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Fluidic Actuation for Aeropropulsive Acoustic Improvements

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Abstract

Experiments were performed in NASA's SW-2 cascade facility to compare three turbine blade trailing edge actuation concepts to a turbine blade with no trailing edge treatment. At a Reynolds number of 10^5, trailing edge pulsed ejection using fluidic oscillator devices was shown to fill the momentum deficit in the wake more uniformly than other actuators tested, with expected benefits for tonal noise in engine fans. Furthermore, pulsed ejection was found to alter the acoustic signature of the wake to reduce broadband noise. In some locations in the wake, spectral components of velocity were found to be reduced by 2 to 5 dB across nearly all frequencies. Trailing edge pulsed ejection is established as a feasible concept to alter both tonal and broadband noise emissions from aircraft engines.

Introduction

The current trends in engine development point to a continued transition to higher bypass ratios and smaller cores. As noise from other components is relatively diminished, fan noise will become an even greater proportion of the total engine noise. Fan noise can be explained largely by the interaction of upstream rotor wakes with downstream components. Flow passing over fan blades loses energy and develops complicated secondary structure, creating a low-velocity, rotating, unsteady wake downstream. When this wake impinges on downstream engine components, the unsteady fluctuations are manifested as pressure fluctuations which radiate outward as sound. Figure 1 shows the sources of noise from a typical 1990s turbofan engine (Ref. 1). It is clear from the figure that the majority of noise is generated by the fan.

For Fixed Wing aircraft, the fan noise and noise from the aft turbine components are the dominant sources that contribute to noise that is considered undesirable to humans (Ref. 1). As bypass ratios grow, the percentage of engine noise attributed to the core flow is growing relative to fan noise. In order to control these sources of noise, it is necessary to develop strategies to reduce wakes and nonuniformities in the flow. Flow control has been investigated in the past on low pressure turbines and compressors using synthetic jets, vortex generating jets and dielectric barrier discharge plasma actuators. Grooves and ribs on blades have also been investigated. For the trailing edge, chevrons and other forms of serrations have been attempted on fan blades but these are sensitive to local flow conditions. Halasz (Ref. 1) investigated the use of steady trailing edge blowing (TEB) for fan blades to reduce tonal sources of noise.

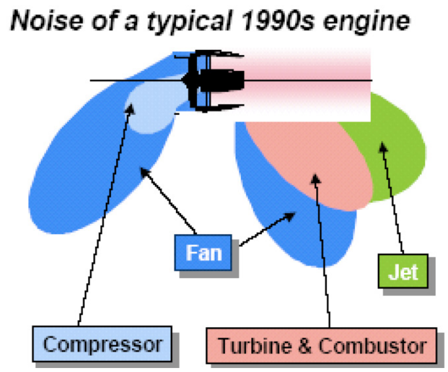


Figure 1.—Noise sources form a turbofan engine (Ref. 1).

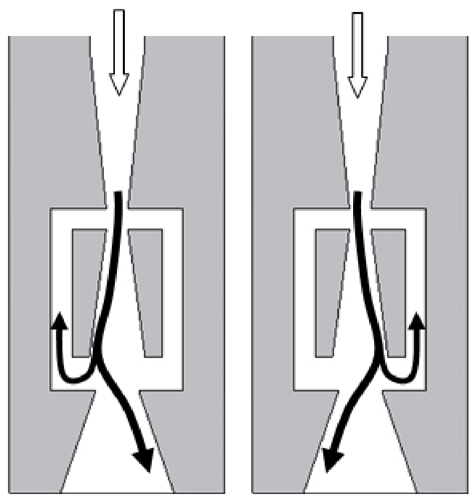


Figure 2.—Schematic and functioning of a fluidic sweeping actuator.

High-frequency unsteady or pulsed blowing has been suggested as a superior method, in particular due to decreased mass flow requirements compared to steady blowing. However, this concept has remained largely unexplored due to lack of suitable actuation technology.

The objective of trailing edge pulsed blowing is twofold. It should be effective in mixing out the blade wake, which should reduce tone noise generated by the interaction of rotor wakes with downstream stators. It should also cause the breakdown of large turbulent structures in the wake into smaller ones with the attendant benefit of shifting the rotor-stator interaction broadband noise content from low to high frequencies. This is beneficial since high frequency noise is more easily absorbed by the atmosphere. This leads to lower noise levels for humans around airports.

The fluidic oscillator is a recently developed actuator with the potential to be used in pulsed trailing edge blowing. Fluidic sweeping jet actuators with no moving parts are based on bi-stable states of a jet of fluid in a cavity caused by a specially designed feedback path as shown in the schematic of Figure 2. A jet of fluid attaches to one of the two sides of a surface due to the “wall attachment”; commonly known as the “Coanda” effect. The pressure distribution in the cavity is accordingly changed and the feedback channel transmits this pressure differential back to the point of the jet separation thus deflecting the jet to the other side. This cycle is repeated on the other side of the cavity through the feedback channel on the right thus producing an oscillating jet at the exit of the cavity. A slight modification at the exit of the actuator (a splitter plate) is required to produce alternately pulsing jets at the exit instead of a single sweeping jet. Thus, these devices do not need external signals or actuation to produce oscillating jets.

Frequencies from 1 to 10 kHz have been obtained with meso-scale (nozzle sizes in the range of 200 μm to 1 mm) fluidic actuators with very low mass flow rates of the order of (10^{-3} Kg/sec) (Ref. 2). Figure 3 shows the frequency as a function of mass flow characteristics of a fluidic actuator (1.69 by 0.95 mm exit area) used by Raman et al. (Ref. 3) in their experiments on cavity noise control.

Advanced Fluidics has recently developed actuator designs that can be integrally fabricated into airfoil sections using 3-D rapid prototyping technologies. An example of an integrated pulsing jet fluidic actuator array fabricated for phase I experiments is shown in Figure 4 with the proprietary designs of the actuators masked. Alternate methods of CNC milling in parts and assembly will also be explored if needed.

Sweeping actuators have been used for separation control on multi-flap airfoils (Ref. 4) and on compressor blades (Ref. 5). It has been shown by Culley et al. (Ref. 5) that pulsed ejection at the trailing edge of a stator vane can reduce the separation on a compressor stage. Both solenoid driven oscillations and fluidic diverters were used for the study. Woszildo et al. (Ref. 4) conducted a parametric study of sweeping jet fluidic actuators for a multi-flap airfoil. They found that actuator spacing, frequency and amplitude had a significant role in reducing separation.

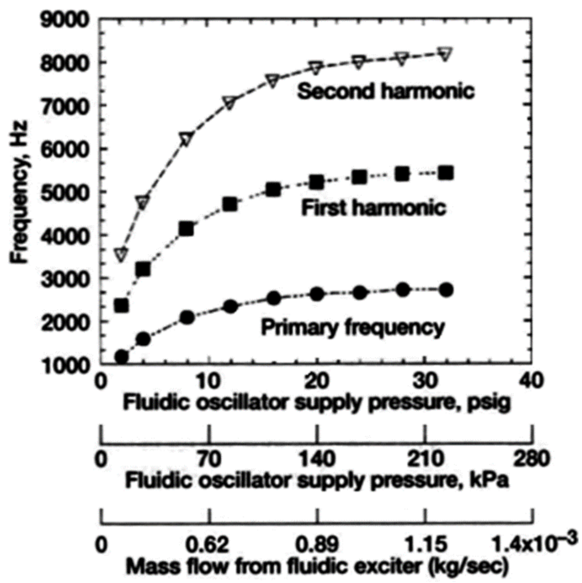


Figure 3.—Frequency and mass flow characteristics of a sweeping jet (Refs. 2 and 3).

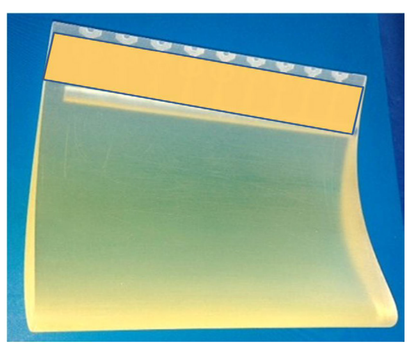


Figure 4.—VSPT blade with trailing edge ejection oscillators.

Setup of Experiment

Testing occurred in the SW-2 facility wind tunnel in the Engine Research Building at NASA Glenn Research Center (GRC). The test section was redesigned to accommodate testing of flow control test articles. The test section, shown in Figure 5, includes a nine-blade turbine cascade with a nominal blade turning angle of 90°. Air flow is controlled by a throttle valve connected to a vacuum supplied by GRC Central Services. A removable ceiling plate allows for rapid exchange of test articles. Two slot locations in the ceiling plate allow wake pressure, hotwire, and thermocouple surveys. The slots run parallel to the exit plane of the turbine cascade and are located at 25% and 75% axial chord length (C_x) downstream of the exit plane. A 3-axis actuator system controls the location of the probe during wake surveys. Thurman et al. (Ref. 6) describe the operation of this facility. In our testing, data was collected from a single-wire hotwire probe reading the streamwise component of velocity. Data were only taken in the wake of the middle blade, and the other 8 were not modified for trailing edge blowing.

The blades used in the wind tunnel are mid-plane extrusions from the 50% span cross section of a Rolls Royce Variable Speed Power Turbine (VSPT) blade (Ref. 6). Four blades based on this geometry were tested: one unaltered (no trailing edge treatment), one with straight holes in the trailing edge, one with sweeping fluidic actuators in the trailing edge, and one with pulsed fluidic actuators in the trailing edge. All blades have a 0.127 m span and a 0.106 m axial chord length, C_x. In blades with TEB, nine actuators were distributed evenly across the span. The two fluidic blades were designed and manufactured by Advanced Fluidics, LLC. All blades were created using 3-D additive manufacturing, and trailing edge actuators were manufactured directly into the blades. In addition, a supply plenum was cut through each blade near the trailing edge to provide blowing air to the actuators. The plenum was attached to an external source of pressurized air by a hole in the bottom of the blade.

In this paper, all tests were run an inlet velocity of 15.24 m/s. The Reynolds number defined by the inlet velocity and axial chord was 10^5. For tests with blowing, the supply pressure was adjusted to achieve a volume flow rate of 0.0018 kg/s through the plenum (~0.005% of passage flow).

Figure 5.—SW-2 wind tunnel facility.

Results and Discussion

Hotwire wake surveys are presented as time-averaged velocity contours in Figure 6, in a plane 75% C_x downstream of the trailing edge. All velocity contours are normalized by the freestream velocity in the survey plane. Velocity contours indicate the effectiveness of wake filling achieved by each test article. Values below 1 indicate a velocity deficit compared to the freestream, while values above 1 indicate a velocity surplus caused by overblowing. The left of each figure is the suction side, and the right is the pressure side.

Part (a) of the figure shows the normalized velocity contour for the baseline case of no TEB. The wake deficit is clearly visible, with velocities reaching as low as 80% of the freestream value near mid-span. The overall pitchwise extent of the wake is roughly 15% of the pitch. Larger low-velocity regions are visible near the ends of the blade span. These regions are caused by horseshoe vortices, an effect of flow interacting with the endwalls. These structures are not the focus of this study and will only be discussed briefly. However, they are significant sources of noise as well as energetic losses in the flow.

Part (b) of the figure shows the normalized velocity contour with TEB provided by an array of 9 straight hole actuators. The array is supplied with 0.0018 kg/s of blowing air through the plenum, as is the case for all test conditions with blowing presented in this paper. The wake deficit is clearly improved by the trailing edge blowing. In the mid-span region, the velocity behind the blade is equal to the freestream value, indicating that the wake is fully filled. However, directly behind the actuators are regions of large velocity surplus, showing that excessive air was injected (overblowing). The magnitude of wake inhomogeneity determines the level of interaction noise, so a velocity surplus is as detrimental as a deficit. It should be noted that the jets do not coincide precisely with the wake, which results in an inefficient use of blowing air. If the TEB direction were adjusted to match the exit angle of the blade, it is possible that a similar degree of wake filling could be achieved with less blowing. Future tests should examine the optimal blowing rate in more detail.

Part (c) of the figure shows the normalized velocity contour with TEB provided by an array of 9 sweeping fluidic actuators and the same blowing rate. The results are largely similar to those of the straight hole actuators. The wake velocities are slightly lower than those obtained with straight holes, but are comparable within the error of the experiment. Overblowing is evident, as large velocity surpluses exist in the jets of the actuators. Again, the jets are offset from the wake, and it is possible that similar results could be obtained with a lower blowing rate if the angle were adjusted.

Part (d) of the figure shows the normalized velocity contour with TEB provided by an array of 9 pulsed fluidic actuators and the same blowing rate. The wake is again filled, although to a lesser extent compared to the straight and sweeping actuators. However, the high-velocity jets behind the actuators are strikingly absent. It appears that the pulsed jets mix out into the main flow effectively, such that by 75% C_x downstream of the trailing edge, there are no localized high-velocity regions. Thus, the pulsed fluidic actuators appear able to fill the wake without introducing high-velocity disturbances. This is an important result for noise reduction. However, it must be noted that an anomaly exists in these data. The low-velocity structure at the bottom of the span is unusually large, and it is even more visible in the plots of turbulence intensity below. The asymmetry of the flow field suggests that an error exists in the experimental setup. One possible explanation is that some portion of the blowing air intended to feed the plenum instead leaked into the main flow. This would not only cause anomalous flow near the bottom of the span, but also starve the actuators of blowing air, which would decrease the strength of the jet. Nevertheless, the result stands that the wake deficit is significantly improved without the introduction of high-velocity jets. It remains to be seen whether the blowing rate was artificially decreased by leakage from the plenum inlet, and how the other actuator types would perform at a similar blowing rate. Also, it is likely that the pulsed jet directions are offset from the wake, due to the similarity in construction to the sweeping fluidic blade.

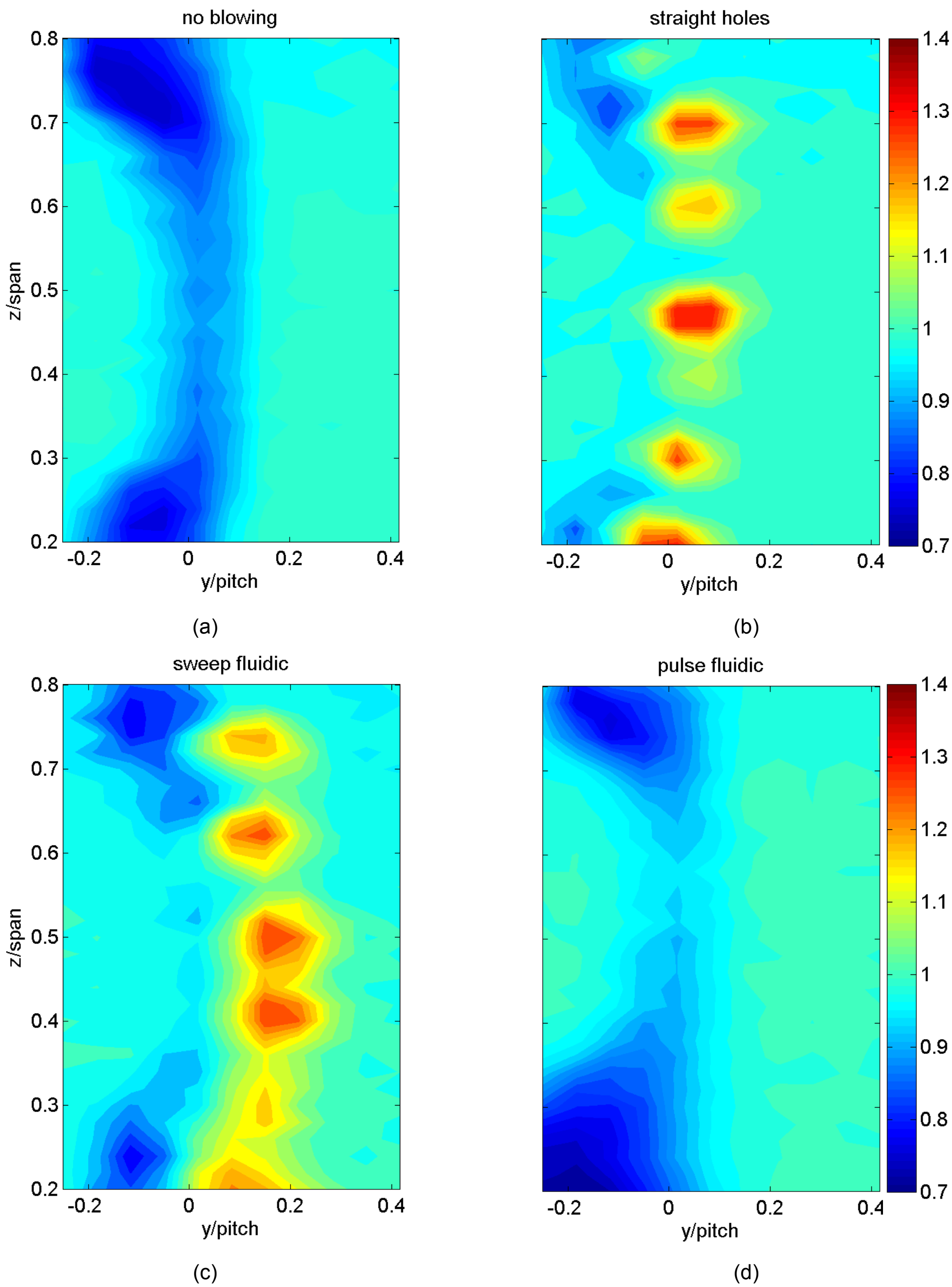


Figure 6.—Time-averaged velocity at 75% axial chord downstream of TE. Velocities are normalized by the free-stream value in the survey plane.

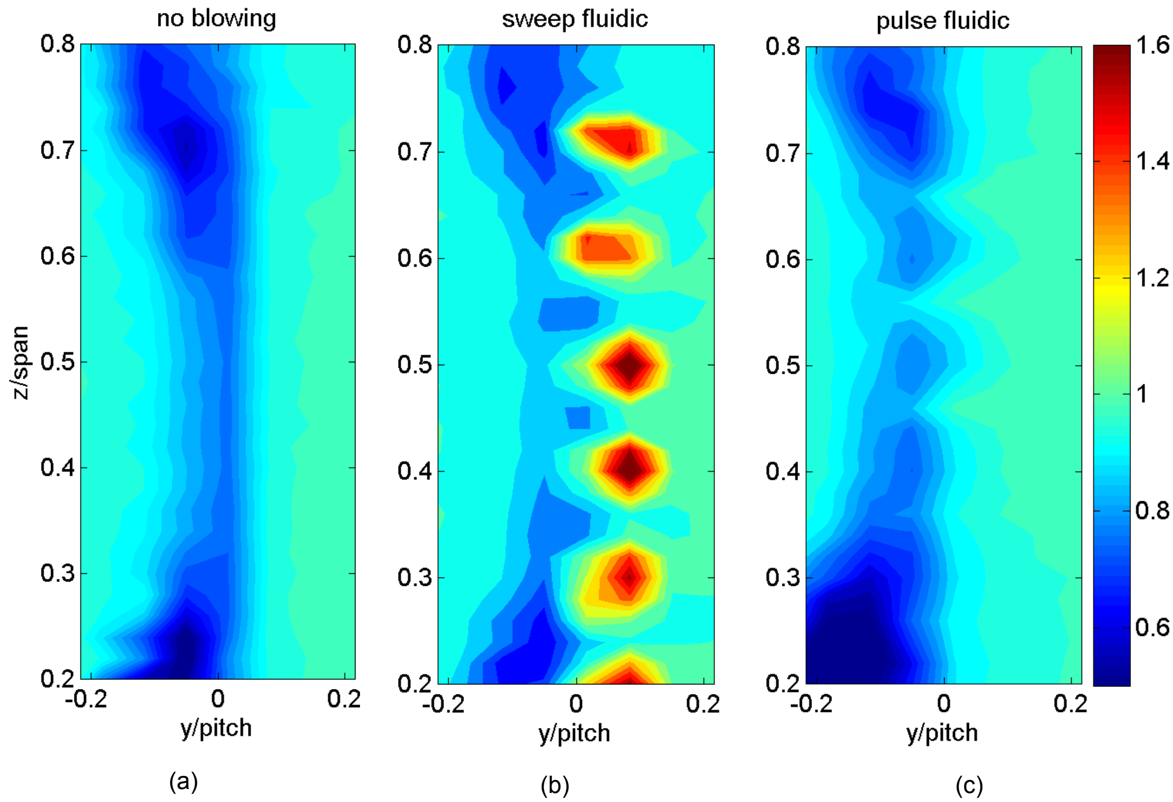


Figure 7.—Time-averaged velocity at 25% axial chord downstream of TE. Velocities are normalized by the free-stream value in the survey plane.

Time-averaged velocity contours in the plane $0.25C_x$ downstream of the trailing edge are presented in Figure 7. The test blade with straight holes was not tested in this position. Otherwise, the conclusions are very similar to those obtained at $0.75C_x$. Even at this further upstream location, the jets from the pulsed actuators are entirely mixed out. The sweeping jets are still visibly offset from the wake region. The wake deficit shows less response to the actuators at this station, likely because the high momentum fluid has had less time to mix into the wake.

Turbulence intensity was also calculated from the hotwire data. Contours of turbulence intensity in a plane $0.75C_x$ downstream of the trailing edge are presented in Figure 8 for all four blade types. The data at $0.25C_x$ lead to similar conclusions and are thus omitted. These calculations are from the same hotwire data, so that the blowing rate is again 0.0018 kg/s.

Turbulence intensity is useful to quantify the level of unsteadiness in the flow, and to visualize anomalous areas of the flow. Compared to the baseline configuration, the blades with straight hole and sweeping fluidic actuators have significantly higher turbulence intensity. The sweeping actuators, in particular, seem to create a region of high turbulence larger than the region of velocity deficit in the wake. The flow through the fluidic oscillator is quite complicated, which introduces large turbulent fluctuations into the flow.

The blade with pulsed fluidic actuators has comparable or even lower turbulence intensity than the baseline, in most regions. Mathematically, the turbulence intensity is just the normalized RMS of the velocity fluctuations about the mean, which is in turn equal to the RMS of the non-zero-frequency Fourier components of the signal. Thus, the pulsed fluidic blade must have less energy stored in its unsteady modes—a fact that will be examined more thoroughly in the next section. Physically, this shows that the pulsed actuators help diminish the activity of unsteady flow structures.

However, the anomalous region at the bottom of the span shows turbulence intensity values up to 23%, far higher than anywhere else in the flow. The magnitude of this difference supports the hypothesis of an experimental error, perhaps a leak in the blowing air intended to feed the plenum.

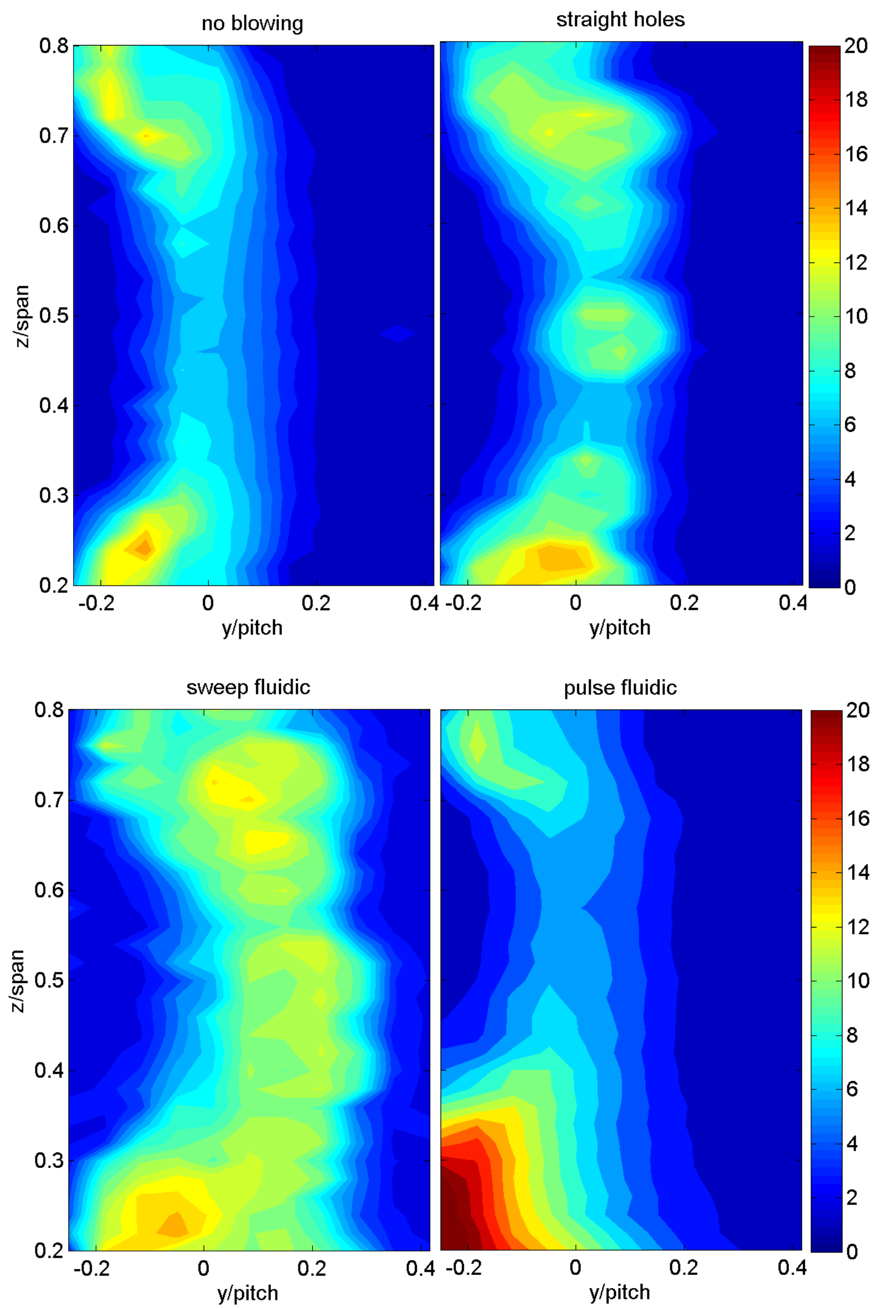
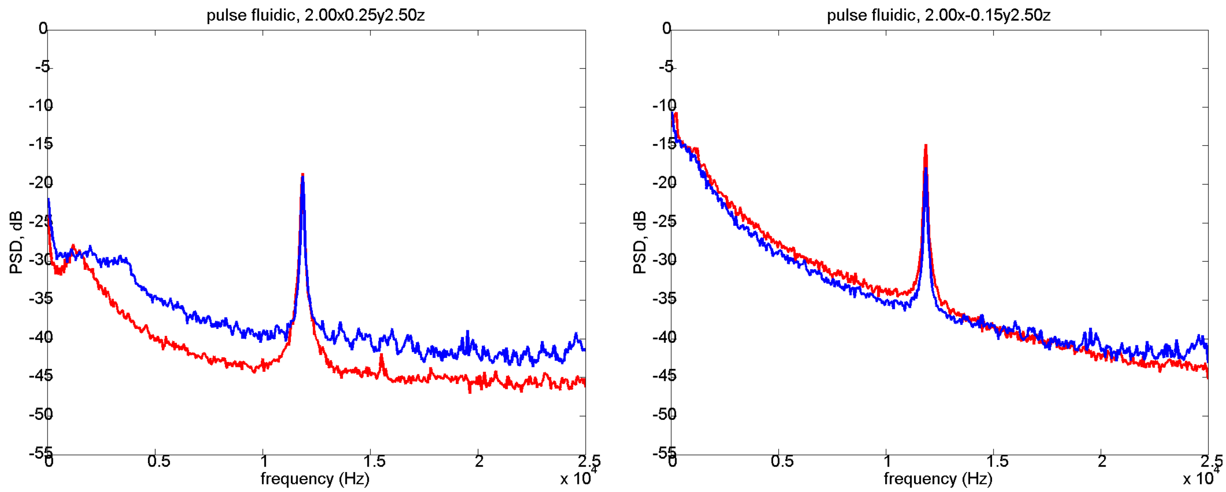


Figure 8.—Time-averaged turbulence intensity at 75% axial chord downstream of TE.



(a) (b)

Figure 9.—Power spectral density (PSD) representative figures at two locations. Blue curves are data from blades without blowing, and red curves are from blades with pulsed actuators. Part (a) is on the pressure side of the blade, and part (b) is on the suction side. Both profiles are taken along the mid-span plane.

Next, we analyze the broadband composition of the velocity fluctuations. The power spectral density (PSD) was calculated from the velocity time series at each spatial point surveyed. In this paper, only a few points were studied, all at a distance of $0.25C_x$ downstream of the trailing edge and near the center of the wake at (y,z) = (0,0). These results are displayed in Figure 9. Similar trends are observed at other points in the flow, but a full spatial analysis is reserved for future work. To improve the signal to noise ratio, the time series was split into intervals of 1024 points each, whose discrete Fourier transforms were evaluated separately, giving a bandwidth of 12.2 Hz. These magnitude of these spectra were then averaged to give a clean spectrum.

Only the pulsed actuator blade showed markedly lower broadband noise compared to a blade without blowing. These benefits appear to be confined to the pressure side of the blade, with slightly decreased performance observed on the suction side. Part (a) of the figure shows PSD curves for both a normal blade and the blade with pulsed actuators from data on the pressure side of the blade. On the pressure side, broadband values are reduced by 2 to 5 dB across nearly all frequencies. This can be expected to translate into a reduction of broadband noise emitted from the fan. The zero frequency is not shown, as this represents the steady part of the signal. However, the zero-frequency component (~1.2 Hz) is higher for the case with blowing, which accounts for the higher mean velocities as seen in Figure 7. Part (b) of Figure 9 shows PSD curves for the same blades on the suction. Here, values for the blade with actuation are to 2 dB higher except above frequencies of about 20 kHz.

Future Work

This paper characterized the performance of two types of fluidic oscillators as actuators for trailing edge blowing. Only a limited range of test conditions were attempted, leaving the possibility for further optimization of the concept. Possible targets for optimization include the size, frequency, and sweeping direction of the fluidic oscillators. Additionally, future experiments should alter the blowing direction of trailing edge actuators to blow directly into the wake. Further validation may be required to assess the performance of pulsed fluidic oscillators due to the unexplained anomalous results near the bottom of the span. Fluidic devices that have frequencies independent of flow rate may be beneficial if particular frequencies need to be maintained regardless of flow conditions. An example of this is shown in Figure 10. Here a Helmholtz resonator that can be tuned to resonate at a fixed frequency is used to perturb the flow entering the inlet and thus cause a fluidic sweeping or pulsing at the exit.

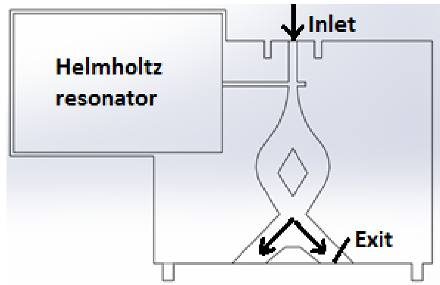


Figure 10.—Helmholtz resonator driven fluidic pulser or sweeper (Ref. 7).

Conclusions

There appears to be merit from trailing edge blowing using fluidic oscillators. The pulsed fluidic oscillator shows great promise for reducing both tonal and broadband noise from an engine. Compared to traditional trailing edge holes, pulsed ejection appears to be able to fill the wake while mixing out the velocity surplus of the jet more effectively. Furthermore, application of pulsed ejection shows promise in reducing unsteady velocity components in the wake. These results suggest that further analysis of fluidic oscillator trailing edge blowing should be performed. Future studies should vary pulse and sweep frequency independent of mass flow through the devices.

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