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Jet Noise at Take-off and Landing†

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Abstract

During take-off or landing, the jet of an aircraft is not aligned with the direction of flight. Effectively, the jet is in forward motion at an angle of attack. This causes significant distortion of the jet flow and its turbulence intensity and characteristics. In turn, this could lead to changes in the radiated noise spectrum and directivity. A quantitative investigation of this effect is carried out using the Tam and Auriault theory for noise from the fine scale turbulence. Numerical results indicate that for high subsonic and supersonic jets, the effect is generally small; in the order of 1 to 2 dB in parts of the spectrum, even though the jet flow is greatly distorted. This finding is new and quite unexpected.

1. Introduction

When a commercial jet aircraft takes off (see figure 1) or comes down for landing, it climbs out or descends at a relatively steep angle. In this configuration, the jet moves forward at an angle of attack. In the past, most jet noise investigations, both theoretical and experimental, concentrated on noise radiation into a static environment. To account for forward flight effects, fly-over experiments were carried out. However, as far as is known, fly-over measurements were confined, invariably, to level flights over a microphone or an array of microphones. Accuracy of fly-over measurements are generally affected by outdoor meteorological conditions. To remove such uncertain influence, simulated forward flight experiments[1−4] and theoretical prediction[5−9] were performed using an open wind tunnel. However, in almost all these works, the jet was aligned in a forward flight direction at zero angle of attack. Thus these experiments and prediction models did not actually simulate the actual aircraft take-off or landing configuration.

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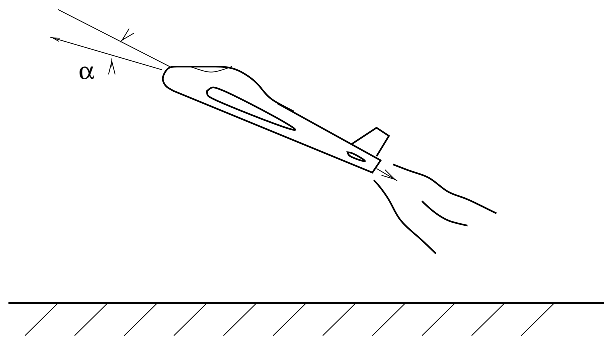


Figure 1. The take-off configuration of a jet.

For jets in forward flight at an angle of attack, the jet velocity profile becomes increasingly distorted in the downstream direction. If a circular nozzle is used, the constant velocity contours will no longer remain circular a few diameters downstream of the nozzle exit. The distortion of the jet flow will inevitably change the turbulence distribution in the jet and would, therefore, affect the radiated noise. For noise from the fine scale turbulence of the jet, the distortion of the mean flow will also affect the mean flow refraction effect. This has the potential to further modify the radiated noise spectrum and directivity.

The purpose of this paper is to assess, for the first time, the effect of angle of attack on the flow and noise radiation of a high speed jet in a take-off or landing configuration. According to Tam & Chen[10] and Tam, Golebiowski & Seiner[11] jet noise consists of two components. They are the noise from the large turbulence structures and the fine scale turbulence of the jet. Here, we will restrict our consideration to the noise from the fine scale turbulence only. The present method of investigation consists of two steps. First, we calculate the jet mean flow at an angle of attack inside an open wind tunnel. In this computation, a $k-\varepsilon$ turbulence model, Ref [12], is used to account for the turbulence of the jet flow. The computation solves the parabolized Reynolds Averaged Navier-Stokes Equations (RANS) by a marching scheme following the work of Ref [13]. Second, we calculate the radiated noise according to the theory of Tam & Auriault[14]. The computed values of k and ε from the first step are now used to provide turbulence information to the noise source function. To account for mean flow refraction, the adjoint Green's function method of Tam & Auriault[15] is employed. Since the jet profile is distorted, the adjoint Green's function will be computed numerically. In this work, it is recast as a sound scattering problem and solved by the DRP scheme[16] as described in Ref[13].

The changes in jet mean flow velocity as well as turbulence intensity, length and time scales due to angle of attack in forward flight will be reported. The effect of these changes on jet noise spectrum and directivity are investigated. The present study includes cold and hot jets at high subsonic and supersonic Mach numbers. Numerical results appear to indicate that at an angle of attack of 10 degrees or less, there are only minor changes in the jet noise spectrum; of the order of 1 to 2 dB in parts of the spectrum, even though the jet mean flow is highly distorted. This finding is unexpected but is useful from the point of view of aircraft community noise prediction.

2. Physical Model and Computational Methods

Let us consider a jet inside an open wind tunnel at an angle of attack α as shown in figure 2. Interest is in determining the noise radiated to the microphones outside the open wind tunnel and to compare the spectra and directivity with those at zero angle of attack.

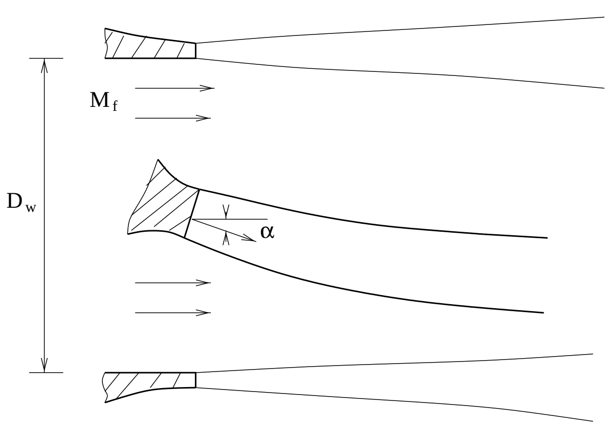


Figure 2. Jet at an angle of attack α in a simulated forward flight experiment.

Computationally, the present problem is quite similar to the forward flight effect study of Ref[9]. The major difference is that, at an angle of attack, the jet mean flow is highly distorted and three-dimensional. Because of the lack of strong upstream influence, the parabolized Reynolds Averaged Navier-Stokes equations (RANS) would be adequate for mean flow calculation. In the present investigation, the $k-\varepsilon$ turbulence model with model constants given by Thies and Tam[11] is used throughout. The parabolized RANS equations can be found in Ref[13] and will, therefore, not be repeated here. To calculate the flow and the $k-\varepsilon$ turbulence information for a jet in forward flight at an angle of attack, the computer code used in Ref[13] is used. What is required is a proper prescription of the starting conditions at the nozzle exit. Here we will let the x-axis be along the centerline of the open wind tunnel pointing in the direction of the flow as shown in figure 2. The z-axis points vertically up. The angle of attack is measured in the $x-z$ plane. The flow profiles at $x=0$ plane are taken to be,

$$u = \begin{cases} u_j \cos\alpha, & (y^2+z^2\cos^2\alpha) \le h_1^2 \\ u_f + (u_j\cos\alpha - u_f)\exp\left[-(\ln 2) \cdot \left(\frac{(y^2+z^2\cos^2\alpha)^{\frac{1}{2}}-h_1}{b_2}\right)^2\right], & (y^2+z^2\cos^2\alpha) \ge h_1^2 \text{ and } (y^2+z^2) \le h_2 \\ u_\infty + (u_f - u_\infty)\exp\left[(-\ln 2) \cdot \left(\frac{(y^2+z^2)^{\frac{1}{2}}-h_2}{b_2}\right)^2\right], & (y^2+z^2) > h_2^2 \end{cases} \quad (1)$$

$$v = \begin{cases} u_j \sin\alpha, & (y^2+z^2\cos^2\alpha) \le h_1^2 \\ u_j \sin\alpha \exp\left[(-\ln 2) \cdot \left(\frac{(y^2+z^2\cos^2\alpha)^{\frac{1}{2}}-h_1}{b_1}\right)^2\right], & (y^2+z^2\cos^2\alpha) > h_1^2 \end{cases} \quad (2)$$

$$T = \begin{cases} T_j, & (y^2 + z^2\cos^2\alpha) \le h_1^2 \\ T_f + (T_j - T_f)\exp\left[(-\ln 2) \cdot \left(\frac{(y^2+z^2\cos^2\alpha)^{\frac{1}{2}} - h_1}{b_1}\right)^2\right], & (y^2 + z^2\cos^2\alpha) > h_1^2 \text{ and } (y^2+z^2) \le h_2^2 \\ T_\infty + (T_f - T_\infty)\exp\left[(-\ln 2) \cdot \left(\frac{(y^2+z^2)^{\frac{1}{2}} - h_2}{b_2}\right)^2\right], & (y^2+z^2) > h_2^2 \end{cases} \quad (3)$$

$$p = \frac{\rho_j u_j^2}{\gamma M_j^2} \quad (4)$$

where u_j, u_f are the jet and the open wind tunnel velocities. $u_\infty = 0.02u_j$ is added to the outside flow to support the parabolized marching scheme. T_j, T_f and T_∞ are the jet, the open wind tunnel and the ambient temperatures. b_1 is the half-width of the shear layer separating the jet and the open wind tunnel flow and b_2 is that of the shear layer between the open wind tunnel and the ambient air. h_1 and h_2 are the core radii of the jet and the wind tunnel respectively.

To account for flow refraction effect on noise radiated by the fine scale turbulence of a jet, Tam and Auriault[14] employed the adjoint Green's function. For a three-dimensional non-axisymmetric jet, Tam and Pastouchenko[13] recast the adjoint Green's function as a scattering problem after invoking the locally parallel flow approximation. The scattering problem was solved in the time domain by marching the solution to a time periodic state. In this work, the same method is used. One distinct advantage of this method is that the shear layer refraction effect of the open wind tunnel is automatically included in the computation of the adjoint Green's function.

Once the mean flow and the values of k and ε of the jet flow as well as the adjoint Green's function are found, the far field noise spectrum $S(R,\Theta,\phi,fD_j/u_j)$ can be computed by the theory of Tam and Auriault[14]. The formulas for the far field noise spectrum are,

$$S\left(R,\Theta,\frac{fD_j}{u_j}\right) = 10\log\left[\frac{S(R,\Theta,\phi,f)}{p_{\text{ref}}^2\left(\frac{D_j}{u_j}\right)}\right] \quad (5)$$

where

$$S(R,\Theta,\phi,f) = (4\pi)^2\left(\frac{\pi}{\ln 2}\right)^{\frac{3}{2}} \iiint\limits_{\text{jet}} \frac{A^2 q^2 \ell_s^3}{\tau_s} \cdot \left\{ \frac{|p_a(\mathbf{x_2},\mathbf{x},\omega)|^2 \exp\left[\frac{-\omega^2\ell_s^2}{\overline{u}^2(4\ln 2)}\right]}{1+\omega^2\tau^2(1-\frac{\overline{u}}{a_\infty}\cos\Theta)^2} \right\} \mathbf{dx_2}. \quad (6)$$

In (6) $\mathbf{x_2}$ is the source point, and $\mathbf{x}$ is the far field measurement point with spherical coordinates (R,Θ,ϕ). The spherical coordinate system is centered at the nozzle exit with the polar axis coincides with the x-axis. Θ is the polar angle and ϕ is the azimuthal angle. Θ is related to the more often used inlet angle χ by $\chi = \pi - \Theta$. ϕ is measured from the z-axis as shown in figure 3. Also $\omega = 2\pi f$ is the angular frequency. p_{ref} is the reference pressure for the decibel scale. D_j and u_j are the fully expanded jet diameter and velocity. $\frac{fD_j}{u_j}$ is the Strouhal number. $\overline{u}$ is the mean flow velocity at the source point. a_∞ is the ambient sound speed. $p_a(\mathbf{x_2},\mathbf{x},\omega)$ is the adjoint Green's function. Equation (6) contains a number of turbulence quantities including q, the turbulence intensity, ℓ_s, the eddy size, and τ_s, the eddy decay time. They are related to k, the turbulence kinetic energy and ε, the dissipation rate, of the $k-\varepsilon$ turbulence model as follows:

$$\ell_s = c_\ell \ell = c_\ell\left(\frac{k^{\frac{3}{2}}}{\varepsilon}\right), \tau_s = c_\tau \tau = c_\tau\left(\frac{k}{\varepsilon}\right), q = \frac{2}{3}\overline{\rho}k$$

where $\overline{\rho}$ is the density of the jet mean flow at $\mathbf{x_2}$. c_ℓ, c_τ and A are the three constants of the theory. Their numerical values are[14]

$$c_\ell = 0.256, \qquad c_\tau = 0.233, \qquad A = 0.755.$$

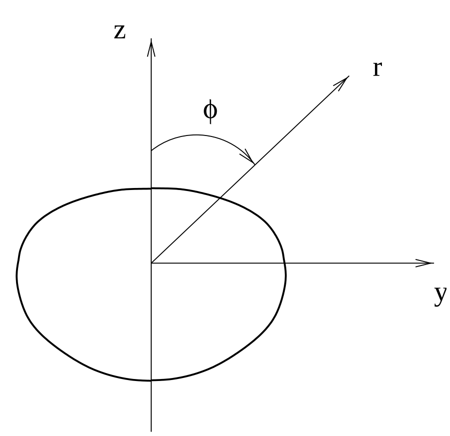


Figure 3. Definition of azimuthal angle ϕ and the $y-z$ plane.

3. Numerical Results

In this paper, the numerical values of the various jet parameters are taken to be,

$$\alpha \text{ (angle of attack) } = 10°,$$

$$M_f \text{ (forward flight Mach number) } = 0.2$$

$$\frac{h_1}{D_j} = 0.47, \qquad \frac{b_1}{D_j} = 0.03,$$

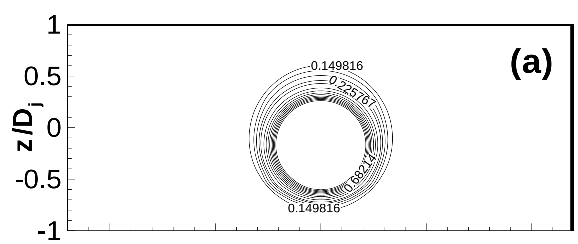
$$\frac{h_2}{D_j} = 9.5, \qquad \frac{b_2}{D_j} = 0.5.$$

In addition, the turbulence quantities at the $x = 0$ plane are assigned the following values,

$$\frac{k}{u_j^2} = 10^{-6}, \qquad \frac{\varepsilon D_j}{u_j^3} = 10^{-6}$$

3.1. Mean Velocity Contours

To show the significant distortion of the jet flow at 10° angle of attack, axial velocity contours at different downstream locations are plotted in the $y - z$ plane in figure 4. Shown in this figure is the case of a Mach 0.9 hot jet at a temperature ratio (T_r/T_a) of 2.8 where T_r is the jet reservoir temperature and T_a is the ambient temperature. Figures 4a to 4d show the distribution of contours of u/u_j at $x/D_j = 1.0$, 5.0, 10.0 and 20.0. Clearly, because of the jet is at an angle of attack, the flow is greatly distorted especially around the bottom side of the jet. The incoming flow (relative to the nozzle) compresses the lower part of the jet resulting in closely spaced velocity contours. What is shown in this figure is typical of all the cases examined in the present investigation. There is no question that the jet mean flow is non-axisymmetric and three-dimensional.



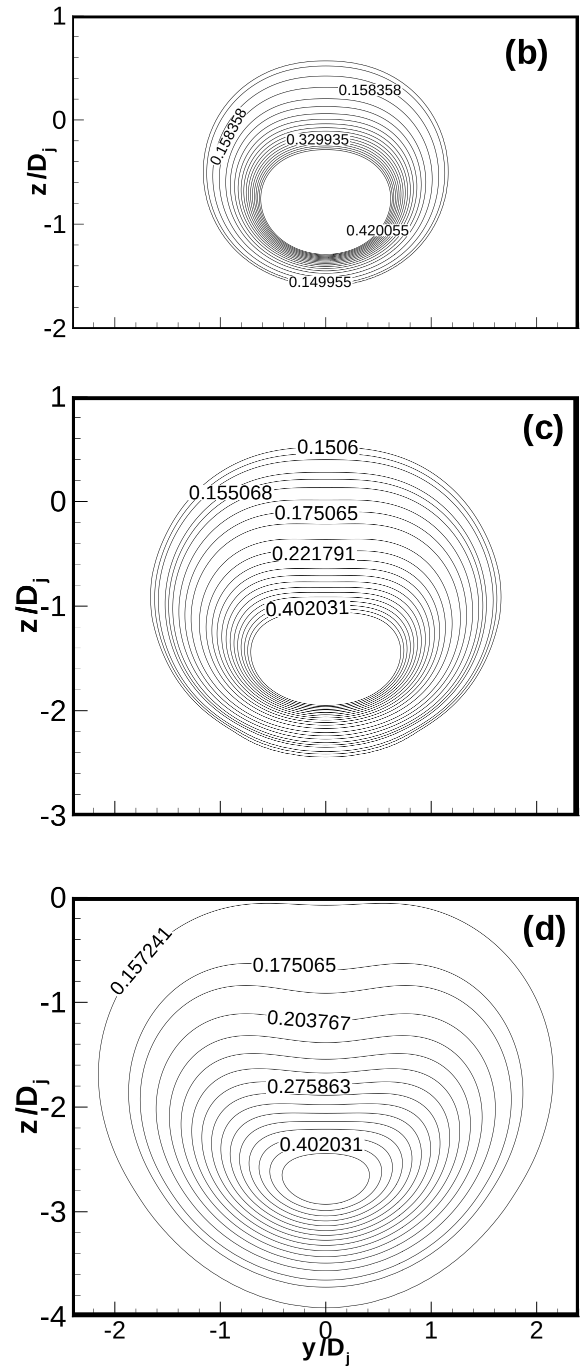


Figure 4. Contours of U/U_j for a Mach 0.9 jet at 10° angle of attack. $T_r/T_a = 2.8$, $M_f = 0.2$. (a) x/D_j = 1.0, (b) x/D_j = 5.0, (c) x/D_j = 10.0, (d) x/D_j = 20.0.

3.2. Effects on Jet Turbulence

The large distortion of the mean flow due to angle of attack also affects the distribution of turbulence intensity and its length and time scales. Figure 5 shows a comparison between the turbulence intensity distributions of a Mach 0.9 hot jet with $T_r/T_a = 2.8$ at zero angle of attack and at $10°$ angle of attack in the $x - z$ plane. An examination of these figures indicates that despite the obvious fact that the distribution is highly unsymmetric at $10°$ angle of attack, the magnitude of k/u_j^2 has not substantially changed.

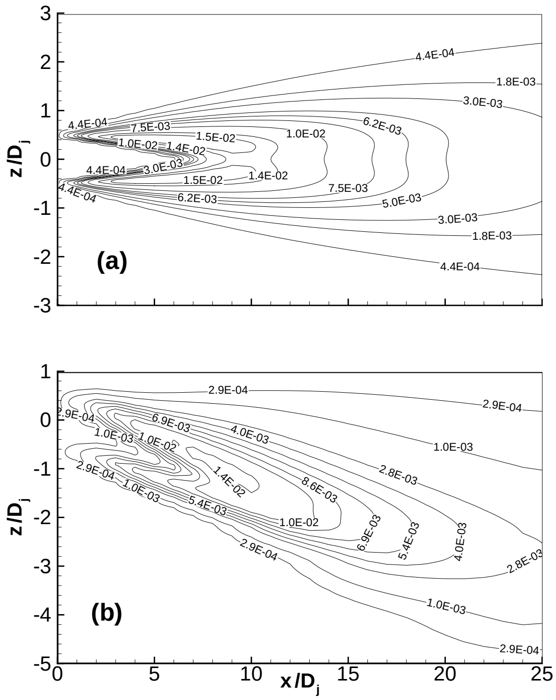
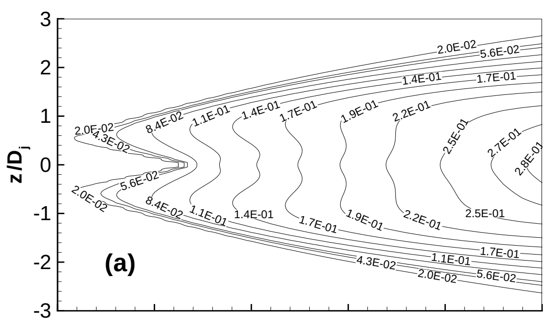


Figure 5. Contours of k/u_j^2 in the $x - z$ plane for a Mach 0.9 jet, $T_r/T_a = 2.8, M_f = 0.2$. (a) angle of attack = $0°$, (b) angle of attack = $10°$.

Figures 6a and 6b compare the eddy size $\ell s/D_j$. Because the thickness of the mixing layer on the bottom side of the jet is significantly reduced due to angle of attack, the eddy size is reduced. On the other hand, the thickness of the mixing layer on the top side of the jet is increased. The eddy size becomes larger. However, it is not immediately clear from this figure what the overall effect of these changes on the radiated noise could be.



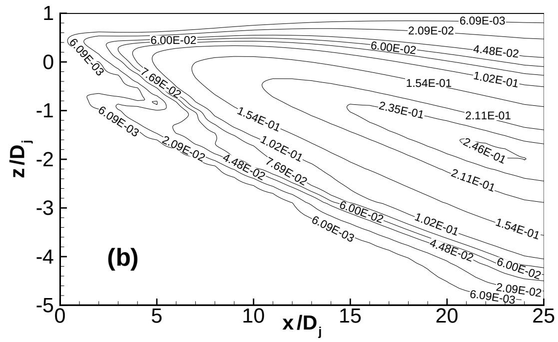


Figure 6. Contours of l_s/D_j in the $x - z$ plane for a Mach 0.9 jet, $T_r/T_a = 2.8, M_f = 0.2$. (a) angle of attack = $0°$, (b) angle of attack = $10°$.

Figure 7 shows contours of the eddy decay time $\tau_s u_j/D_j$ in the $x - z$ plane of the jet at zero and at $10°$ angle of attack. In the highly compressed bottom mixing layer of the jet at an angle of attack, the decay time becomes much shorter. On the other side of the jet, the turbulent eddies persist much longer before complete decay. Physically, the distortion of the jet mean flow and turbulence reduces the generation of high frequency sound on the top side of the jet mixing layer in favor of low frequency sound. The opposite is true on the bottom side. Thus it appears that there is a compensating effect on the overall noise radiated from the jet.

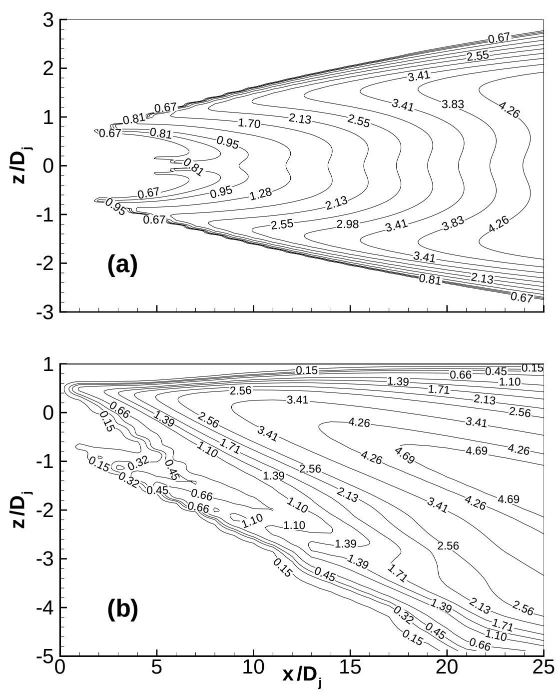


Figure 7. Contours of $\tau_s u_j/D_j$ in the $x - z$ plane for a Mach 0.9 jet, $T_r/T_a = 2.8, M_f = 0.2$. (a) angle of attack = $0°$, (b) angle of attack = $10°$.

3.3. Effect on Jet Noise Spectra

The effect of angle of attack on the noise spectrum and directivity for both high subsonic and supersonic jets are investigated. For directivity study, changes in the inlet angle χ as well as the azimuthal angle ϕ are included.

Figure 8 compares the calculated and measured noise spectra for a Mach 1.5 cold jet ($T_r = T_a$) with forward flight Mach number $M_f = 0.2$. The measured data are from Norum and Brown[4]. The angle of attack is zero. The calculated noise spectrum at zero angle of attack agrees well with the measurements. Plotted in this figure also are the calculated noise spectra for 10° angle of attack at azimuthal angle $\phi = 180°$, 150° and 120°. Figure 8a shows the case at $\chi = 120°$. Figure 8b and 8c show the cases at $\chi = 90°$ and 80° respectively. based on these results, it appears that angle of attack, up to 10 degrees, has only minor effects on the radiated noise spectra.

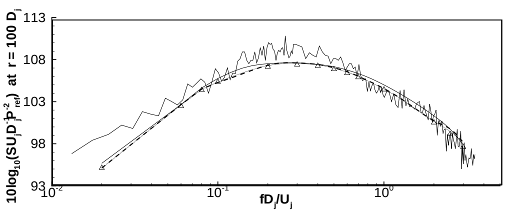


Figure 8a.

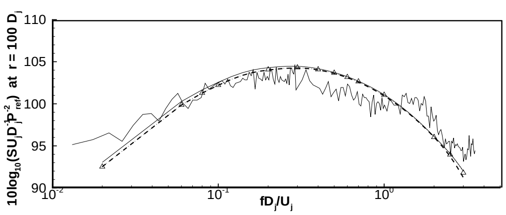


Figure 8b.

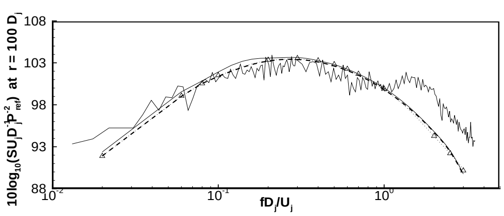


Figure 8c.

Figure 8. Comparisons of calculated and measured noise spectra for a Mach 1.5 cold jet ($T_r/T_a = 1.0$) at $M_f = 0.2$. 10° angle of attack; - - - - - - $\phi = 180°$, · · · · · · · · $\phi = 150°$, Δ $\phi = 120°$. Zero angle of attack ———. (a) $\chi = 120°$, (b) $\chi = 90°$, (c) $\chi = 80°$. Experimental data (Ref. 4) at zero angle of attack.

Figure 9 is again for a cold jet ($T_r = T_a$) but at subsonic Mach number of 0.98. The experimental data are from Ref[17]. The jet in the experiment is at zero angle of attack. The calculated noise spectra at zero angle of attack are in good agreement with measurements. Figure 9a shows the noise spectra at $\chi = 120°$ amd figure 9b those at $\chi = 90°$. Again the spectra at 10° angle of attach at different azimuthal angle ϕ remain essentially the same as those at zero angle of attack.

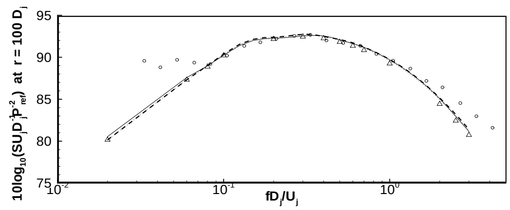


Figure 9a.

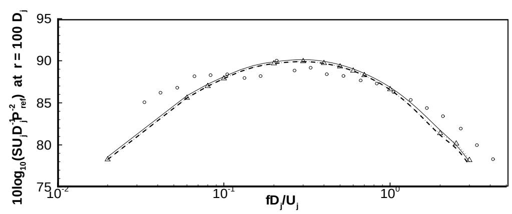


Figure 9b.

Figure 9. Comparisons of calculated and measured noise spectra for a Mach 0.98 cold jet ($T_r/T_a = 1.0$) at $M_f = 0.2$. 10° angle of attack; - - - - - - $\phi = 180°$, ······· $\phi = 150°$, Δ $\phi = 120°$. Zero angle of attack ———. (a) $\chi = 120°$, (b) $\chi = 90°$. $\circ$ experimental data (Ref. 17) at zero angle of attack.

Figures 10 and 11 are similar to figures 8 and 9 except that the jets are hot. Figures 10a and 10b at Mach 0.9 and temperature ratio 2.8 suggest that at $\chi = 60°$ and 90° there is a reduction of low frequency noise up to about 1.5 dB due to angle of attack. However, at $\chi = 120°$, figure 10c shows a noise increase at high frequencies, of the order up to 2.0 dB, at 10° angle of attack. Figures 11a and 11c at Mach 1.5 and temperature ratio 2.0 reveal that angle of attack can produce opposite effect in different direction of radiation. At 60° inlet angle, there is a reduction in high frequency noise. However, at 120° inlet angle, there is an increase in high frequency noise. The reduction and increase are around 1.0 to 1.5 dB.

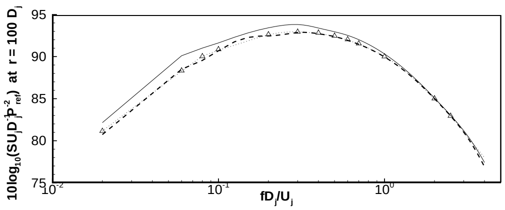


Figure 10a.

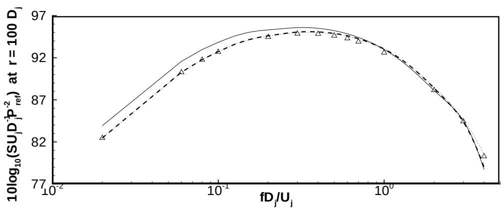


Figure 10b.

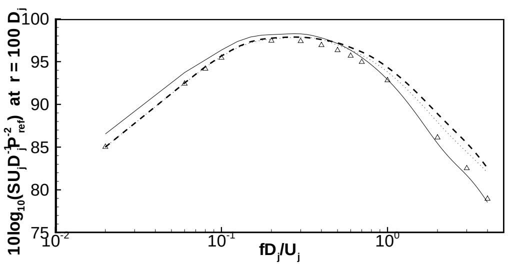


Figure 10c.

Figure 10. Calculated noise spectra for a Mach 0.9 hot jet at $T_r/T_a = 2.8$ and $M_f = 0.2$. ——— zero angle of attack; - - - - - - 10° angle of attack, $\phi = 180°$; · · · · · · · · 10° angle of attack, $\phi = 150°$; Δ 10° angle of attack, $\phi = 120°$. (a) $\chi = 60°$, (b) $\chi = 90°$, (c) $\chi = 120°$.

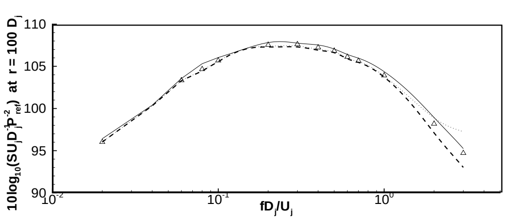


Figure 11a.

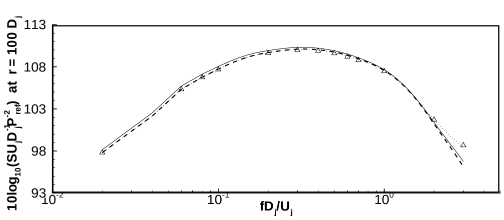


Figure 11b.

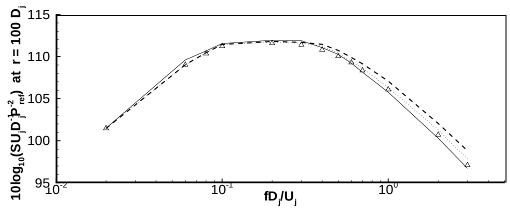


Figure 11c.

Figure 11. Calculated noise spectra for a Mach 1.5 hot jet at $T_r/T_a = 2.0$ and $M_f = 0.2$. ——— zero angle of attack; - - - - - - 10° angle of attack, $\phi = 180°$; · · · · · · · · 10° angle of attack, $\phi = 150°$; Δ 10° angle of attack, $\phi = 120°$. (a) $\chi = 60°$, (b) $\chi = 90°$, (c) $\chi = 120°$.

The results of figures 8 and 9 indicate that for cold jets at high subsonic and supersonic Mach number, angle of attack up to 10° causes no more than minor changes in the noise spectra. For hot jets, it is different. An increase or a decrease of noise level up to 1.5 to 2.0 dB is possible in part of the noise spectrum. As noted in Sections 3.1 and 3.2, angle of attack can lead to a redistribution of turbulence intensity and large distortion of the mean flow. With a thinner shear layer on the bottom side of the jet there is a significant change in the mean flow refraction effect on radiated noise. In the present study, there is no indication that either the noise source redistribution or the change in mean flow refraction effect is dominant. Without a dominant mechanism associated with a jet at an angle of attack, it is not possible to anticipate by simple reasoning whether there is a noise increase or decrease. It appears that only a full calculation of the noise spectrum can provide an assessment of the effect of angle of attack at a given jet operating condition.

4. Concluding Remarks

At take-off or landing, the jet of an aircraft moves forward at an angle of attack. The effect of angle of attack on jet noise has not been investigated before. In this paper, the case of a jet at an angle of attack of 10 degree in simulated forward flight is considered. Only the effect of angle of attack on the noise from the fine scale turbulence of the jet flow is studied. Calculated results for high subsonic and supersonic jets reveal that the effect is unexpectedly small. It is not a significant factor (only about 1 to 2 dB change in noise level in some part of the spectrum for hot jets) for community noise consideration.

It must, however, be reminded that turbulent mixing noise of a jet is made up of two components. In this work, only the fine scale turbulence noise is investigated. It is likely that the distortion of the mean flow of a jet due to angle of attack could cause considerable changes in the large turbulence structures of the jet flow. This, in turn, could affect the radiated noise. The magnitude of this effect has yet to be quantified. It is hoped that such a study could be carried out either computationally or experimentally in the near future.

Acknowledgments

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