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EFFECTS OF CHOKING ON THE AEROACOUSTICS OF AN AXISYMMETRIC SUPERSONIC INLET

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An experimental study was conducted to determine the effect of choking on the aerodynamic and acoustic performance of a supersonic inlet. The investigated inlet was a prototype model of a mixed compression, axisymmetric supersonic inlet designed for the high speed civil transport aircraft. A 10·4 cm (4·1 in) turbofan engine simulator was used in conjunction with the inlet. The inlet was tested with the centerbody in the fully extended position at different fan speeds. Results show that "soft choking", as characterized by a reduction in forward propagating fan noise, can occur when the Mach number at the inlet throat exceeds 0·5. In the forward sector (0°–60° from the inlet axis), the overall sound pressure level was reduced by about 7 dB as the fan speed increased from 50,000 to 70,000 rpm, due to the increase in the Mach number at the inlet throat. Additional comparison was made between the inlet configurations with the centerbody fully extended and fully retracted at a fan speed of 50,000 rpm. The results show that the higher Mach number at the inlet throat for the full retracted centerbody configuration was successful in reducing the overall sound pressure level by about 4 dB between 0° and 30° angular sector. While there is no measurable difference in the total pressure recovery for the two inlet configurations, there is, however, a significant increase in the circumferential flow distortion at the fan face for the higher throat Mach number test case.

1. INTRODUCTION

Recently there has been renewed interest in the development of a new-generation supersonic cruise aircraft for commercial application. In order for a high speed civil transport to be successful, its acoustic impact on airport community noise due to aircraft takeoff and landing approach must be minimized. In addition to jet noise, forward propagated engine fan noise can also be a significant component during aircraft takeoff and landing approach. The complicated noise radiation directivity pattern from the fan is influenced by the design of the engine inlet. Unlike conventional subsonic inlets, inlets for supersonic aircraft incorporate many complex features, such as translating centerbody and support struts. Noise generated by each of these features is a complicated phenomenon and needs to be studied in detail to quantify the individual contribution to noise. In the literature, only a few studies were found that investigate the aeroacoustics of supersonic inlets [1–5].

The purpose of this paper is to investigate experimentally the effect of increasing Mach number at the inlet throat on the noise attenuation in the forward sector of the inlet. A higher flow Mach number at the throat of a supersonic inlet increases the propagation time of the acoustic wave moving upstream, thereby dissipating the acoustic energy.

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Theoretically, if the Mach number at the inlet throat is uniformly at one (choked inlet), no sound can propagate upstream and radiate to the forward sector. The questions to be addressed in this research are as follows. For a supersonic inlet, what minimum Mach number is needed at the throat of the inlet in order to have an appreciable effect on noise attenuation? Furthermore, can the translating centerbody be positioned such as to increase the throat Mach number during the aircraft landing approach, in order to employ the choking effect to minimize forward propagating fan noise, and how will the increase in the throat Mach number affect the flow distortion at the fan face?

There have been a few studies on sound propagation through a variable area duct for subsonic type inlets. Jones [6] performed an experimental investigation of sound attenuation in a high-subsonic Mach number inlet. Silcox *et al.* [7] and Nayfeh *et al.* [8] studied the sound propagation through a variable area duct. However, the geometries of all these configurations pertain to subsonic type inlets with a cylindrical duct and a simple cylindrical centerbody. Furthermore, these experiments were conducted with either no flow in the duct, or with very low speed flow in the duct.

Sound attenuation in a supersonic type inlet has also been investigated. In particular, Bangert *et al.* [4], and Woodward *et al.* [1] both observed suppression of noise in the forward sector due to an increase in throat Mach number of supersonic inlets. However, in their experiments, no inlet flow field measurements were taken at the fan face to document the inlet distortions due to the difference in inlet throat Mach numbers. Higher distortion at the fan face can lead to engine instability and should be minimized to ensure safe operation.

The present experiments are an attempt to fill the void in the literature by providing detailed aerodynamic measurements at the fan face of a supersonic inlet in order to document the inlet flow distortion with increasing throat Mach number. The experiment was conducted with a scale model of a supersonic inlet coupled to a 10·4 cm (4·1 in) diameter turbofan engine simulator. The geometry of this inlet is identical to that of the P-inlet tested by Woodward *et al.* [1]. The tests were conducted in an anechoic facility under static conditions.

2. THE EXPERIMENT

2.1. TURBOFAN ENGINE SIMULATOR

A model turbofan engine simulator was used in conjunction with the supersonic inlet to provide a characteristic engine noise signal. The fan is powered by a single stage turbine, which is in turn driven by compressed air. The model fan, which has a diameter of 10·4 cm (4·1 in), is designed to operate at a maximum design speed of 80 000 rpm. The simulator incorporates 18 fan blades and 26 stator vanes. The Reynolds number based on fan tip speed and fan diameter was $1{\cdot}7 \times 10^6$. The small scale engine simulator is suitable for the test purpose because the intent of the investigation is to quantify the difference in aeroacoustic performance between different inlet configurations and not the absolute values. Nuckolls and Ng [2] demonstrated similarities in the noise radiation behavior between the present inlet and the larger inlet (five times) tested by Woodward *et al.* [1], and concluded that despite the difference in the Reynolds number, the present small scale inlet could be used to investigate acoustic trends and inlet noise mechanisms.

2.2. SUPERSONIC INLET

The test inlet used in this research is a mixed-compression axisymmetric inlet developed by NASA, commonly referred to as the “P-inlet” (Figure 1). The inlet has a design flight Mach number of 2·65. The P-inlet has auxiliary doors to meet the air flow requirements of the engine. In this investigation, the auxiliary doors were closed. The inlet also has a translating centerbody to control the inlet throat area. The centerbody assembly was supported by four equally spaced struts located near the entrance of the fan (Figure 1). In this experiment, the inlet was tested with the centerbody located at two positions: the fully extended position and the fully retracted position (see Figure 1). The fully extended centerbody position corresponds to the inlet with a maximum throat area and is the desired configuration for takeoff and landing. The fully retracted centerbody position is nominally the configuration for supersonic cruise only. As mentioned previously, the attempt here is to use the retracted centerbody to produce the highest Mach number in the inlet throat at simulated aircraft approach conditions, and allows the effect of choking to be investigated.

2.3. TEST SPEEDS OF THE SIMULATOR

For the fully extended centerbody position, most of the data were acquired at fan speeds of 50 000 rpm and 70 000 rpm. The 50 000 rpm condition (corresponding to about 60% design speed) is to simulate the aircraft at landing approach. The tip speed of the fan blade at this condition is subsonic at 265 m/s. The 70 000 rpm condition (corresponding to about 88% design speed) is to simulate the aircraft at takeoff conditions. (Considerations due to safety and air supply limit the test speed to 70 000 rpm.) Note that at 70 000 rpm the blade tip velocity is supersonic at 382 m/s, and therefore a fan noise spectrum comprised of combination tones will be generated.

For the fully retracted centerbody position, only data at 50 000 rpm were taken. At this fan speed, due to the smaller throat area compared to the fully extended centerbody position, the inlet throat Mach number is nearly one. A further increase in fan speed is not possible, unless the centerbody is translated forward, or unless auxiliary doors are opened to meet the airflow requirements of the simulator.

2.4. ANECHOIC CHAMBER

The investigation was conducted at the Virginia Tech Anechoic Chamber. The simulator was mounted in a test stand inside the anechoic chamber 122 cm (48 in) above the ground to reduce the possibility of exciting a ground vortex within the inlet flow field. The exhaust from the fan and the turbine were directly ducted out of the anechoic chamber. The inlet was tested under static conditions, without simulating the forward flight effects. Measurements showed that there was flow separation at the inlet cowl lip. The effect of lip separation on the aeroacoustics of supersonic inlets will be investigated with a round-edged bellmouth attached to the inlet entrance. Results from these experiments will be presented in the future.

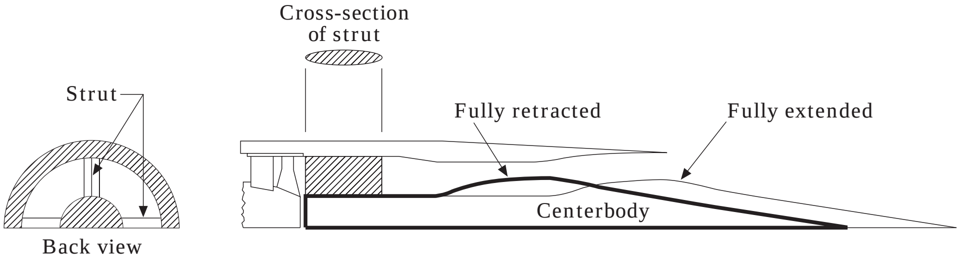


Figure 1. The inlet test configurations.

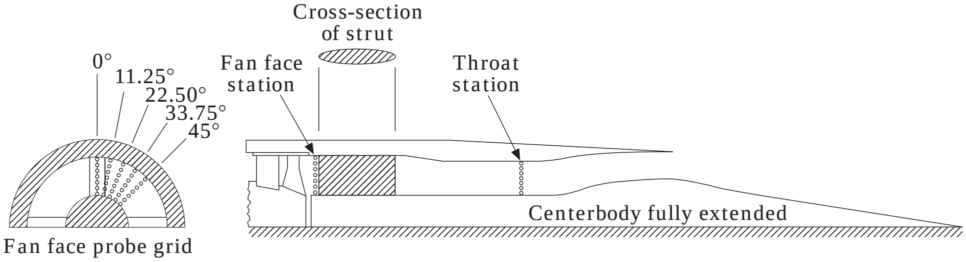


Figure 2. The aerodynamic instrumentation.

The anechoic chamber was considered to be anechoic above frequencies of 200 Hz. The interior dimensions of the anechoic chamber were 4·0 × 2·7 × 2·2 m. The walls and the ceiling were constructed of Owens–Corning Type 705 industrial fiberglass 0·91 m thick. The floor had metal grating to minimize the sound reflection. The ambient noise level was measured to be 45 dB below the rotor spectrum noise. These results indicate that the acoustic research facility is acceptable for the frequency range of interest and has acceptable ambient noise levels.

2.5. AERODYNAMIC MEASUREMENTS

Measurements of total pressure recovery and flow distortion were used to compare the overall aerodynamic performance of the inlet and to facilitate the interpretation of the acoustic results. The aerodynamic measurements on the inlet configuration with the centerbody fully retracted and fully extended were made at two locations, as shown in Figure 2. These locations will be referred to as throat and fan face stations. At the fan face station, Mach number and total pressure measurements were made at five circumferential locations and seven radial locations, as shown in Figure 2. The aerodynamic measurements were made with two conventional pressure probes. Total pressure measurements were taken with a 3·16 mm (1/8 in) diameter Kiel probe. The Mach number was calculated isentropically from the measurement of total and static pressures from a 1·6 mm (1/16 in) diameter Pitot-static probe.

2.6. ACOUSTIC MEASUREMENTS

The acoustic measurements for the noise spectra in the far field (i.e., $kl \gg 1$, where k is the wavenumber and l is the distance of noise source from the measurement location), were made as shown in Figure 3. The microphones were placed along a circular arc at a radius of 122 cm (48 in). Acoustic measurements were taken at 12 microphone locations at increments of 10° from 0° to 110° (inlet centerline axis at 0° position). The condenser microphone was mounted on a microphone stand placed 122 cm (48 in) above the floor level. A Brüel & Kjær model 4136 condenser microphone was used to measure the noise spectra in the far field.

The microphone signals were analyzed on a Brüel & Kjær model 2030, dual channel spectrum analyzer. The spectrum analyzer performed narrow-bandwidth FFT (fast Fourier transform) conversions of the acoustic data. The upper frequency limit of the spectrum was set to 25·6 kHz, providing a spectrum bandwidth of 32 Hz. The FFT results from the spectrum analyzer were used to record the BPF tone level and to investigate other fan-related tones. To compensate for the effect of random turbulence, the analyzer was configured to calculate the linear average of ten consecutive noise spectra. Ten consecutive values of the *average* BPF tone level were then recorded at each microphone position.

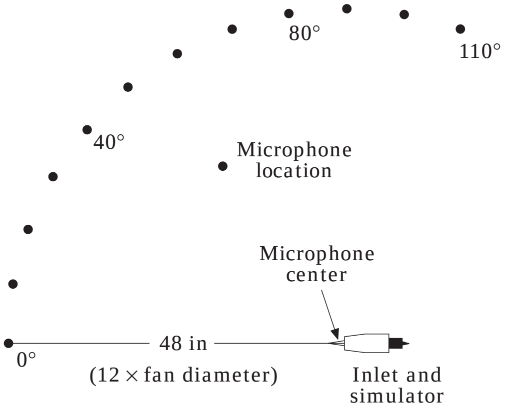


Figure 3. The microphone location.

The overall sound pressure level (*Oaspl*) represents the integration of noise over the frequency range. The frequency spectrum obtained by the signal analyzer was integrated from 0 to 25·6 kHz to obtain the overall sound pressure level.

3. RESULTS

3.1. EFFECT OF TEST SPEED

The results for the inlet configuration with the centerbody fully extended are presented in this section. The issue to be addressed is that as the throat Mach number increases due to the increase in fan speed, at what point would the effect of noise attenuation be observed in the forward sector. In Figure 4 is shown the influence of the fan rotational speed on the inlet throat Mach number. The inlet throat Mach number is taken with the Pitot-static probe located at the mid-span of the throat. The abscissa is given in terms of blade tip speed, which covers a fan speed of 30 000 rpm (tip speed of 159 m/s) to 70 000 rpm (tip

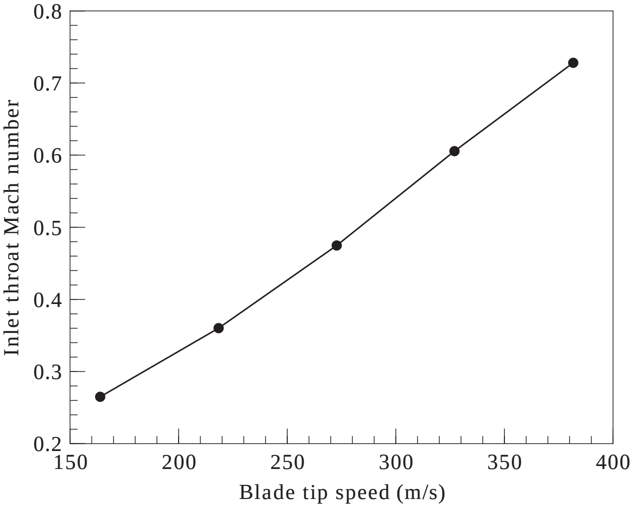


Figure 4. The inlet throat Mach number as a function of blade tip speed: fully extended centerbody, configuration.

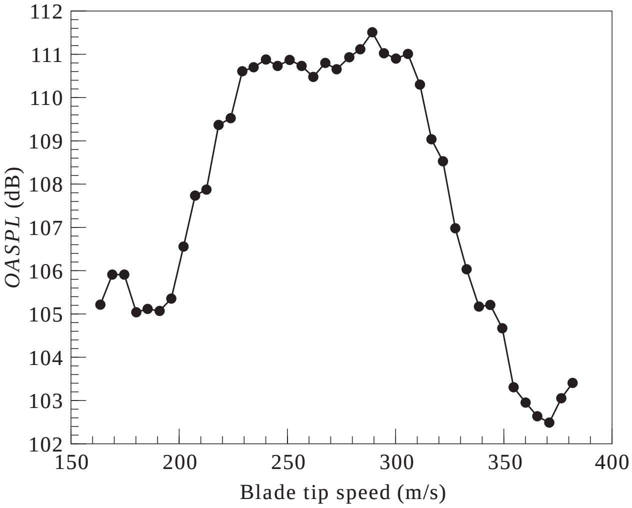


Figure 5. The effect of choking in fan noise: 20° microphone location, fully extended centerbody configuration.

speed of 382 m/s). Figure 4 reveals that with the centerbody fully extended, the Mach number at the midspan of the inlet throat is about 0·73 at 70 000 rpm. The overall sound pressure level as a function of fan speed measured with a microphone located at 20° angular position is presented in Figure 5. There is clear evidence of noise attenuation at a blade tip speed of about 305 m/s. From Figure 4, this corresponds to a Mach number at the mid-span of the inlet throat of about 0·54. In Figure 5 it is shown that the overall sound pressure level at the 20° microphone position can be reduced by as much as 8 dB due to the increase in the Mach number at the midspan of the throat from 0·54 to 0·73. Sample narrow-band frequency spectra taken at the 20° microphone location are presented in Figure 6 for the fan speed of 50 000 rpm (tip speed of 265 m/s) and 70 000 rpm. The reductions in both the blade passing frequency tone and the broadband level are quite evident as the fan speed increases from 50 000 rpm to 70 000 rpm. The existence of combination tones in Figure 6 is consistent with the fact that the blade tip speed is supersonic at 70 000 rpm. The directivity plot for the overall sound pressure level at 50 000 and 70 000 rpm is shown in Figure 7 for comparison. In the forward sector (0–60°), the overall sound pressure level was reduced by almost 7 dB on average. One would expect that as the fan speed increases from 50 000 to 70 000 rpm, the corresponding increase in fan blade loading should have led to a higher overall sound pressure level. Instead it is shown in Figure 7 that, due to the increase in the Mach number at the mid-span of the inlet throat, a reduction in the overall sound pressure level is observed in the forward sector.

The results presented in Figures 5–7 reveal that it is not necessary to have the Mach number at the inlet throat equal to unity in order to have significant noise attenuation in the forward sector of the inlet. “Soft choking”, as established for this particular inlet geometry and this experimental set-up, can occur at a throat Mach number as low as 0·54. This experimental observation can be employed to help reduce fan noise radiated from the inlet during takeoff or landing conditions. One possible scenario is to position the centerbody so that for a given fan speed, a higher Mach mumber can be achieved at the throat to employ choking in order to reduce noise radiated from the inlet. In an attempt to use this technique to reduce noise during simulated aircraft approach conditions, the

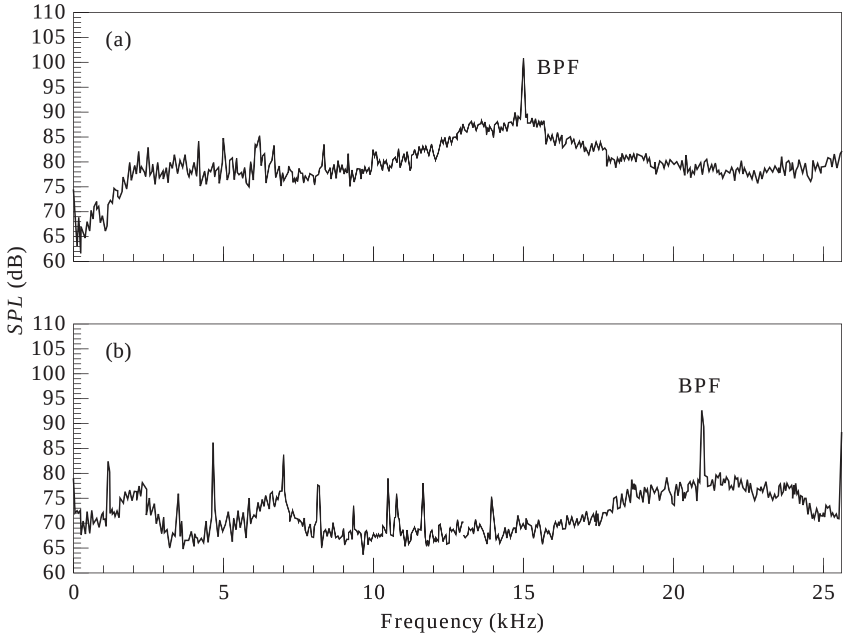


Figure 6. Sample spectra at 20° microphone location: fully extended centerbody configuration. (a) Fan speed = 50 000 rpm, blade tip speed = 164 m/s; (b) fan speed = 70 000 rpm, blade tip speed = 382 m/s.

inlet was tested with the centerbody in the fully retracted position at a fan speed of 50 000 rpm. The results of this investigation are presented in the next section.

3.2. EFFECT OF CENTERBODY POSITION

The geometry of the inlet with the centerbody fully retracted was presented in Figure 1. In comparison to the configuration with the fully extended centerbody, the geometry

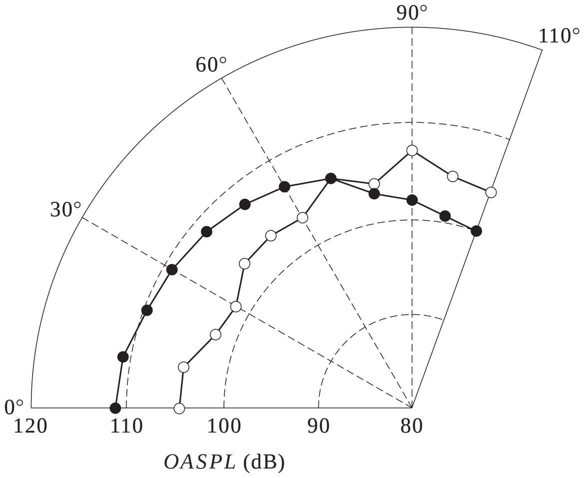


Figure 7. The directivity pattern of the overall sound pressure level: fully extended centerbody configuration. ●, 50 000 rpm; ○, 70 000 rpm.

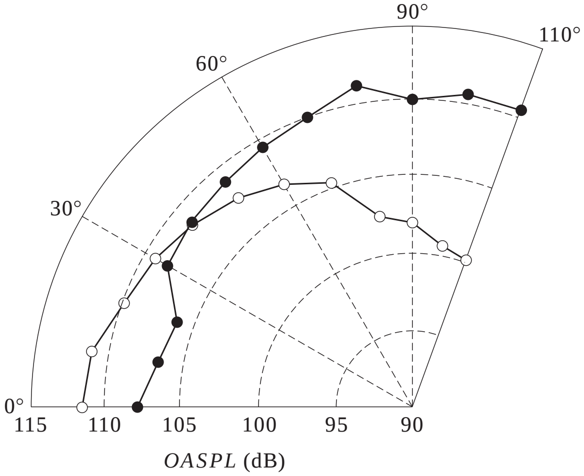
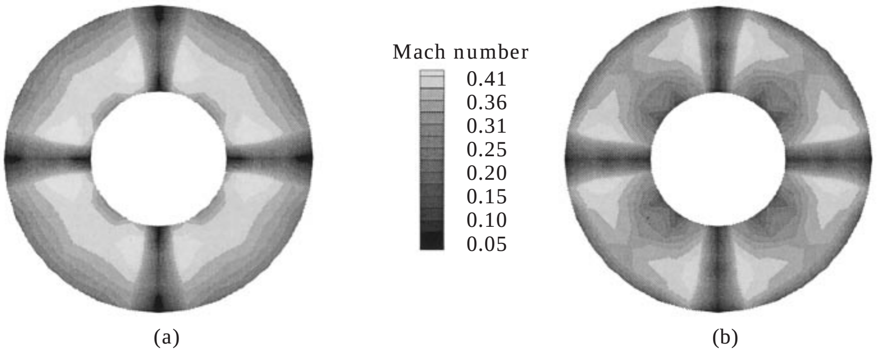


Figure 8. A comparison of directivity patterns at 50 000 rpm: ○, Fully extended centerbody; ●, fully retracted centerbody.

with the centerbody fully retracted has a smaller throat area. For the same fan speed of 50 000 rpm, the inlet throat Mach number measured at mid-span is about 0·90 for the fully retracted centerbody, while the corresponding Mach number for the fully extended centerbody is only 0·47. The effect of the throat Mach number on the noise radiation, due to the difference in centerbody position, is compared in the directivity plot of Figure 8. It is shown in Figure 8 that between 0° and 30° angular position, the overall sound pressure level can be reduced by about 4 dB due to the increase in throat Mach number.

Note that in the rearward sector (60–110°), the overall sound pressure level for the fully extended centerbody configuration is about 8 dB lower than for the fully retracted centerbody configuration. Although the reason for this is not fully known at this point, one possible explanation is due to the increase in circumferential distortion at the fan face. Circumferential flow variations at the fan face were of particular concern because they caused the blade loading to vary as the fan blades rotated, and unsteady blade loading increased the noise generation of the fan [9]. (In contrast, radial variations of the flow parameters did not cause fluctuating blade loadings and had little effect on noise generation.) The extent of the circumferential distortion for the two inlet configurations



(a) (b)

Figure 9. The Mach number distribution at the fan face: 50 000 rpm: (a) Fully extended centerbody; (b) fully retracted centerbody.

can be illustrated by the Mach number contour plots of Figure 9, which are obtained with data taken at the fan face station at a fan speed of 50 000 rpm. The axial Mach number contours clearly show regions of low Mach number behind the struts for both inlet configurations. These low Mach number regions in front of the fan face are a result of the wakes being shed by the trailing edge of the strut, which is placed 0·05 strut chord length upstream of the fan face. The Mach number of the flow near the fan tip changes from 0·40 to 0·05 from 0° to 10° for both cases. This gradient of the Mach number will cause a fluctuating loading on the fan blade as it spins through this region, resulting in the generation of noise. Notice that in Figure 9, for the inlet configuration with the centerbody fully retracted, the Mach number contour shows an additional circumferential distortion near the centerbody, between two adjacent struts. This pattern is not observed in the Mach number contour plot for the fully extended centerbody configuration. The existence of this additional circumferential distortion may have led to the higher overall sound pressure level in the rear sector for the fully retracted centerbody configuration, as shown in the directivity plot of Figure 8. The origin of this circumferential distortion will be discussed in the next section.

4. DISCUSSION

As is evident from Figure 1, the fully retracted centerbody configuration has a rapid increase in the flow area downstream of the throat. This causes a significant flow deceleration and sets up a strong adverse pressure gradient, which leads to the separation of the boundary layer on the centerbody downstream of the throat. The presence of the struts near the fan face, coupled with this separated flow on the centerbody, led to the generation of a strong secondary flow. This secondary flow has two effects: it causes higher total pressure losses at the fan face, and it leads to the circumferentially distorted flow near the centerbody behind the two struts, as is illustrated in the Mach number contour plot of Figure 9. Details of this flow development are presented in the companion paper on the 3-D viscous numerical simulation of the inlet/strut flowfield by Yamamoto and Ng [10].

The total pressure recovery of the two inlet configurations were also obtained by area-average of the total pressure measured at the fan face. The results show that within experimental uncertainty, there is no measurable difference in the total pressure recovery of the two inlets. The total pressure contours at the fan face for the two inlet configurations are somewhat similar to the Mach number contours shown in Figure 9. For the fully retracted centerbody configuration, in addition to the wake of the strut, there is a high loss region due to the distorted flow near the centerbody between two adjacent struts, while the region of high losses near the tip section of the fan face (from the casing boundary layer) was relatively small. For the fully extended centerbody configuration, the total pressure contours show a somewhat different loss distribution, with a much thicker tip casing boundary layer, and a much smaller region of high losses near the centerbody between two adjacent struts. The overall effect is that the area-averaged total pressure recovery for both inlets is about the same. This conclusion for total pressure recovery may be influenced by the separated flow at the cowl tip, and the addition of a bellmouth to the inlet cowl may have some effect on this conclusion. Results for the experiment with the use of a bellmouth to eliminate lip separation will be reported in the future.

The results presented in this paper demonstrate that noise attenuation can be achieved even though the inlet throat Mach number is well below Mach one. This observation is consistent with that reported in references [1] and [4]. In this experiment, it was shown that "soft choking" can occur when the throat Mach number exceeds 0·5. In principle, if the inlet throat is completely choked at Mach one, no sound can propagate to the forward sector of the inlet. In practice, the variations in flow Mach number at the throat station, such as those caused by the presence of wall boundary layers, contribute to "noise leakage".

Detailed modal analysis of the fan noise, due to the interaction of the rotor with the four centerbody support struts, as well as with the row of stator blades behind the fan, was presented in reference [3].

5. CONCLUSIONS

The present research was conducted to evaluate the effect of choking on the acoustic and the aerodynamic performance of a supersonic inlet. A small-scale model of an axisymmetric, mixed-compression, supersonic inlet was tested in conjunction with a 10·4 cm (4·1 in) diameter turbofan engine simulator. Two inlet configurations were tested, one with the inlet centerbody fully extended and another with the inlet centerbody fully retracted.

For the centerbody at the fully extended configuration, evidence of soft choking was observed in the experiment, in which appreciable noise attenuation was obtained when the Mach number measured at the mid-span of the throat of the inlet exceeded 0·50. In the forward sector, the overall sound pressure level was reduced by 7 dB as the fan speed increased from 50 000 to 70 000 rpm, due to increasing Mach number at the inlet throat.

Choking was employed to reduce forward propagating fan noise under simulated aircraft approach conditions. Testing was performed with the simulator running at 50 000 rpm and the centerbody fully retracted to achieve a higher Mach number at the throat of the inlet. Comparing the results to that from the fully extended centerbody configuration, the fully retracted centerbody configuration was successful in reducing the overall pressure level by 4 dB between 0° and 30° angular position. Associated with this noise reduction, however, was a significant increase in the flow distortion at the fan face.

ACKNOWLEDGMENT

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