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Summary

Detailed laser Doppler velocimeter flow field measurements were made upstream of two fans, one forward-swept and one aft-swept, in order to learn more about the shocks which propagate upstream of these rotors when they are operated at supersonic tip speeds. The blade-to-blade variations in the flows associated with these shocks are thought to be responsible for generating Multiple Pure Tone (MPT) noise. The measured blade-to-blade variations are documented in this report through a series of slideshows which show relative Mach number contours computed from the velocity measurements. Data are presented for the forward-swept fan operating at three speeds (corresponding to tip relative Mach numbers of 0.817, 1.074, and 1.19), and for the aft-swept fan operating at two (tip relative Mach numbers of 1.074 and 1.19). These LDV data illustrate how the perturbations in the upstream flow field created by the rotating blades vary with axial position, radial position and rotor speed. At those radial locations at which shocks do not form on the blades, a strong disturbance is generated just upstream of the leading edge, but this disturbance decays exponentially toward zero within a short distance (less than one axial chord) of the leading edge. At those radial locations at which shocks exist, the variation in the disturbance with upstream distance is much more complicated. When the shocks are free to propagate upstream of the blades there are two distinct decay regions in the upstream flow: 1) a rapid-decay region just upstream of the leading edge in which the rate of decay varies inversely with the relative flow speed and 2) a region further upstream in which the decay is much more gradual and not always monotonic. The amplitude of the disturbance generated by a propagating shock at a given location upstream was found to depend upon whether the shock bends around the leading edge of the adjacent blade. The disturbance amplitude can decrease as rotor speed is increased if the shock is pushed downstream so that it transitions from being a normal shock propagating straight out into the upstream flow to an oblique shock which bends around the leading edge of the adjacent blade. At the highest tested speed, the forward-swept fan was found to swallow the passage shocks occurring in the tip region of the blades. Despite the fact that the shocks were swallowed, a relatively strong disturbance was still present in the flow upstream of the tip. The flows just upstream of the two fans were found to be quite different at the highest test speed due in large part to the fact that the forward-swept fan swallowed the tip shocks occurring at this speed, but the aft-swept fan did not. Despite these distinct differences just upstream of the two rotors, the two fan flows were much more alike a bit further upstream.

Introduction

Narrow band noise spectra of high bypass ratio turbofan engines operating at subsonic fan tip speeds normally contain tones at harmonics of the fan blade passing frequency (BPF). If the rotational speed of the fan is increased so that the relative tip speed becomes supersonic, extra tones normally appear in the spectra at multiples of the shaft rotational speed (multiples of the once-per-rev frequency). These extra tones have been attributed to blade-to-blade differences in the shocks propagating upstream of the fan blades. These blade-to-blade differences in the shocks occur due to slight differences in the blades and/or to differences in how the blades "seat" into the hub when they are spun up to speed. The differences in the shocks generate a pressure pattern upstream of the rotor which contains features which repeat on a once-per-revolution basis. Hence, a spectrum analysis of such a pressure field will contain harmonics of the once-per-rev frequency. Any such tones which occur at multiples of the once-per-rev frequency which are not also multiples of the blade passing frequency are known as multiple pure tones (MPTs).

One approach to reducing multiple pure tone noise focuses on attenuating the noise after it has been produced. There are a number of methods of doing this. One is to absorb the sound using an acoustic liner or splitter in the inlet duct (ref. 1). Unfortunately, adding these sound suppression devices can add weight and length to the inlet and/or reduce aerodynamic efficiency (ref. 2). Another method is to design the inlet so that the shock waves which produce the MPT noise are attenuated before they propagate out the inlet. The shocks can be attenuated by designing the inlet so that the flow speed at the inlet throat approaches Mach 1. As explained by Prasad et al., "the larger axial Mach number prolongs the residence time of the shocks in the duct, permitting them to decay further" (ref. 3).

The second approach involves designing the fan blades so that the shocks which normally form at high rotor speeds are reduced in strength or prevented from propagating into the inlet. This was the approach taken in a NASA-sponsored program conducted jointly by Bolt Beranek and Newman Inc. and AVCO Lycoming (ref. 2) during the 1970s. The high-speed QF-12 fan was developed under this program. The QF-12 blades were swept so that the flow normal to the leading edges was subsonic over its entire operating range. This design was effective in preventing the formation of most of the upstream propagating shocks normally associated with high speed operation and did result in reduced MPT noise; however, it did not meet aerodynamic performance goals.

More recently, the swept-rotor concept was investigated once again, this time as part of NASA's Advanced Subsonic Technology (AST) Noise Reduction Program. Two different fan models – one forward-swept and one aft-swept – were tested at the NASA Glenn 9 X 15 Foot Wind Tunnel. Both models were designed and built by Honeywell Engines and Systems (ref. 4). The forward-swept fan is known as the Quiet High Speed Fan (QHSF); the aft-swept design is a scale model of Honeywell's TFE731-60 engine. This test was conducted in order to demonstrate that the forward-swept model would produce less noise than the aft-swept when operating at high speeds. The goal was for the forward-swept model to be 6 EPNdb quieter than the aft-swept design when operating near the takeoff condition. One of the primary reasons why the forward-swept model was expected to generate less overall noise was that it was designed to create less multiple pure tone noise. The forward-swept fan was expected to generate less MPT noise since it was designed to swallow the shocks occurring within the tip region of the rotor, whereas the aft-swept fan was not. It turns out, however, that although the forward-swept model did meet the noise reduction goal, the reasons that it did had little to do with multiple pure tone noise. The multiple pure tone levels of both models were found to be much lower than the tones occurring at the blade passing frequency (BPF) and its harmonics. Acoustic mode measurements made using a rotating rake indicate that most of this BPF noise was due to rotor/strut interaction. The main reason that the forward-swept model met the noise reduction goal is that it produced less rotor-strut interaction tone noise. For more information on the acoustic results from this test see the papers by Dittmar et al. (ref. 5) and Heidelberg (ref. 6). The aerodynamic performance of these two models is discussed in a paper by Fite (ref. 7).

In addition to the acoustic and aerodynamic performance measurements made during this test, detailed flow field diagnostic data were also obtained. This test phase involved using a laser Doppler velocimeter (LDV) system to measure the flows generated by both the forward-swept and aft-swept fans. Although some LDV data were obtained downstream of these rotors, most of this testing concentrated on measuring the flows upstream of the two fans. The upstream flows were measured in order to learn more about the shocks propagating upstream of the rotors. As mentioned above, these shocks are responsible for generating multiple pure tone noise, and prior to the test it was anticipated that these two fans would generate different levels of MPT noise. These LDV data were obtained to help explain the anticipated differences in MPT noise.

The purpose of this paper is to present the LDV flow field data that were obtained upstream of these fans. These data were obtained via constant-axial and constant-radial traverses of the LDV probe volume. Data were obtained upstream of the forward-swept fan at three different speeds and upstream of the aft-swept rotor at two speeds. The data obtained from these surveys are presented in a series of slideshows which illustrate the blade-to-blade variations in the flows. The decay of the perturbations in the flow generated by the each fan are also depicted.

Apparatus and Procedure

Test Model

Figure 1 shows the 22-in. (55.9 cm) diameter turbofan model installed in the test section of the NASA Glenn 9 X 15 Foot Wind Tunnel. (Figures are available on a supplemental CD-ROM as a Microsoft PowerPoint (Microsoft Corporation) file (.ppt) and a Microsoft PowerPoint slideshow (.pps).) The model is shown here in the "performance" configuration, with a bellmouth inlet and variable flow exit nozzle (VFEN) installed. This is the configuration used during LDV testing, except that the VFEN shown in the photo was replaced with a flight (fixed area) nozzle.

The rotors and stators used during the LDV test phase are shown in figure 2. The aft-swept rotor was tested with aft-swept stators; the forward-swept rotor was tested with aft-swept stators that were leaned in the tip region. The aft-swept rotor/aft-swept stator combination represents a scale model of the fan stage found in the Honeywell TFE731-60 engine.

This stage was chosen as an example of a modern, conventional turbofan design. As such, it was to serve as a baseline model with which the more unconventional forward-swept model could be compared. The forward-swept fan, known as the Quiet High Speed Fan (QHSF), was designed to produce less fan noise while maintaining or improving on the performance characteristics of the aft-swept model. During the aerodynamic performance phase of this test it was determined that the forward-swept model outperformed the aft-swept model at the design point operating speed of 15357 RPMC in terms of fan pressure ratio (1.770 vs. 1.755), mass flow (98.28 vs. 97.97 lbm/s), and efficiency (87.1 vs. 83.7 percent). However, problems arose when the forward-swept model was operated near 75 percent of the design speed. At this speed the operability margin of the forward-swept fan approached 0 percent. In contrast, the aft-swept design maintained sufficient operability margin throughout the operating range. For more information regarding the aerodynamic performance results see ref. 7.

Laser Velocimeter System and Data Acquisition

In order to obtain these LDV data it was necessary to place part of the LDV system inside the wind tunnel next to the model. Figure 3 shows a photograph of some of the LDV hardware inside the tunnel. This photo shows LDV optics mounted onto a vertical breadboard which, in turn, is mounted onto a traverse system. The traverse system was used to move the LDV probe volume axially and radially inside the model. Only some of the LDV system optics are shown in this photo; other optics, including the laser, were located outside the test section. The laser beams were brought into the tunnel via fiber optic cables. The set-up shown here allowed two components of velocity – axial and tangential - to be measured simultaneously. Radial velocities were not measured during this test.

The contour of the internal flow path was not the same for the two fans, therefore two different windows had to be made to permit optical access to the internal flow. These two windows are shown in figure 4. The window shown at the top of the figure was used during testing of the forward-swept fan; that shown at the bottom was used with the aft-swept rotor. The window glass was slumped in a furnace so that the window contour would conform to the flow path of the model with which it was used. For each of these windows, the upstream edge of the glass was at the same physical axial location relative to the rest of the model hardware. Therefore, the location of the upstream edge of the glass (highlighted in the photos) was chosen as an axial reference location during the LDV testing. This axial location was chosen as the origin of the LDV reference frame such that locations downstream of the edge were considered to be in the negative x direction. The static position of the tip leading edge of the forward-swept blades was 4.85 in. downstream of the window edge (i.e., at x = –4.85 in.), while that of the aft-swept blades was 7.35 in. downstream (at x = –7.35 in.).

As the model was brought up to speed from the static condition it moved forward slightly in the test section (approx. 0.25 in. when going from 0 to 100 percent speed). The following procedure was implemented to keep the LDV system aligned with the model as the model changed speed:

Before a tunnel run the LDV probe volume was located at the upstream edge of the window. With the probe volume at this location, the readout of the LDV traverse table was set to x = 0.00 in.

The model was brought up to the desired test speed.

The LDV traverse table was moved so that the probe volume was once again at the window edge. The x-location of the traverse was recorded and the x-location readout was once again set to x = 0.00 in.

Using this procedure it was not only possible to keep the LDV system aligned with the model, but it was also possible to determine how far axially the model moved when going from the static condition to a given test speed.

The locations at which LDV measurements were made upstream of the two fans are shown in figure 5. Parts a, b, and c of this figure show the measurement locations corresponding to the fans operating at 9510, 12500, and 13830 RPMC, respectively. Throughout this report, these three speeds will be referred to as the “low”, “mid”, and “high” speeds, respectively. The low speed represents a subsonic rotor tip speed (913 ft/s, 0.817 tip Mrel), whereas the mid (1200 ft/s, 1.074 tip Mrel) and high speeds (1328 ft/s 1.19 tip Mrel) are transonic. At the low-speed condition data were only obtained upstream of the forward-swept fan, while at the two higher speeds data were obtained upstream of both fans. As can be seen in this figure, data were obtained via constant-axial and constant-radial traverses of the LDV probe volume.

Polystyrene Latex (PSL) particles were used as the LDV seed material. Figure 6 shows a photograph taken using a scanning electron microscope of a sample of the PSL particles. The length of the white line in the figure represents a distance of one micron. Based on this photo, the diameter of the PSL spheres is estimated to be approximately 0.7 micron. Due to the manufacturing process, the solid PSL particles are supplied suspended in water. Before introduction into the tunnel this solution is mixed with 190 proof ethanol. This diluted solution is then sprayed into the tunnel using a set of nine spray nozzles located approximately 80 feet upstream of the test section. The liquid evaporates in the time it takes to reach the test section, leaving behind the solid PSL seed on which the LDV data were obtained.

The individual velocity measurements are sorted into circumferential bins around the rotor using shaft angle encoders fed with the once-per-rev signal of the rotor. These encoders segmented the 360 degrees of rotor revolution occurring between two consecutive once-per-rev pulses into 1100 bins (50 bins per blade passage). Each time a velocity measurement was made, the encoder output was sampled to determine the number of bins generated since the occurrence of the previous once-per-rev pulse. The velocity and corresponding bin number were then stored in the computer as a data pair.

Data were acquired at each measurement location over many rotor revolutions until either a preset number of measurements had been acquired on the two LDV channels, or until the maximum time allotted for the data acquisition had elapsed. On-line data plots were used to determine the number of measurements required to accurately resolve the flows occurring within the individual blade passages. In general, the higher the unsteadiness in the flow, the greater the number of measurements required to resolve the flow. On average, more than 40,000 velocity measurements per component were obtained at each combination of measurement location and operating speed.

LDV Data Reduction

Figure 7 illustrates the data reduction process for a velocity component measured at a given location within the model. The top plot shows raw, unaveraged velocities sorted into the 1100 bins of a rotor revolution. The first step in the data reduction process is to simply find the average of the velocities occurring within each of the 1100 bins. The resulting ensemble-averaged mean velocity profile across the entire rotor rev is shown in part b of figure 7. The next step is to compute the standard deviation (rms) with respect to the mean of the velocities occurring within each bin. This standard deviation, which is a measure of the unsteadiness of the velocity component, will be referred to as the turbulent velocity. Figure 7c shows the resulting turbulent velocity distribution across the rev. Next, the data of the 22 individual blade passages are phase-lock averaged into one passage. The process of computing these average passage distributions from the data is illustrated in figure 7d for the mean velocities, and in 7e for the turbulent velocities. This step involves folding the mean and turbulent (rms) velocity data of the 22 individual blade passages into one passage and computing the mean within each bin. Velocity distributions which span the 50 bins of a single passage result from this process. A final step in the data reduction is to compute a circumferentially-averaged mean and turbulent velocity from the average passage distributions. The circumferentially-averaged mean velocity is found by determining the mean of the 50 average passage mean velocities, while the circumferentially-averaged turbulent velocity is the mean of the 50 average passage turbulent velocities.

Results

Forward-Swept Rotor Flow Field

Figure 8 shows contour plots of ensemble-averaged relative Mach number computed from LDV data obtained at axial station 1, upstream of the forward-swept rotor. Parts a, b, and c of the figure show contours corresponding to the rotor operating at tip relative Mach numbers of 0.817, 1.074, and 1.189, respectively. Throughout the following discussion these three speeds will be referred to as the low, mid, and high speeds, respectively. The view depicted in this figure is from downstream of the flow, looking upstream. A comparison of the subsonic (part a) and transonic tip speed (parts b and c) data reveals that the flow upstream of the rotor is much more uniform when the fan is operating at subsonic speeds. At low speed (part a), the flow exhibits a smooth, sinusoidal-like variation in the circumferential direction. In contrast, at the two transonic tip speeds (parts b and c) a sawtooth-like variation in the flow is illustrated. The steep gradients in the flow associated with this sawtooth pattern result from the shocks on the blades propagating upstream to this axial location. Note that at the high speed condition the sawtooth pattern does not extend all the way out to the outer case. This suggests that the shocks are swallowed inside the blade passages at those radial locations outboard of where the sawtooth pattern occurs. These data indicate that at the high speed condition the shocks are swallowed over approximately the outer 10 percent of the blade span.

Figure 9 shows a photograph taken after a wind tunnel run in which LDV data were acquired with the forward-swept fan operating at the highest LDV test speed (Mrel tip = 1.189). This photo shows the build-up of LDV seed particles on the suction side of the forward-swept blades. As can be seen in the photo there is a noticeable dividing line between where seed built up on the blades and where it did not. This line is thought to represent the location on the suction surface of the blade where a shock occurs when operating at this speed. Note that in the tip region the shock occurs relatively far downstream within the blade passage. This is further evidence that the shocks in the tip region were swallowed inside the blade passages when the rotor was operating at the high speed condition.

Although the contour plots presented above in figure 8 are useful for comparing the average-passage mean flows upstream of the forward-swept rotor at different speeds, they do not provide much good, quantitative information regarding the mechanism which creates multiple pure tone noise - the passage-to-passage variations in the flow created by the shocks. The slideshow presented in figure 10 is meant to provide this information. This slideshow presents the same data depicted in figure 8, but it does so by presenting only two blade passages of data at a time. Twenty-two different slides are presented—one for each of the 22 different passages. On each successive slide, a new blade passage of data is rotated into view. By stepping through the slides it is possible to see the passage-to-passage variations in the ensemble-averaged mean flow upstream of the forward-swept fan at each of the tested speeds. The plots presented for the two transonic tip speeds show that the shock location upstream of the rotor can vary significantly from one passage to the next.

The contour plots presented in the slideshow of figure 10 represent one way of illustrating the disturbance generated within the flow upstream of the rotor at these three different speeds. Another, more quantitative method of presentation is provided in the slideshow of figure 11. The plot at the center of each of these slides shows three circumferential distributions of relative Mach number—one for each of the three different speeds. The radial location at which each distribution was measured is indicated by the location of the dashed line overlaid on top the corresponding contour plot presented at the top of the slide. Although the contour plots only show two blade passages of data, the line plots presented at the center of the figure show the variation of relative Mach number across the entire rotor rev (all 22 blade passages). The first slide shows distributions corresponding to the outermost radial location; successive slides step radially into the flow. By stepping through the slides, it is possible to see how the relative Mach number distributions vary with decreasing radius. Based on these line plots the following observations can be made:

1) The subsonic tip speed data (shown in red) show the aforementioned sinusoidal circumferential variation in the flow, except in the outer 10 percent of the span where the sinusoidal pattern is a bit skewed.

2) Strong shocks are not seen in the mid-speed data (black) until about 90 percent span (about the fifth slide)

3) At mid-speed, the shocks are strongest from about 85 to 75 percent span (slides 6 through 9 of fig. 11); they then decrease in strength further inboard.

4) At the highest speed (blue), strong shocks aren't seen until about 80 percent span (slide 8 of fig. 11).

5) At the high-speed, the shocks reach their max strength at about 75 percent span (slide 9 of fig. 11), remain at about this strength through 65 percent span (slide 13 of fig. 11), and then decrease further inboard.

6) As stated above, the subsonic tip speed data show less blade-to-blade variations than the supersonic tip speed data.

The slides provided in figure 11 also show a plot in the upper-right-hand-corner of each slide being “built” as the slideshow proceeds. With each successive slide, three additional data points are added to this plot; these additional red, black, and blue data points represent the amplitude of the low, mid, and high speed relative Mach number distributions, respectively, shown on the plot at the center of the slide. When completely “built” (i.e., at the end of the slide show), this plot depicts the spanwise variation in the amplitude of the disturbance upstream of the rotor for each of the three different speeds. At the low-speed condition (red), the amplitude of the disturbance increases slightly with radius. At the mid-speed condition (black) the amplitude of the disturbance in the upstream flow is small inboard of r = 6 in.; increases almost linearly with radius between r = 7 and r = 9 in.; and then dips down to lower values in the tip region. In that part of the flow in which the amplitude increases linearly with radius (between r = 7 and r = 9 in.), the shocks are thought to propagate directly out away from the suction side of the blades such that their path is not altered (either bent or swallowed) by the adjacent blades. Further outboard, in the tip region the shocks do interact with the adjacent blades, and this interaction results in a lower amplitude disturbance upstream of the blade tips. At the high-speed condition, the trend with radius is similar to that at the mid-speed condition, but the region over which the disturbance increases linearly with radius does not extend as far outboard. Relative to the mid-speed condition, the low-amplitude tip region extends over a larger spanwise extent of the blade at the higher speed. This is likely due to the shock being pushed further back in the blade passage as the rotor speed is increased. When the shock is pushed downstream, it gets swallowed over a larger spanwise extent of the blade, resulting in a lower amplitude disturbance upstream of the rotor tip. It is thought that if the shocks in the tip region did not get altered by the adjacent blades (that is, if they were free to propagate out of the blade row without being bent or swallowed) then the almost linear relationship between the disturbance amplitude and radius shown in the mid-span region would continue to hold out to the outer case. This would result in a very high amplitude disturbance upstream of the blade tips, especially at the high-speed condition. The forward sweep of the blades prevents the shocks in the tip region from propagating freely out into the flow. This effectively reduces the amplitude of the flow disturbance upstream of the blade tips relative to what it would be if the shocks were not altered by the adjacent blades.

Autospectra computed from the circumferential distributions of relative Mach number are shown in the plots at the bottom of each slide presented in figure 11. Autospectra for each of the three speeds are shown, with the low-speed data in red, mid-speed in black, and high-speed in blue. The autospectra are plotted vs. shaft order over a range spanning from m = 1 to m = 22; m = 1 corresponds to the rotor once-per-rev frequency; m = 22 represents the blade passing frequency of the 22-bladed rotor. In order to clearly see the spectra of each of the three different speeds on the same plot, the low-speed data were shifted slightly to the left and the high-speed data were shifted slightly to the right of the corresponding m-order. By stepping through the slides one can see that for each speed there is a strong correlation between the size of the spike occurring at m = 22 (corresponding to the BPF frequency) and the amplitude of the corresponding relative Mach number "wave." Hence, one can think of the height of the BPF spike (m = 22) as a measure of the average amplitude of the flow oscillation at a given location and rotor speed. If the flows upstream of the blades were identical, then only this BPF spike would be visible in the spectrum plots. In other words, the spikes at shaft orders less than m = 22 (i.e., the sub-BPF spikes) exist only because of the blade-to-blade variations in the flow. In general, as the blade-to-blade variations in the flow increase, so does the overall height of these sub-BPF spikes. Hence, the average level of the sub-BPF spikes can be thought of as a measure of the blade-to-blade variations in the flow. This slideshow indicates that the blade-to-blade variations increase with rotor speed. The individual spectra plots also show that the BPF spikes are much higher than the sub-BPF spikes at most combinations of rotor speed and measurement location. This was found to be true for most of the data obtained during this test - not only for the forward-swept data shown here, but for the aft-swept data as well.

In addition to the surveys made within this constant axial plane, data were also obtained during constant radial surveys made upstream of the forward-swept fan. The schematic at the left of figure 12 shows the measurement locations at which constant radial surveys were made with the rotor operating at the high speed condition. Two surveys were made at this speed – one at a radius of 10.6 in., the other at a radius of 8.5 in. The plot at the right in this figure is a repeat of a plot shown previously in the slideshow of figure 11; it shows the spanwise distribution of the amplitude of the disturbance measured during the constant axial plane survey made at axial station 1 at the high-speed condition. The red horizontal lines overlaid on top of this distribution show the relative locations of the two radial surveys. As can be seen from this figure, the outermost survey was conducted at a location where the shocks were swallowed inside the blade passages; while the inner survey was conducted in that part of the flow where the strongest shocks were propagating upstream of the forward-swept blades.

The slideshow of figure 13 shows relative Mach number contours computed from data measured during the two constant radial surveys conducted upstream of the forward-swept rotor at the high-speed condition. The upper contour plot on each slide shows data measured at the outer location; the lower plot shows data measured at the inner location. The schematics at the left show the measurement locations corresponding to the data presented in the contour plots at the right. The relative Mach number data are plotted such that the x and y-axes correspond to the axial and circumferential directions, respectively. The range of the y-axis on each plot is 4.85 in. This circumferential distance is equivalent to 1.64 and 2.00 blade passages for the outer (top plot) and inner (bottom plot) radial locations, respectively. The view provided is from outside-looking-in such that the rotor blades would be to the left of the contour plots. These blades would rotate downward in this view, and the axial flow would be right-to-left. Each successive slide shows a new passage of data rotated into view. By stepping through the slides it is possible to observe the blade-to-blade variations in the flow. The bottom plots show the classic blade-to-blade variations in upstream propagating shocks which are often illustrated schematically in papers which discuss the origins of multiple pure tone noise (refs . 8 and 9). At the outer radial location the passage shocks are swallowed inside the blade passages, so any flow field nonuniformities shown in the top contour plots are not due to these shocks propagating upstream. Even though the passage shocks are swallowed at this radius, a disturbance still exists upstream of the blade tips and significant blade-to-blade variations in the flow still occur. These data indicate that swallowing the shocks within the blade passages does not completely eliminate the disturbance upstream of the rotor.

More details regarding the flows measured at these two radial locations are provided in the slideshow of figure 14. Each slide corresponds to a different axial location in the flow with the data obtained closest to the rotor shown first; successive slides then step away from the rotor. The plots presented at the center of each data slide depict circumferential distributions of relative Mach number; the plots presented at the bottom show the autospectra computed from these relative Mach number distributions. The axial location corresponding to the data presented on a given slide is indicated by the location of the black vertical lines overlaid on top of the two contour plots presented at the top of the slide. By looking at the circumferential relative Mach number distributions (the center plots) while stepping through the data slides, it is possible to see how the measured flow perturbation varies with increasing distance upstream of the rotor. The slideshow reveals that there is a significant difference in how the perturbation evolves at the two different radial locations. Apparently, this evolution depends upon whether or not the shock occurring at a given radial location is swallowed inside the blade passage. At the outer radial location, where the shock is swallowed, the following observations can be made:

1) The amplitude of the flow disturbance starts out relatively low near the blade and remains practically constant with increasing distance upstream of the rotor.

2) Just upstream of the leading edge, the individual blade-to-blade relative Mach number distributions do not show the characteristic rapid drop-off associated with a shock wave.

3) Further upstream, however, these distributions take on the characteristics of a shock pattern (i.e., a sawtooth pattern, with a rapid drop-off).

In contrast, at the inner radial location, where strong upstream propagating shocks exist, the amplitude of the flow disturbance is much higher near the blade but rapidly decreases to approximately the same level as that measured at the outer radial location. Once the amplitude decays to this lower level, it remains relatively constant as the distance upstream of the rotor increases. Thus, the data measured at this inner radius show two distinctively different regions in the flow - a rapid-decay region and a constant-amplitude region. The transition between these two regions occurs relatively close to the rotor – at about one axial chord upstream of the leading edge (at around slide 13 of fig. 14).

It is interesting to compare the amplitude of the disturbance measured at the upstream-most axial location in the flow common to these two radial surveys. These data are shown on slide 10 of the sequence provided in figure 14. At this axial location the amplitude of the disturbance measured at the outer radial location is shown to be only slightly lower than that measured at the inner location. This is somewhat surprising considering that at the outer location the passage shocks are swallowed inside the blade passages, whereas at the inner location they propagate freely upstream of the rotor. Thus, although the flows just upstream of the leading edge at these two radial locations are distinctly different, they tend to be much more similar a short distance further upstream. This does not mean, however, that swallowing the shocks within the blade passages at the tip does not help to reduce the amplitude of the upstream disturbance. It is likely that if the shocks were not swallowed that a much stronger disturbance would be present in the flow upstream of the blade tips.

The nature of the disturbance upstream of the forward-swept rotor at these two radial locations is also illustrated in figure 15. The line plots presented at the right show the amplitude of the disturbance measured upstream of the rotor vs. axial distance upstream of the leading edge. The data presented on this plot exhibit the behavior mentioned above. That is, at the outer location, where the shock is swallowed (shown in blue), the amplitude of the flow disturbance remains relatively constant; whereas at the inner location (in black), where the shock is not swallowed, the amplitude of the disturbance starts out at a much higher level but quickly decays with increasing distance upstream of the fan.

The slideshow presented above in figure 14 illustrated the blade-to-blade variations in the flow upstream of the forward-swept rotor at two different radial locations with the rotor operating at the high-speed condition. The slideshow presented in figure 16 shows the blade-to-blade variations occurring at one radial location but at two different speeds. The bottom contour plots presented in this series of slides are the same high-speed relative Mach number plots presented in the previous slideshow for the inner radial location, r = 8.5 in. The top plots show the relative Mach number contours measured for this same radius but at the lower, mid-speed condition. Note that it is much easier to identify the flow disturbance propagating upstream of the rotor blades in the high-speed data. Obviously, this indicates that at this radius the perturbation in the flow upstream of the rotor has a higher amplitude at the higher speed.

These flow perturbations are shown again in the slideshow presented in figure 17. This slideshow presents both the circumferential distributions of relative Mach number (center plots) and the corresponding autospectra computed from these distributions (bottom). Once again, the slides are presented such that the data measured closest to the rotor are shown first; successive slides step away from the rotor. The sawtooth pattern (an N-shape, but flipped left-to-right) exhibited by the relative Mach number distributions presented on the first few slides indicate that shocks exist upstream of the blades at this radius at both the mid and high speeds. At each of these two speeds the disturbance measured upstream of the leading edge decays rapidly with distance upstream of the rotor. This is also illustrated by the line plots presented in figure 18. The data presented in this figure show that the disturbance upstream of the rotor decays more rapidly and down to a lower level at the lower of the two speeds.

Aft-Swept Rotor Flow Field

The slideshow presented in figure 19 illustrates the blade-to-blade variations in the flow measured upstream of the aft-swept rotor operating at the highest tested speed (RPMC = 13,800). Data are shown for two different axial planes upstream of the rotor, referred to in the slides as axial stations 1 and 2. As can be seen in the schematic diagrams at the left of each slide, axial station 2 is just upstream of the upstream-most point on the leading edge of the aft-swept rotor blades. Axial station 1 is 1.27 in. upstream of station 2; it corresponds to the same axial location within the model at which data were obtained with the forward-swept fan (see fig. 5). Significant blade-to-blade variations in the upstream flow can be seen by stepping through the slides. The contour plots presented for axial station 2 (the upper plots) show that the rotor blades generate a significant disturbance in the flow just upstream of the blades over the entire blade span. The data of axial station 1 (the lower plots) indicate, however, that the disturbance generated by the inner part of the blades all but disappears by the time it reaches this upstream location; only the disturbance created by the outer part of the blades can be seen in the upstream data. The disturbance persists further upstream in this outer region because it is created by shocks propagating upstream of the blade tips. Unlike the forward-swept fan, this aft-swept design does not swallow the tip shocks at this rotational speed.

These same data are presented in a different format in the slideshow of figure 20. The line plots at the center of each slide show circumferential distributions of relative Mach number, while the plots at the bottom show autospectra computed from these distributions. The measurement locations corresponding to the data presented on a given slide are indicated by the dashed lines overlaid on top of the contour plots at the top of the figure. The first slide shows data measured near the fan case; successive slides step radially into the flow. Outboard of about the midspan location (slide 20 of fig. 20), the relative Mach number distributions have a sawtooth pattern (an N-shape, but flipped left-to-right) which indicates that shocks are present in the flow. Further inboard, the distributions measured at station 2 resemble an N-shaped pattern (here the N-shape is not flipped left-to-right). The steep gradients in the flow associated with this pattern result from the flow adjusting to the leading edges of the blades, not from shocks in the flow. At these inboard locations the blade leading edges are axially only a short distance downstream of this measurement plane. Note that the gradients in the flow measured near 30 percent span (slide 26 of fig. 20) at station 2 are even steeper than the shock-generated gradients measured within this plane in the tip region. However, since this inboard disturbance is not created by shocks in the flow, it does not persist very far upstream. This is also illustrated in the plot in the upper-right-hand-corner of the slides. The black distribution presented on this plot shows the amplitude of the disturbance measured at station 2, just upstream of the leading edge, while the blue distribution shows the disturbance measured at station 1, about 1.27 in. upstream of station 2. The very strong perturbation in the flow measured inboard near r = 6 in. at station 2 all but disappears by the time it reaches axial station 1.

In addition to the data obtained at the high speed condition within these two constant axial planes, data were also obtained during constant radial surveys at r = 10.6, 8.5, 7.0, and 5.5 in. The locations of these surveys are depicted in figure 21. The diagram at the left in the figure shows the measurement locations relative to a schematic of the model hardware; the plot at the right shows these four radial locations relative to data measured during the two constant axial plane surveys made with the rotor operating at this speed. The blue and black lines presented on this plot represent the amplitude of the disturbance measured upstream of the fan at axial stations 1 and 2, respectively. These distributions were shown in the previous slideshow. The red horizontal lines overlaid on top of these data indicate where these four radial surveys would cut through this flow. The outermost survey location, r = 10.6 in., cuts right through the strongest part of the shock propagating upstream of the rotor. The other three radial locations, r = 8.5, 7.0, and 5.5 in., correspond to regions in the flow where the shock is either much weaker (r = 8.5 in.) or nonexistent (r = 7.0 and 5.5 in.).

Figure 22 presents a slideshow of the data measured during these four constant radial surveys. Each slide presents relative Mach number contours computed from the measured data. Twenty-two slides are presented, with each new slide showing a new blade passage of data rotated into view. The x and y-axes of these plots correspond to the axial and circumferential directions, respectively. The span of the y-axis is the same for each of the four plots presented on a given slide. Consequently, the smaller the radius at which the data were acquired, the larger the percentage of the complete rotor rev depicted in the corresponding contour plot. By stepping through these slides it is possible to see the blade-to-blade variations in the flow upstream of the aft-swept rotor at this speed. Shocks are shown to exist in the flow upstream of the rotor at the two outer radial locations (r = 10.6 and r = 8.5 in.) At r = 10.6 in., the shocks emanating from the suction surface of the blades pass only a short distance upstream of the adjacent blades. In fact, these shocks pass so close to the blades that they end up bending around the leading edges of these blades. At the next radial location inboard, r = 8.5 in., the shocks pass a bit further upstream of the blades; here the shocks appear to propagate straight out into the upstream flow without being bent by the adjacent blades.

The data obtained from these constant radial surveys are presented again in the slideshow provided in figure 23. As before, the plot at the center of each slide shows circumferential distributions of relative Mach number, and the plot at the bottom shows the autospectra computed from these relative Mach number distributions. The first slide in this sequence shows data measured at the downstream-most location in the flow; successive slides step upstream, away from the rotor. At the downstream-most location, data were only obtained at the outermost radius, r = 10.6 in. Data measured at the three inner radial locations do not appear until later in the sequence – the r = 8.5 in. data don't appear until slide 4, the r = 7.0 and 5.5 in. data don't appear until slide 7 of figure 23. By stepping through these slides it is possible to see how the disturbance generated by the fan varies with distance upstream of the rotor. At each radial location, a high amplitude disturbance was measured just upstream of the fan. This disturbance is shown to decay more slowly as radius increases. When there are no shocks in the flow (r = 7.0 and r = 5.5 in.) the disturbance decays asymptotically toward zero; when shocks are present, the disturbance appears to decay towards a nonzero value (at least over the distance over which data were acquired). The data corresponding to the two locations in the flow at which shocks are present (the outer two locations) exhibit an interesting behavior – they show that the amplitude of the disturbance doesn't always decrease with increasing distance upstream of the rotor. Each of these two sets of data show that the initial decay of the disturbance is followed by a region over which the amplitude of the disturbance actually increases slightly as the distance upstream of the rotor increases.

The decay of the flow perturbation measured upstream of the aft-swept rotor operating at the high speed condition is also illustrated in figure 24. This figure shows the amplitude of the disturbance measured at the four different radial locations plotted vs. distance upstream of the blade leading edge. This plot clearly illustrates a number of the points made in the preceding paragraph: 1) the disturbance decays more slowly as radius increases, 2) when shocks are not present, the disturbance decays monotonically toward zero, and 3) when shocks are present, the decay in not necessarily monotonic and not necessarily to zero (at least not over the axial distance over which data were acquired during this investigation.)

All of the aft-swept rotor data presented above were obtained with the fan operating at the high-speed condition. The slideshow presented in figure 25 illustrates the blade-to-blade variations in the upstream flow measured while the fan was operating at the lower, mid-speed condition. The overall character of the flow measured at this speed is similar to that measured at the high-speed condition in the following respects: 1) shocks exist upstream of the blade tips, 2) significant blade-to-blade variations exist in that part of the flow in which shocks are propagating upstream, 3) a strong perturbation in the upstream flow is measured at axial station 2 everywhere along the blade span, and 4) at the inner radial locations - where the perturbation is not created by shocks in the flow – the disturbance dissipates almost completely by the time it reaches axial station 1.

Relative Mach number distributions and autospectra computed from these data are provided in the slideshow of figure 26. The slides presented in this figure also contain a plot in the upper-right-hand-corner which shows the amplitude of the disturbance measured upstream of the rotor at this mid-speed condition. It is interesting to compare the data within this plot with similar data obtained at the high-speed condition. This comparison is provided in the plot at the right in figure 27. This plot shows spanwise distributions of the amplitude of the disturbance measured in these two axial planes while the fan was operating at both the mid and high-speed conditions. Inboard of where shocks exist on the blades, the data behave as expected; that is, the amplitude of the disturbance measured at station 2 increases with rotor speed. In the outer regions of the flow, however, where shocks exist, the trend depicted might not be expected. In this part of the flow, the disturbance measured at mid-speed is actually slightly higher in amplitude than that measured at high-speed. The reason for this is related to whether or not the shocks get bent backward around the leading edges of the adjacent blades. At the high speed condition, the shocks in the tip region do get bent backward; whereas at the mid-speed condition they do not. At the mid-speed condition the shocks propagate straight out into the upstream flow without being altered by the adjacent blades. The data presented in figure 27 indicate that there may be some acoustic advantage to operating the rotor at the high speeds required to get the shocks to bend backward. Doing so tends to produce a lower amplitude disturbance just upstream of the rotor. This lower amplitude disturbance may produce less noise.

Data were also obtained from four constant radial surveys conducted at the mid-speed condition. The radial locations of these surveys were the same as those conducted at high speed: r = 10.6, 8.5, 7.0 and 5.5 in. Relative Mach number contour plots generated from these data are provided in the slideshow of figure 28. This slideshow illustrates the blade-to-blade variations in the flow upstream of the rotor at this speed. The slideshow of figure 29 presents circumferential distributions of relative Mach number and autospectra computed from the data obtained during these surveys. These data show that strong shocks exist upstream of the rotor at the outermost radius, r = 10.6 in., when the fan is operated at this mid-speed condition. Further inboard, however, at r = 8.5 in. the shocks are very weak; apparently this radial location is just outboard of the innermost location at which shocks form on these blades when they are operating at this speed.

Figure 30 compares the decay of the disturbance measured upstream of the aft-swept rotor at these two speeds. The data presented for the three inner radial locations behave as expected – that is, the disturbance decays more quickly at the lower rotor speed. At the outermost radius, however, the opposite occurs – the disturbance decays more quickly at the higher rotor speed. Once again, this rather unexpected behavior is associated with whether or not the shocks in this region get bent by the adjacent blades. At the high speed condition they do get bent, whereas at the mid-speed condition they do not. This is illustrated in the contour plots of figure 31. The upper plot shows bent shocks associated with high-speed operation; the lower plot shows unbent shocks measured at mid-speed. Bending the shock around the adjacent blade results in a weaker part of the shock being measured at a given upstream location relative to what would be measured if the shock were not bent. As mentioned above, there may be some acoustic advantage associated with operating the fan so that the shocks bend back toward the rotor in the manner depicted in the top plot of figure 31.

Comparison of Forward-Swept and Aft-Swept Flow Fields

The slideshow presented in figure 32 provides a comparison of the flow fields measured upstream of the two rotors while they were operating at the high speed condition. The first slide shows measurements made near the outer case; successive slides step radially into the flow. The data provided in black were measured upstream of the aft-swept rotor; the blue were measured upstream of the forward-swept. The data presented in the first six slides of the slideshow illustrate that the amplitude of the disturbance measured upstream of the tip of the aft-swept rotor was at least twice as large as that measured upstream of the forward-swept. This is due to the differences in the shocks occurring in the tip region- with the forward-swept fan the shocks were swallowed, whereas with the aft-swept fan they were not. Although the amplitude of the disturbances in the tip region are different, both flows exhibit the same trend—between r = 11 and r = 10 in. each disturbance tends to decrease in amplitude with decreasing radius. Near r = 10 in., however, the trends become dissimilar – inboard of this location the disturbance upstream of the aft-swept fan continues to decrease in amplitude, while that measured upstream of the forward-swept fan increases. This r = 10 in. location on the forward-swept rotor is thought to represent that radial location at which the shocks transition from being swallowed to expelled. Just inboard of this transition point the shock which forms along the suction surface of the blade will experience a maximum amount of bending as it makes its way around the leading edge of the adjacent blade. The amount of bend then decreases with radius until near r = 8.5 in. the shock propagates roughly straight out into the upstream flow without being altered by the adjacent blade. Inboard of r = 8.5 in., the amplitude of the disturbance upstream of the forward-swept fan decreases with radius as the strength of the propagating shock decreases. The flat distribution shown inboard of r = 6.25 in. suggests that shocks do not form on the forward-swept blades in this region when the rotor is operating at this high-speed condition.

Figure 33 shows spanwise distributions of the amplitude of the disturbance measured upstream of the two rotors at axial station 1 while they were operating at the high speed condition. This plot clearly illustrates the differences in the upstream flows generated by the two fans at this speed. In the tip region the disturbance is much larger with the aft-swept fan, whereas near 70 percent span (r = 8.5 in.) it is much larger with the forward-swept. These differences are associated with the strength of the shocks propagating upstream of the rotors – with the aft-swept fan the propagating shocks are strongest upstream of the tip, whereas with the forward-swept fan they are strongest near r = 8.5 in.

The slideshow presented in figure 34 provides another view of the flow fields generated upstream of these two rotors. This slideshow presents data obtained upstream of the two fans during constant radial surveys made at r = 10.6 in. while the fans were operating at the high-speed condition. The first slide in this sequence illustrates where this r = 10.6 in. survey location (shown in red) would be relative to the constant axial plane data that were presented in the previous figure. At this radial location a strong disturbance was measured upstream of the aft-swept fan, and a relatively weak disturbance was measured upstream of the forward-swept. Again, these differences are due to the differences in the shocks associated with the two fans - at this radius, the shocks are expelled with the aft-swept rotor and swallowed with the forward-swept. The slides are presented such that the downstream-most data are shown first, and successive slides step upstream. At this radius, data could be obtained further downstream within the model when the aft-swept rotor was tested. Consequently, the first nine slides only show data obtained upstream of the aft-swept rotor. Data obtained upstream of the forward-swept fan do not appear until slide 10. Slide 12 shows data obtained near axial station 1 - the axial plane in which data were obtained upstream of both fans. The data presented on this slide agree with the axial station 1 data presented earlier in that they show a much stronger disturbance upstream of the aft-swept rotor. Note, however, that upstream of this location the two disturbances behave quite differently. The disturbance generated by the aft-swept rotor continues to decay, while that of the forward-swept fan remains relatively constant until, at the upstream-most location in the flow at which data were obtained on both fans, the two disturbances have roughly the same amplitude. This is interesting considering the differences in the nature of the shocks associated with the two fans - the shocks of the aft-swept rotor are propagating and those of the forward-swept fan are swallowed, yet they both end up generating roughly the same disturbance at this location in the flow field.

The slideshow provided in figure 35 shows data obtained during radial surveys conducted at r = 8.5 in. with the two rotors operating at the high-speed condition. The locations of these surveys are shown relative to the axial station 1 data on the first slide. At axial station 1 and a radius of 8.5 in. a much stronger disturbance was measured upstream of the forward-swept fan. This is the opposite case to that presented in the previous slideshow; the previous data, which were obtained at a radius of 10.6 in., showed a much stronger disturbance measured upstream of the aft-swept fan. The slides of figure 35 are presented such that the downstream-most data are shown first and successive slides step upstream. Once again, at this radial location it was possible to obtain data further downstream when the aft-swept rotor was tested. Therefore, the first 11 slides only contain aft-swept rotor data. These show a relatively strong shock just upstream of the leading edge of the aft-swept rotor blades. This shock dissipates quickly, however, and by the time it reaches the axial location at which the station 1 data were measured it represents a weaker disturbance than that generated by the forward-swept fan. Once again, however, the decay rates of these two disturbances differ upstream of this location, and toward the end of the slideshow the two disturbances end up looking much more similar. Therefore, these data are like the r = 10.6 in. data in that they show two distinctly different disturbances at station 1 which end up looking much more similar further upstream.

Based on the data presented in this slideshow it is not possible to determine if the shocks occurring at this radius are stronger with the aft-swept rotor or the forward-swept. Although a weaker disturbance was measured upstream of the aft-swept rotor at station 1, this does not necessarily mean that the shocks associated with this fan were weaker. At this radius, the aft-swept blades were a bit further downstream than forward-swept, so it may be that the disturbance with the aft-swept rotor was smaller simply because the shocks had more time to decay. Figure 36 provides more information regarding the decay of these two disturbances. Here the disturbance amplitudes are plotted vs. distance upstream of the leading edge of the respective rotors. This plot shows that the decay rate was slower for the forward-swept rotor. Although this is not conclusive evidence, it does suggest that the shocks on the forward-swept fan were stronger. The schematics at the left of figure 36 show planform views of the two different blade types. Based on this diagram it appears that the forward-swept fan has less sweep at this radius. This may account for what appears to be the stronger shocks associated with these blades at this radius.

Conclusion

LDV data were obtained upstream of the forward-swept fan at three speeds corresponding to rotor tip relative Mach numbers of 0.817, 1.074, and 1.19. These data indicate that:

1) Of the three speeds, the flow upstream of the rotor is much more uniform at the subsonic tip speed.
2) At the mid-speed condition the strongest shocks occur in the upstream flow between 75 and 85 percent span.
3) At the high-speed condition the strongest shocks occur further inboard, between 65 and 75 percent span.

4) The passage shocks are swallowed inside the blade passages in the tip region at the high speed condition.

5) After the rotor speed is increased to the point at which the tip shocks just become swallowed, further increases in speed result in the shocks being swallowed over a larger spanwise extent of the blade.

6) At the high speed condition there are four distinctly different radial regions in the upstream flow. Starting with the outermost, these are

a) a region in which the shocks are swallowed inside the blade passages.
b) a region in which the shocks propagate upstream of the blades, but bend around the adjacent blades.
c) a region in which the shocks propagate straight out into the upstream flow without bending around the adjacent blades
d) an innermost, subsonic region in which no shocks occur. The strongest disturbance in the upstream flow occurs at the radial location at which the propagating shocks transition from being bent to unbent (i.e., between the regions mentioned above in 6b and 6c). The data suggest that bending the shocks around leading edges of the adjacent blades may offer some acoustic advantage since the disturbance in the region of the bent shocks is lower than what it would be if the shocks were not bent.

7) There are significant blade-to-blade variations in the flow upstream of the rotor at all radial locations at which shocks occur, even when the shocks are swallowed inside the blade passages. Swallowing the shock does not eliminate the disturbance upstream of the rotor.

8) The amplitude of the disturbance generated by a shock which propagates straight out into the upstream flow decays more rapidly with distance from the leading edge as rotor speed is decreased.

9) In the tip region, where the shocks are swallowed when operating at high speed, the amplitude of the disturbance just upstream of the leading edge is significantly lower than that measured further inboard, where the shocks are propagating. The low-amplitude disturbance measured in the tip region remains relatively constant with increasing distance upstream of the rotor. Further inboard, the high amplitude disturbance created by the propagating shocks quickly decays with increasing distance upstream of the fan. The disturbance, however, does not decay to zero (at least not over the distance over which measurements were made).

LDV data were obtained upstream of the aft-swept fan at two speeds corresponding to rotor tip relative Mach numbers of 1.074, and 1.19. These data indicate that:

1) Unlike the forward-swept fan, the aft-swept rotor does not swallow the shocks in the tip region when operating at the high-speed condition.

2) A high amplitude disturbance was measured just upstream of the rotor everywhere along the blade span at each of the tested speeds. At a given spanwise location, the decay of the disturbance with distance upstream of the rotor depends upon whether or not shocks occur at that location.

a) When the flow is entirely subsonic the disturbance decays asymptotically toward zero over a short distance with the decay rate a function of the relative flow speed (the lower the relative speed, the faster the decay).
b) When shocks occur on the blades, the disturbance decays at a slower rate to a nonzero level (at least not to zero over the distance for which measurements were obtained).

3) The amplitude of the disturbance at a given upstream location depends upon whether or not the shock occurring at that radius bends around the leading edge of the adjacent blade. The disturbance at a given upstream location can actually decrease in amplitude as rotor speed increases if the shock occurring at that radius transitions from straight (a normal shock) to bent (an oblique shock). There may be some

acoustic advantage to operating the rotor at speeds at which the shocks bend around the leading edges of the adjacent blades.

A comparison of the flows measured upstream of the two rotors at the high speed operating condition indicates that:

1) The flows measured upstream of the two fans at axial station 1 (the axial plane within the model at which data were obtained with both fans) were quite different. In the tip region the disturbance generated by the aft-swept rotor was significantly stronger than that generated by the forward-swept, whereas near 70 percent span the disturbance produced by the forward-swept fan was stronger.

2) These differences in the flows, however, diminished upstream of axial station 1, and at the upstream-most locations in the flow at which data were obtained with both fans the two flows look much more similar.

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13. ABSTRACT ***(Maximum 200 words)***

Detailed laser Doppler velocimeter (LDV) flow field measurements were made upstream of two fans, one forward-swept and one aft-swept, in order to learn more about the shocks which propagate upstream of these rotors when they are operated at supersonic tip speeds. The blade-to-blade variations in the flows associated with these shocks are thought to be responsible for generating Multiple Pure Tone (MPT) noise. The measured blade-to-blade variations are documented in this report through a series of slideshows which show relative Mach number contours computed from the velocity measurements. Data are presented for the forward-swept fan operating at three speeds (corresponding to tip relative Mach numbers of 0.817, 1.074, and 1.189), and for the aft-swept fan operating at two (tip relative Mach numbers of 1.074 and 1.189). These LDV data illustrate how the perturbations in the upstream flow field created by the rotating blades vary with axial position, radial position and rotor speed. As expected, at the highest tested speed the forward-swept fan swallowed the shocks which occur in the tip region, whereas the aftswept fan did not. This resulted in a much smaller flow disturbance just upstream of the tip of the forward-swept fan. Nevertheless, further upstream the two fan flows were much more similar.

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