blade-passing tone from 0 to 110° was 2·6 dB, with a maximum reduction of 5·5 dB (Figure 9). On average, the overall SPL was reduced by less than 1 dB at each location. At 70 000 r.p.m., the average reduction in blade passing

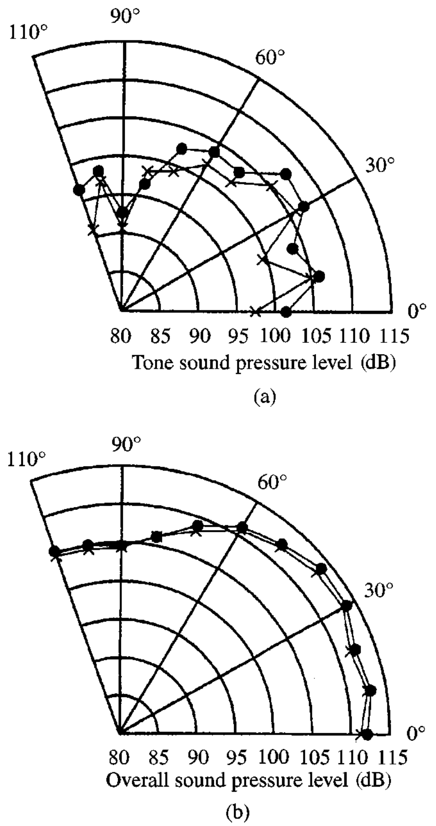


Figure 9. Directivity plots for 50k r.p.m.: (a) tone sound pressure level, (b) overall sound pressure level; ●, without blowing; ×, with blowing.

tone was 1·2 dB, with a maximum reduction of 2·6 dB. The overall SPL at 70 000 r.p.m. was reduced by less than 1 dB at all positions.

There are two possible reasons as to why the reduction in tone was more dramatic at 30 000 r.p.m., as compared to results for 50 000 and 70 000 r.p.m. First, the current set-up for the blowing hole may not be providing enough blowing air to re-energize the wakes as the flow velocities increase with increasing fan speed. Secondly, as the tip speed of fan reaches supersonic Mach number, the noise-generating mechanism is dominated by a combination tone (buzz-saw noise), and trailing edge blowing for wake filling may not be an effective mean to reduce noise.

The turbofan simulator has 18 fan blades and 26 outlet guide vanes (OGV). At 30 000 r.p.m., the (8·0) mode produced by rotor/OGV interaction is cut-off and the only modes which propagate to the far field are due to the interaction of the four upstream stators with the rotor. Not surprisingly, this speed showed the greatest noise reduction from trailing edge blowing.

4. CONCLUSIONS

This study was a first step toward investigating the aeroacoustic effects of blowing from the trailing edges of stators in an aircraft inlet. A reduced number of stators (four) was tested in a 1/14 scale model inlet attached to a 4·1 in diameter turbofan simulator. These tests were performed at three different speeds, 30 000, 50 000 and 70 000 r.p.m.

The acoustic results show notable reductions of the blade passing tone sound pressure level (SPL) at all test speeds. In addition, the overall SPL was reduced at nearly all measurement locations. The aerodynamic results indicate the ability of trailing edge blowing to re-energize the stators' wakes. In doing so, the circumferential distortion was clearly reduced. The most dramatic noise reductions were recorded at 30 000 r.p.m. The results at this speed are of particular interest because the interaction between rotors and the fan stators in the simulator was cut-off, leaving only the upstream stator/rotor interaction present in the inlet. There was a maximum reduction of 8·9 dB in the tone SPL, and an average of 6·2 dB between the 30 and 90° microphone locations. The overall SPL was reduced by approximately 1 dB at each microphone position, and was not increased at any measurement location by the trailing edge blowing.

The results from this experimental research clearly demonstrate that trailing edge blowing from upstream stators can be effective in reducing unsteady stator/rotor interaction and the subsequent forward-radiated fan noise. These results encourage more in-depth investigations using different inlet geometries, increased stator counts, and more advanced blowing techniques. Follow-on work in applying active control to the current set-up is documented in a separate paper by Rao *et al.* [11]

ACKNOWLEDGMENT

This research was supported by the Mechanical Engineering Department at Virginia Tech. The authors are indebted to Mr Woodie Woodward of NASA Lewis Research Center for many useful discussions. The authors are grateful for the assistance offered by Drs J. Fleming and S. Li, Mrs Carol Hanuska and Mr Nikhil Rao.

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