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The Impact of Subsonic Twin Jets on Airport Noise

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Abstract

Subsonic and supersonic aircraft concepts proposed through NASA's Fundamental Aeronautics Program have multiple engines mounted near one another. Engine configurations with multiple jets introduce an asymmetry to the azimuthal directivity of the jet noise. Current system noise predictions add the jet noise from each jet incoherently, therefore, twin jets are estimated by adding 3 EPNdB to the far-field noise radiated from a single jet. Twin jet effects have the ability to increase or decrease the radiated noise to different azimuthal observation locations. Experiments have shown that twin jet effects are reduced with forward flight and increasing spacings. The current experiment investigates the impact of spacing, and flight effects on airport noise for twin jets. Estimating the jet noise radiated from twin jets as that of a single jet plus 3 EPNdB may be sufficient for horizontal twin jets with an s/d of 4.4 and 5.5, where s is the center-to-center spacing and d is the jet diameter. However, up to a 3 EPNdB error could be present for jet spacings with an s/d of 2.6 and 3.2.

Nomenclature

f	frequency (Hz)
c	sound speed
R	microphone arc radius
NPR	nozzle pressure ratio, referenced to atmospheric pressure
NTR	nozzle temperature ratio, referenced to ambient temperature
s	twin jet spacing, center-to-center
d	jet diameter
U_j	ideally expanded jet velocity (fps)
M_{fj}	free stream Mach number
n	velocity power factor
θ	microphone polar angle from the inlet axis
ψ	microphone azimuthal angle, referenced to the in-plane axis
St	Strouhal number, $f\,d/U_j$
SPL	sound pressure level, referenced to 20 μPa
OASPL	overall sound pressure level
PNL	perceived noise level
EPNL	effective perceived noise level
ΔSPL	$SPL_{twin} - SPL_{single+3dB}$
ΔEPNL	$EPNL_{twin} - EPNL_{single+3EPNdB}$

1.0 Introduction

For several years, various subsonic and supersonic vehicle concepts have been proposed to meet a variety of goals including fuel burn, emissions, and noise. Since noise is one of many factors in the vehicle design, it has become increasingly important to quantify the potential noise benefit or penalty associated with various engine configurations. In order to predict the exhaust noise radiated from the propulsion systems, many effects must be understood. Adding multiple jets to an propulsion system has the ability to affect both the source and propagation of the jet noise. Experiments were performed to predict the impact of multiple jets on the radiated noise from a variety of engine configurations.

The Fundamental Aeronautics Program of NASA's Aeronautics Research Mission Directorate derives its goals from the National Aeronautics Research and Development Policy[1] and Plan.[2] This R&D plan provided near-term (N+1), mid-term (N+2), and long-term (N+3) aeronautics goals from the current (N) generation of aircraft. NASA's Subsonic Fixed Wing and Supersonics Projects (Figure 1 and Figure 2) are each working towards their own noise, emissions, and fuel burn goals. Each project defined concept vehicles through NASA Research Announcements (NRAs) with industry and academia. A few of the N+3 vehicles submitted to the Subsonic Fixed Wing Project are shown in Figure 1.[3] These concepts have both conventional and unconventional engine configurations (Refs. 1 to 3). The Supersonics Project has also defined N+2 and N+3 vehicle concepts with a variety of engine configurations as shown in Figure 2.[4] These vehicle concepts utilize a highly variable cycle to reduce airport noise by utilizing subsonic jet exhausts at takeoff (Refs. 4 and 5). The current study investigates the impact of subsonic twin jets since both projects only have a community noise goal.

The most comprehensive twin jet experiments were performed by Kantola at the General Electric Corporate Research and Development Center under a U.S. Department of Transportation and Federal Aeronautics Administration contract (Refs. 6 and 7). These experiments evaluated convergent round and rectangular nozzles at three different spacings. The results from the experiments show that in the plane containing the jets, the noise emitted is up to 5 dB less than that of a single jet of the same size plus 3 dB,

(a) (b) (c)

Figure 1.—NASA's Fundamental Aeronautics Program Subsonic Fixed Wing Project N+3 concept vehicles from (a) Boeing (Ref. 1), (b) MIT (Ref. 2), and (c) Northrop Grumman(Ref. 3).

(a) (b) (c)

Figure 2.—NASA's Fundamental Aeronautics Program Supersonics Project concept vehicles (a) Boeing N+3 (Ref. 4), (b) Lockheed Martin N+3 (Ref. 5), (c) Lockheed Martin N+2.

[1]http://www.aeronautics.nasa.gov/releases/national_aeronautics_rd_policy_dec_2006.pdf
[2]http://www.whitehouse.gov/sites/default/files/microsites/ostp/aero-rdplan-2010.pdf
[3]http://www.nasa.gov/topics/aeronautics/features/future_airplanes.html
[4]2011 Fundamental Aeronautics Program Technical Conference, Mar. 2011, Cleveland, OH. Supersonics Project Overview Presentation. http://www.aeronautics.nasa.gov/pdf/supersonics.pdf

while the noise emitted out of the plane of the jets is equal to that of a single jet plus 3 dB. The data from this study were used by Lockheed to evaluate four engine supersonic cruise vehicle concepts under a contract with NASA Langley Research Center (Refs. 8 and 9). Lockheed estimated a 3 to 5 dB difference in emitted noise between four under wing engines and an over/under engine configuration. Recent experiments at NASA have added the effect of forward flight and found an increase in noise emitted out of the plane containing the two jets (Ref. 10). This data will be used to evaluate the effect of twin jet configurations on airport noise.

2.0 Experimental Setup

The experimental data reported in this paper were obtained in the Aeroacoustic Propulsion Laboratory (AAPL) at NASA Glenn Research Center. The AAPL is a 65 ft radius anechoic dome that encloses the Nozzle Acoustic Test Rig (NATR). The NATR is a free jet wind tunnel capable of providing up to Mach 0.35 through a 53 in. duct to simulate forward flight. The free jet wind tunnel surrounds the High Flow Jet Exit Rig (HFJER) which is a dual stream jet engine simulator that provides heated core and bypass flow to nozzle systems. The AAPL also contains a far-field overhead microphone array. The microphone array contains 24 microphones on a 45 ft arc at inlet polar angles every 5° from 45° to 160° (Ref. 11).

The twin jet model was mounted onto the core stream of the HFJER. Therefore, the bypass stream of the HFJER was matched to the conditions of the free jet in order to provide forward flight over the exterior of the twin jet model. Figure 3 shows the installation of the twin jet model onto the HFJER in the NATR. By rotating the model relative to the overhead microphone array, three different azimuthal directivity measurements were made for each configuration. The azimuthal angles, shown in Figure 4, correspond to an observer in the plane of the two jets, out of the plane of the two jets, and at 23° from the in-plane observer. This 23° position corresponds to the approximate lateral microphone location for a horizontal twin jet during FAA takeoff noise certification.

Figure 3.—Twin jet model installed on the High Flow Jet Exit Rig (HFJER) in the Nozzle Acoustic Test Rig (NATR) in the Aeroacoustic Propulsion Laboratory (AAPL) at NASA Glenn Research Center.

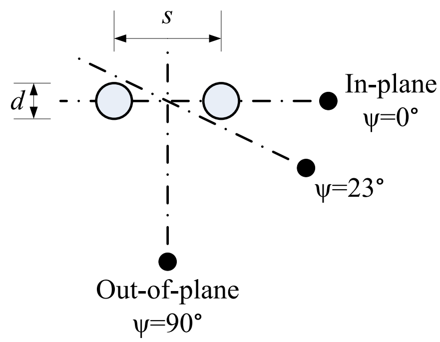

Figure 4.—Azimuthal microphone directivity.

Conic convergent 2-in. nozzles were tested at the four different spacings shown in Table I. The spacings range from a s/d of 2.63 to 5.54, where s is the center-to-center spacing and d is the nozzle diameter. The jet operating conditions presented are shown in Table II. The nozzle pressure ratios (NPR) shown are the ratios of jet stagnation pressure to the atmospheric pressure and the nozzle temperature ratios (NTR) are the ratios of jet stagnation temperature to the ambient temperature. The conditions are heated, but have different flight stream Mach numbers (M_{fj}). Single jet measurements were made by putting a cone over one of the twin nozzles to block the flow of air.

TABLE I.—TWIN JET SPACINGS

Spacing, s/d	
S1	2.63
S3	3.25
S5	4.39
S8	5.54

TABLE II.—JET OPERATING CONDITIONS

NPR	NTR	M_{fj}
1.70	3.11	0.00
1.70	3.11	0.10
1.87	3.12	0.30

3.0 Results

Acoustic data were acquired on the far-field overhead microphone array and microphone sensitivity, actuator, and diffraction corrections have been made. Background noise has been subtracted and free jet shear layer corrections have been applied using Amiet's method (Ref. 12). Atmospheric attenuation effects have been removed (Ref. 13) and the data were propagated to a 1-ft lossless arc and presented in 1/3 octave sound pressure level.

The single jet data are first compared against single jet measurements made by Kantola (Ref. 7) as well as with data taken on the Small Hot Jet Acoustic Rig (SHJAR) in the AAPL at NASA Glenn Research Center (Ref. 14). Then twin jet data at two polar and two azimuthal angles are compared against the twin jet measurements made by Kantola (Ref. 7). The twin jet data are then displayed in contour plots to show the twin jet effects on both the directivity and spectral shape. In order to show the significance of the twin jet effects, effective perceived noise levels (EPNLs) are calculated. The EPNL show the potential impact of twin jet effects to a system noise assessment.

3.1 Spectral Comparisons

In order to check the accuracy of the data obtained in this experiment, both single and twin jet data are compared against the data obtained by Kantola. Kantola's data were obtained with 1.5-in. convergent nozzles and microphone measurements were made on a 9-ft arc. Single jet data taken on NATR and SHJAR were both with 2-in. nozzles, but SHJAR data were measured on a 8.3-ft arc while NATR data were measured on a 45-ft arc. The NASA NATR and SHJAR data were scaled to a 1.5-in. diameter to account for the frequency and amplitude difference, and then propagated to a 9-ft arc at standard day to compare with the Kantola data. The jet velocity and temperature differences were accounted for by using the scaling presented by Khavaran and Bridges in Reference 14. The jet conditions and velocity power factors used in this comparison are shown below in Table III.

A comparison of scaled 1/3 octave SPL for single jet data is shown below in Figure 5. The 1/3 octave SPLs have been scaled to a 1.5 in. nozzle diameter at a 9 ft arc with the velocity power factors shown in Table III and are plotted against Strouhal number. At an inlet angle of 90°, the Kantola data is up to 2 dB louder than the NATR and SHJAR data when all data are scaled to the same. At an inlet angle of 150°, the Kantola data is 4 dB louder than the NATR and SHJAR data below St = 0.1, as shown in Figure 5(b). Some differences in spectral shape were expected due to the temperature difference of the jets, but higher noise levels are seen in Kantola's single jet data.

TABLE III.—CONDITIONS FOR SINGLE AND TWIN JET COMPARISONS

	d, in.	R/d	s/d	NPR	NTR	U_j/c	n (NTR, 90°)	n (NTR, 150°)
GE Kantola (Ref. 7)	1.5	72	2.67	1.64	2.38	1.36	5.85	7.50
NASA SHJAR (Ref. 14)	2.0	50	N/A	1.69	3.21	1.50	5.40	7.15
NASA NATR	2.0	270	2.63	1.70	3.11	1.48	5.42	7.18

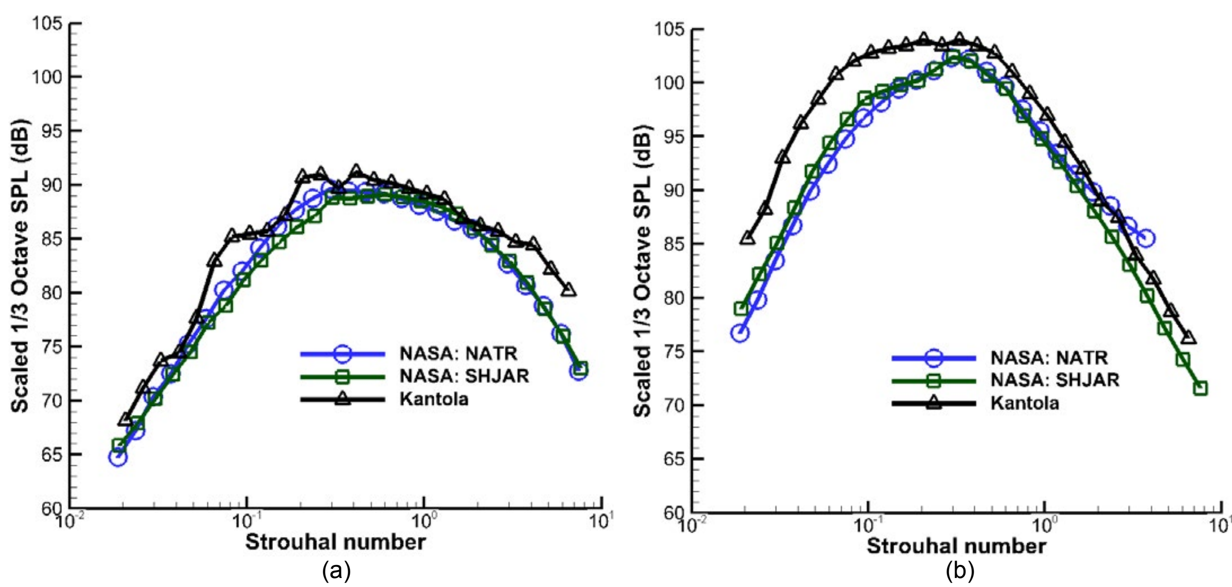

Figure 5.—Single jet scaled 1/3 octave SPL comparison at (a) θ = 90°, and (b) θ = 150°.

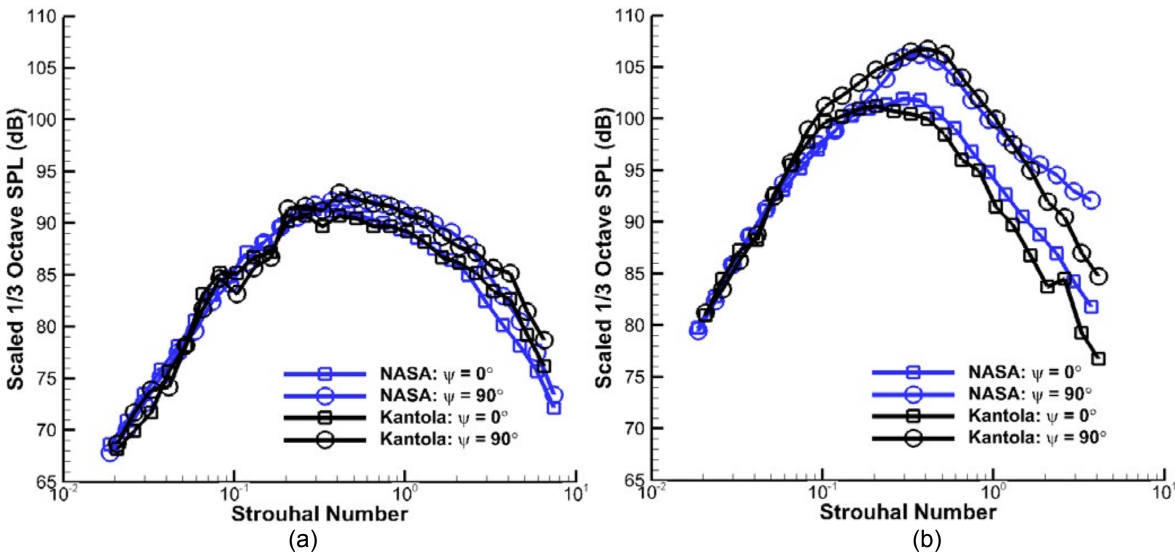

Figure 6.—Twin jet scaled 1/3 octave SPL comparison at (a) θ = 90°, and (b) θ = 150°.

A comparison of twin jet scaled 1/3 octave SPL between NATR and Kantola is shown below in Figure 6. The NATR twin jet s/d of 2.63 is compared against the Kantola twin jet spacing of 2.67. After applying the same scaling as used for the single jet comparison, the sound levels are within 1 dB for nearly all frequencies. The sound pressure levels are in agreement both in-plane (ψ = 0°) and out-of-plane (ψ = 90°) at the 90° and 150° inlet angles. When the same scaling is applied, the twin jet data collapses while the single jet data does not. This discrepancy is significant because the evaluation of twin jet data relies heavily on comparisons made with single jet data.

3.2 Octave Sound Pressure Level Contours

In Figure 7 and Figure 8, 1/3 octave sound pressure levels are presented in contour plots with the vertical axis showing the inlet angle and the horizontal axis showing the Strouhal number. The black lines show the corresponding sound pressure levels of a single jet plus 3 dB. The single jet plus 3 dB levels subtracted from the twin jet levels are defined as ΔSPL and are indicated with the colors. Red indicates that the twin jet levels are louder than those of a single jet plus 3 dB while blue indicates the twin jet levels that are lower than those of a single jet plus 3 dB at the same conditions. Figure 7 and Figure 8 are shown with each row at the same spacing and each column at the same jet conditions. The spacing increases down the columns as the free stream mach number increases from left to right. The three jet conditions in Table II correspond to the jet conditions shown in Figure 7 and Figure 8.

Figure 7 shows the 1/3 octave twin jet sound pressure levels out of the plane containing the two jets (ψ = 90°) relative to the sound pressure levels of a single jet plus 3 dB. The areas most affected are higher frequencies and downstream polar angles, indicated by the red regions. The increase in out-of-plane noise decreases with increasing forward flight Mach number (M_{fj}) relative to a single jet plus 3 dB. A valley bisects the peak jet noise at the larger spacings of S5 and S8, but weakens as the forward flight Mach number is increased. This valley is due to a cancellation of sound between the sound emitted from one of the jets and its reflection off the adjacent jet. While the noise emitted by each jet is incoherent of each other, it is possible to have reflections cancel the noise emitted from a jet at aft angles where the jet noise is coherent over a limited range of polar and azimuthal angles. The valley scales linearly with increasing spacing and weakens when sound between the jets is advected downstream by forward flight.

Figure 8 shows the 1/3 octave twin jet sound pressure levels in the plane of the two jets (ψ = 0°) relative to the sound pressure levels of a single jet plus 3 dB. Jet-by-jet shielding is evident at higher frequencies and at downstream angles, indicated by the blue regions in Figure 7. The magnitude of this shielding slightly decreases with increasing forward flight Mach number (M_{fj}), but is not sensitive to jet spacing.

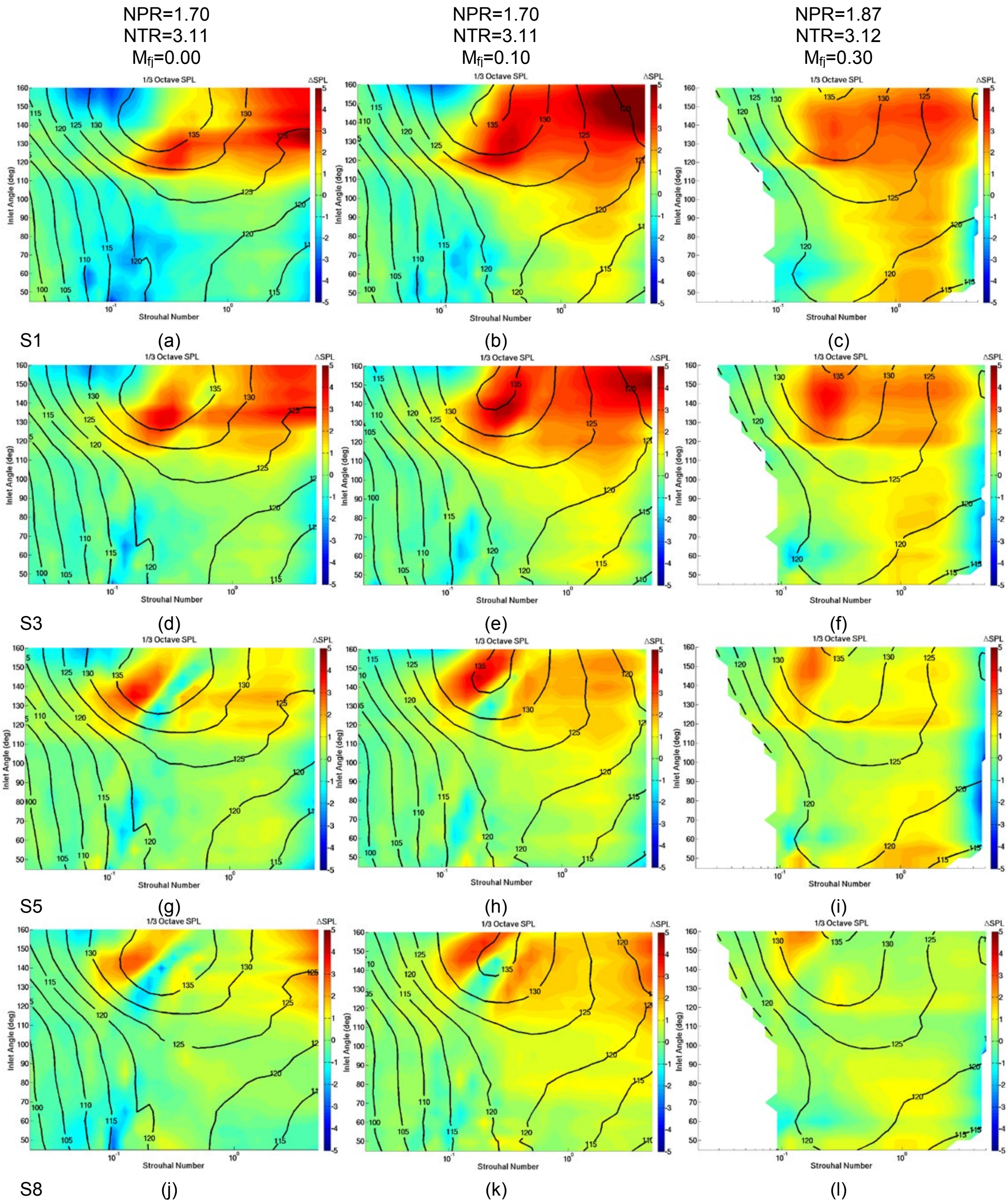

Figure 7.—Out-of-plane (ψ=90°) ΔSPL contours as colors and single jet levels as black lines for rows S1 (s/d 2.63) S3 (s/d 3.25), S5 (s/d 4.39), and S8 (s/d 5.54); and columns NPR=1.70, NTR=3.11, and M_{fj}=0.00; NPR=1.70, NTR=3.11, and M_{fj}=0.10; NPR=1.87, NTR=3.12, and M_{fj}=0.30.

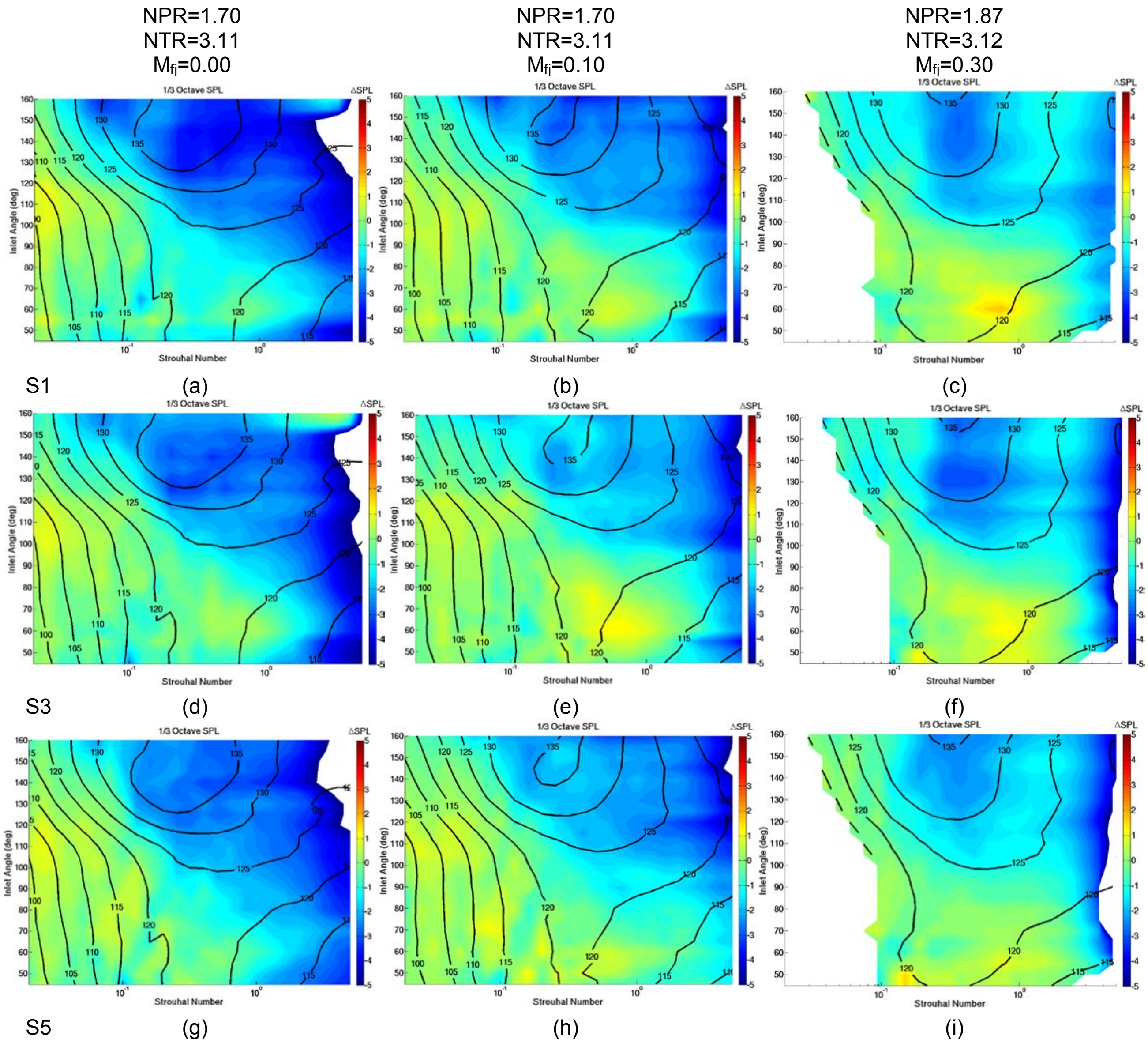

Figure 8.—In-plane (ψ = 0°) ΔSPL contours as colors and single jet levels as black lines for rows S1 (s/d 2.63) S3 (s/d 3.25), and S5 (s/d 4.39), and columns NPR=1.70, NTR=3.11, and M_{fj}=0.00; NPR=1.70, NTR=3.11, and M_{fj}=0.10; NPR=1.87, NTR=3.12, and M_{fj}=0.30.

Since the twin jet effects are concentrated at aft angles where jet noise is loudest, they have a significant potential impact on overall sound pressure level and effective perceived noise level calculations. Increases in sound pressure levels out of the plane of the jets (ψ = 90°) and decreases in the plane of the jets (ψ = 0°) weaken as sound is advected downstream due to forward flight.

3.3 Effective Perceived Noise Levels

In order to evaluate overall effect of twin jets on airport noise, effective perceived noise levels (EPNLs) were calculated . One-ft lossless narrowband 2-in. model scale data was scaled to full size jet diameters of 20-, 40-, 60-, and 100-in. Then the data were propagated to a 1775 ft linear array at standard day to give the approximate coordinates of the lateral microphone location used in FAA takeoff noise certification (Ref. 15). Since data were obtained at fixed azimuthal angles, a constant height flyover at Mach 0.3 was used for all jet conditions to account for the Doppler effect. Perceived noise levels were calculated and EPNLs were obtained for each full scale jet diameter. The addition of an incoherent jet is accounted for by adding 3 dB to the noise levels from a single jet at all frequencies. EPNLs are the sum of the maximum PNL, a duration factor, and a tone correction factor. The tone correction factor is not needed for subsonic jet noise and the duration factor would remain constant. The maximum PNL would increase by 3 dB, therefore, the EPNL would increase by 3 EPNdB. The twin jet effects will be evaluated by subtracting the EPNL from a single jet plus 3 EPNdB from the twin jet EPNL, which will be referred to as ΔEPNL. While jet noise is most significant at the lateral microphone location, the ΔEPNLs are valid for the flyover microphone location, which is measured at a distance of 1500 ft. Since the propagation and atmospheric absorption are linear, their values would cancel when subtracting the single jet plus 3 EPNdB EPNL from the twin jet EPNL.

Acoustic data were acquired with the same configuration and conditions three different days throughout the experiment to give a measure of repeatability. A 95% confidence interval was calculated at each jet condition based on the EPNLs, producing repeatability limits of ± 0.4 EPNdB. Figure 9 and Figure 10 show the calculated ΔEPNLs plotted against the full scale nozzle diameter for each spacing and azimuthal angle. The effect of full scale nozzle diameter is within the repeatability at each of the jet conditions in Figure 9 and Figure 10.

Figure 9 shows the ΔEPNLs at NPR=1.70, NTR=3.11, and M_{fj}=0.10 at four full scale nozzle diameters and four nozzle spacings. For a horizontal twin jet configuration with an s/d of 4.39 and 5.54, the single jet plus 3 EPNdB estimation is sufficient at the lateral microphone location, however, other twin jet configurations would require corrections up to 3 EPNdB. In the out-of-plane (ψ = 90°) direction, ΔEPNL increases with decreasing spacing. At ψ = 23°, ΔEPNL decreases with decreasing spacing, as the far jet becomes hidden by the near jet. In the in-plane (ψ = 0°) direction, the change in ΔEPNL is within the repeatability when the spacing is varied. The out-of-plane noise is up to 5 EPNdB higher than the in-plane noise. At all four spacings in Table I, enhanced mixing did not significantly decrease noise. Each jet resembles an independent source of noise and the differences in noise levels were due to the propagation of noise reflected between the two jets. Therefore, noise was reflected away from the in-plane direction (ψ = 0°) and towards the out-of-plane direction (ψ = 90°).

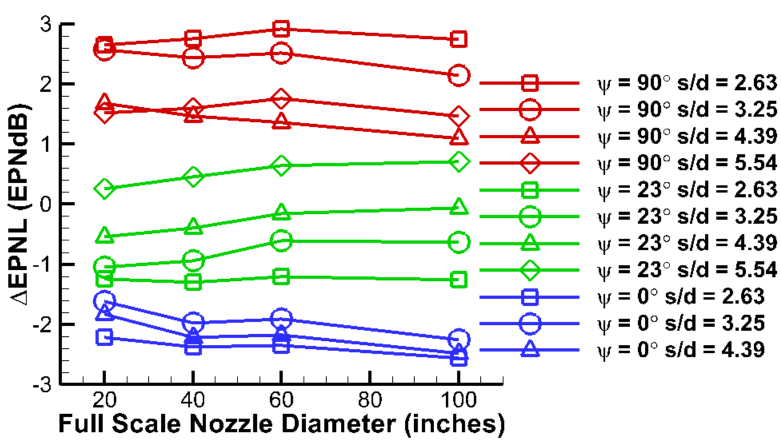

Figure 9.—Twin jet ΔEPNL comparison at NPR=1.70, NTR=3.11, and M_{fj}=0.10. Repeatability of ± 0.4 EPNdB.

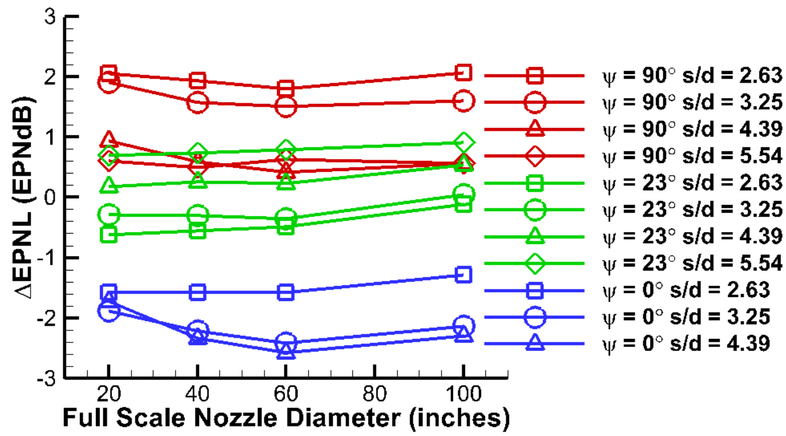

Figure 10.—Twin jet ΔEPNL comparison at NPR=1.87, NTR=3.12, and M_{fj}=0.30. Repeatability of ± 0.3 EPNdB.

Figure 10 shows the ΔEPNLs at NPR=1.87, NTR=3.12, and M_{fj}=0.30 with repeatability limits of ± 0.3 EPNdB. As seen in the contour plots of Figure 7, the ΔEPNLs out-of-plane (ψ = 90°) decrease as the forward flight Mach number is increased to 0.30, while the ΔEPNLs at ψ = 23° increased. The variation with spacing was not affected by the difference in forward flight Mach number. The single jet plus 3 EPNdB estimation would be sufficient for a horizontal twin jet configuration at any of the spacings for the lateral microphone location. The estimation would also be sufficient for an s/d of 4.39 and 5.54 for a horizontal twin jet configuration the flyover microphone location. Other twin jet configurations could require a correction of up to 3 EPNdB.

4.0 Conclusions

Engine configurations with multiple jets introduce an asymmetry to the azimuthal directivity of the jet noise. Current system noise predictions add the jet noise from each jet incoherently. Coherent interactions have been shown to effect the peak jet noise, but these effects are weakened with forward flight. These coherent interactions account for up to a 6 dB increase in out-of-plane noise levels over those of a single jet. At the four spacings tested between an s/d of 2.63 and 5.54, enhanced mixing did not significantly reduce noise levels. Therefore, the two jets acted as independent sources and the twin jet effects shown are due to reflections between the jets. Twin jet effects account for up to a 5 EPNdB difference between in-plane and out-of-plane azimuthal directions. Twin jets are typically estimated by adding 3 EPNdB to the noise radiated from a single jet. While this estimation is sufficient for some twin jet configurations, an error of up to ±3 EPNdB could be present in others.

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14. ABSTRACT Subsonic and supersonic aircraft concepts proposed through NASA’s Fundamental Aeronautics Program have multiple engines mounted near one another. Engine configurations with multiple jets introduce an asymmetry to the azimuthal directivity of the jet noise. Current system noise predictions add the jet noise from each jet incoherently, therefore, twin jets are estimated by adding 3 EPNdB to the far-field noise radiated from a single jet. Twin jet effects have the ability to increase or decrease the radiated noise to different azimuthal observation locations. Experiments have shown that twin jet effects are reduced with forward flight and increasing spacings. The current experiment investigates the impact of spacing, and flight effects on airport noise for twin jets. Estimating the jet noise radiated from twin jets as that of a single jet plus 3 EPNdB may be sufficient for horizontal twin jets with an s/d of 4.4 and 5.5, where s is the center-to-center spacing and d is the jet diameter. However, up to a 3 EPNdB error could be present for jet spacings with an s/d of 2.6 and 3.2.						
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