Effects of External Boundary-Layer Flow on Jet Noise in Flight

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The effects on jet flow of the external boundary-layer flow emanating from the trailing edge of an engine cowl in flight has been shown to be the main reason for the disparity between predicted and experimental results obtained from flight measurements. Flight simulation experiments indicate that the external boundary-layer flow tends to shield the jet flow in flight. This in turn modifies the jet noise source in flight and consequently the radiated noise from aircraft in flight. Close to $\theta_I = 90°$ and in the forward quadrant, this study indicates that the far-field jet noise and its spectrum scales approximately with the absolute jet velocity instead of the relative velocity as has been assumed in the existing prediction models.

Nomenclature

a_0 = ambient acoustic velocity
d = primary nozzle exit diameter
f = frequency
n = flight velocity reduction exponential
M_a = V_I/a_0 flight Mach number
M_c = eddy convection Mach number
M_c' = eddy convection Mach number in flight
u' = velocity fluctuation in x direction
U = mean velocity in x direction
$\bar{U}$ = reference velocity
v' = velocity fluctuations in y direction
V = mean velocity in y direction
V_I = flight velocity
V_J = mean nozzle exit velocity
V_0 = centerline velocity in the jet flow
x = streamwise coordinate
y = transverse coordinate
α = spreading rate of the mixing layer
θ_I = angle to the intake
δ = boundary-layer thickness

Introduction

ACCORDING to the Ffowcs-Williams and Ribner theories of aerodynamic noise from a turbulent jet in flight,[1-3] the effect of forward flight of an aircraft on the far-field jet noise level is that the radiated noise should decrease with an increase in the forward velocity of the aircraft. This noise reduction results from reduced shear in the mixing layer, which in flight is assumed to scale with the relative velocity $V_{rel} \equiv V_J - V_I$, where V_J is the mean jet velocity and V_I is the forward velocity of the aircraft. Flight data of jet noise results[4-9] on the contrary, show no decrease in the noise at $\theta_I = 90°$. In fact, some flight results show an increase in the noise level in the forward quadrant.

Attempts to clarify the reasons for this difference between the theoretical predictions and experimental observations have been undertaken by simulating flight jet noise both in wind tunnel and in spinning rig experiments.[6,7] Results of spinning rig experiments do not show a reduction in jet noise level as expected theoretically. Results of wind tunnel simulation of a jet in flight show that a reduction in jet noise occurs with an increase in flight speed, but this decrease is not as large a power of relative velocity as expected. Furthermore, it is observed that noise reduction follows a power law relationship, $(V_{rel})^n$ where n is a strong function of θ_I, the angle to the intake. The exponent has a value of approximately $n = 7$ close to the jet axis as expected theoretically and decrease gradually to a value of $n \simeq 5$ or less close to $\theta_I = 90°$.

The directional distribution of the forward velocity effect on radiated noise is a strong proof of the effect of the boundary-layer flow over the engine cowl on the development of jet flow in flight. The presence of the outer boundary-layer flow at the nozzle exit will strongly affect the development of the self-preserving plane mixing layer region of the axisymmetric jet flow as defined by Liepmann and Laufer.[10] In this part of the flow, jet flow may generate noise like a static jet in flight. As one would expect, in this region, Reynold stresses $\overline{u'v'}$ will not scale with $V_{rel} \equiv V_J - V_I$. The noise generated from this region (relatively high frequency noise) contributes significantly to radiated noise near $\theta_I = 90°$ and in the forward quadrant. In their study of the effects of forward speed on turbojet exhaust silencers, Brooks and Woodrow[5] also show the jet noise to correlate well with absolute jet velocity rather than relative velocity in the forward quadrant. It is thus believed that improper accounting of the noise sources from the initial part of the jet flow in flight is one of the main causes for disagreement between the predicted results obtained from the Ffowcs-Williams and Ribner analyses and results obtained from the flight measurements.

Development of the shielded jet flow region is critically dependent on the initial engine cowl flow conditions at the point of separate, viz., mean velocity profile, boundary-layer thickness, freestream turbulence, presence of any external body, etc. These initial conditions may differ due to engine installation on various aircraft. Thus the radiated noise from two different aircraft in flight with identical engines may differ. This conclusion is supported by results shown in Figs. 12 and 13 in Ref. 6. In those experiments, the RB-211 engine was tested on two different aircraft, viz., the Lockheed L1011 and the VC-10. Even though the static results look similar, the flight results are quite different. Because of the different engine cowl designs and their installations, the development of the jet mixing layer originating at the nozzle trailing edges may differ under flight conditions for these aircraft. These different designs will result in dissimilar shearing stresses $\overline{u'v'}$ in the two jet flows and consequently a varying acoustic far-field level in flight as observed.

The importance of initial conditions on the development of the mixing layer, shearing stresses, and radiated noise, etc.

Presented as Paper 76-558 at the 3rd AIAA Aero-Acoustics Conference, Palo Alto, Calif., July 20-23, 1976; submitted Sept. 2, 1976; revision received Feb. 14, 1977.

Index categories: Jets, Wakes, and Viscid-Inviscid Flow Interactions; Noise.

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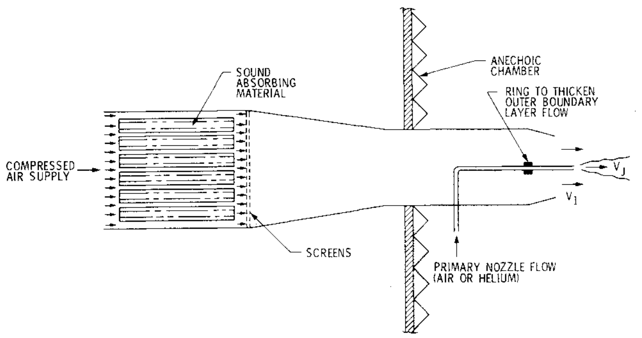

Fig. 1 Sketch of the flight simulation experiment.

has been demonstrated by Bradshaw.[11,12] Bradshaw observed that the high-frequency jet noise content was reduced by tripping the boundary layer. In general the radiated noise was reduced by increasing the boundary-layer thickness at a separation for a given jet Mach number. This reduction may have been caused by a shortening of the high-intensity turbulent region as pointed out by Lighthill[13] or by a change in exit velocity profile as observed by Powell and discussed below. Mollo-Christensen, et al.,[14] Csanady,[15] and Olsen et al.[16] also pointed out the effect on initial flow conditions on radiated jet noise. Measurements of the two-dimensional mixing layer by Batt[17] clearly indicate the effect of tripping of the boundary layer on the mixing layer development and the intensity of the shearing stresses. There is, therefore, no doubt that the engine cowl boundary-layer flow will have a pronounced effect on the development of the jet flow and consequently the radiated noise under flight conditions.

These conclusions are also strongly supported by Powell's results.[18,19] Here the influence of the exit velocity profile on the jet noise was studied. It was pointed out that mean velocity profile at nozzle exit has an influence on the shearing stresses in the mixing layer of the jet flow and on the radiated noise. By reducing the mean shear in the exit velocity profile, i.e., from square to approximately parabolic velocity profile with the same maximum centerline jet velocity, both the radiated noise and the high-frequency contents of it were reduced.

It was therefore concluded that detailed measurements of the effects of outer flow on the jet mixing layer and on the radiated noise were necessary for elucidating the effects of forward flight on jet noise. Such experiments were conducted and the results are discussed in the following sections.

Experimental Facility and Instrumentation

Flight simulation experiments were performed in an anechoic chamber using a 1.27-cm-diam primary nozzle in a 12.7-cm-diam free-jet flow. For the details of the setup, see Fig. 1. A free-jet velocity as high as 100 m/sec could be attained. The primary nozzle was convergent; the exit Mach number $M \equiv V_J/a_0$, was varied up to about 0.9. As shown in Fig. 1, the outer boundary-layer flow could be altered by placing a ring around the outside of the primary nozzle, or by suction of the boundary-layer flow for a fixed flight simulation velocity V_l. By traversing a pitot tube accurately across the jet flow, the mean velocity profiles at various downstream locations were measured. The far-field jet noise was measured with 1.27-cm-diam microphones. The microphone data was recorded on tape and played back through a correlation instrument to obtain the spectrum of the jet noise signal.

The instant spark shadowgraphs of the jet flow were taken using an electronic stroboscope. A density gradient caused by the injection of helium gas through the primary nozzle into the free-jet air flow was employed for taking spark shadowgraphs. The flash duration of this stroboscope was less than 3 μsec, which was short enough to "freeze" the flowfield.

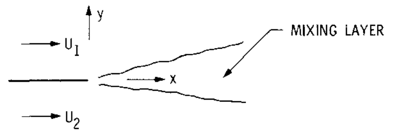

Fig. 2 Incompressible plane mixing layer sketch.

As indicated in Fig. 1, the outer flow passed through a duct approximately 60-cm-long, which contained absorbing material. Throughout the experiments, the background noise caused only by the outer flow was measured. Results showed that up to about $V_l \simeq 100$ m/sec, this background noise was less than 85 dB at all angles. This was much less than the measured jet noise. Since this investigation was undertaken from a conceptual point of view, i.e., to determine whether the outer boundary-layer flow has an effect on radiated jet noise or not, it was not deemed necessary to make any corrections for background noise.

Spreading of a Plane Turbulent Mixing Layer

The results presented on the spreading of the plane turbulent mixing layer shown below were used to interpret the flight simulated jet flow shadowgraph pictures in the following section.

The time mean continuity and x-momentum equation for the incompressible plane mixing layer with velocity U_l and U_2 can be written as (Fig. 2)

Continuity

$$\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0 \tag{1}$$

x-Momentum

$$U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} = -\frac{\partial}{\partial y}\overline{u'v'} \tag{2}$$

The usual boundary-layer approximation that gradients in the y direction are much greater than along the x direction has been made. It is also assumed that the velocity fluctuations u' and v' are comparable in magnitude and they scale with the shear $\Delta U = U_l - U_2$. If $\bar{U}$ is some mean velocity, e.g., $(U_l + U_2)/2$ then from dimensional arguments [using Eqs. (1) and (2)] it can be shown that

$$\overline{u'v'} \sim \alpha^2 \bar{U}^2 \tag{3}$$

$$\overline{u'v'} \sim (\Delta U)^2 \tag{4}$$

α is the spreading rate dy/dx of the mixing layer.

It is clear from Eq. (3) that for a given velocity $\bar{U}$, one can infer the Reynolds stresses $\overline{u'v'}$ qualitatively from the spreading rate of the mixing layer. Increased spreading rate α will result in higher Reynolds stresses in the mixing layer and vice versa.

Flow Visualization

The effect of the outer boundary-layer flow on the development of the primary nozzle jet flow was studied by injecting helium gas from the nozzle jet flow into the outer airstream. Instantaneous shadowgraphs of the jet flow were taken under a wide range of flow conditions.

Figure 3 shows an instantaneous shadowgraph of the jet flow with and without the outer flow. The nozzle jet flow velocity $V_J = 270$ m/sec. In Fig. 3a, there was no outer flow. Figure 3b shows the jet flow with a velocity ratio $V_l/V_j = 0.28$. As compared to shadowgraph a, the spreading in shadowgraph b is quite small. This is expected because the outer flow causes a reduction in the Reynolds stresses.

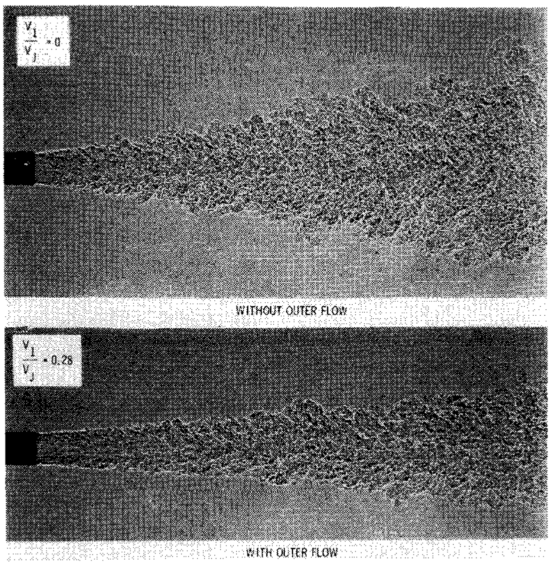

Fig. 3 Shadowgraph showing the effect of outer flow on the development of jet flow.

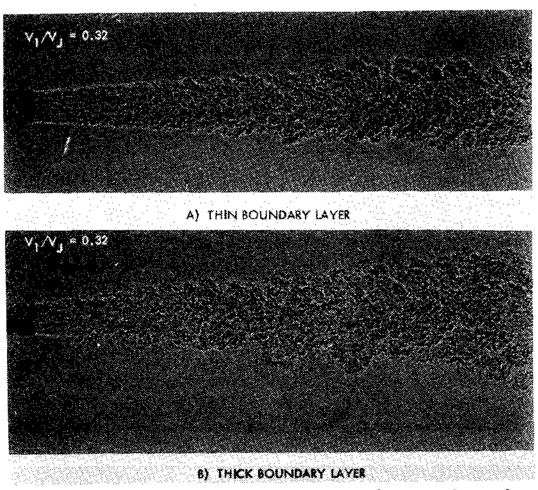

Fig. 4 Shadowgraph showing the effect of outer boundary-layer flow on the development of jet flow.

The shadowgraph in Fig. 4 shows the structure of the jet for a velocity ratio $V_l/V_J = 0.32$ with $V_J = 270$ m/sec for both thin and thick outer boundary layers. The thickness of the initial outer boundary layer was approximately 20% of the nozzle jet diameter d. With the ring in place, this boundary-layer thickness was increased to approximately 25 to 30% of the jet diameter.

It was surprising to observe that the effect of changing the initial outer boundary layer on jet spread was noticed many diameters (as much as $x/d \simeq 8$) downstream from the nozzle exit. Because of the increased jet spreading with the thicker boundary layer (Fig. 4b) as compared to a thinner boundary layer (Fig. 4a) it is expected that more noise would be radiated when the boundary layer was thicker because of the increased Reynolds stresses. It should also be noted that the initial spread of the jet flow with a thicker boundary layer (Fig. 4b) where $V_l/V_j = 0.32$ is quite similar to the one without outer flow as shown in Fig. 3a. This is an indication that the outer boundary-layer flow tends to "shield" the jet flow. Consequently the jet flow initially spreads as though it were unaffected by the presence of the outer flow. In other words the jet flow close to the nozzle exit in flight behaves like a static jet.

Jet Noise Measurements

Flight simulation experiments indicating the effect of outer boundary-layer flow on jet noise is shown in Fig. 5. The

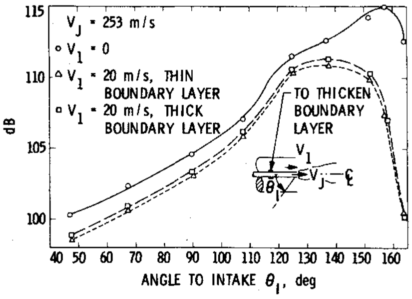

Fig. 5 Effect of outer boundary-layer flow on jet noise in flight.

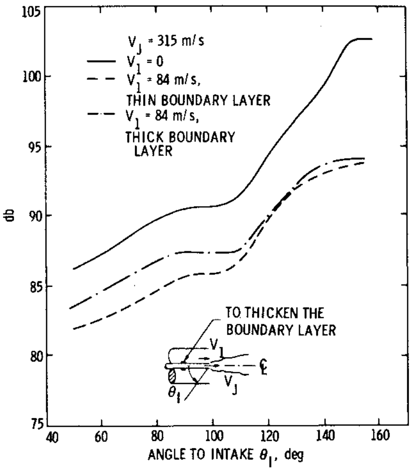

Fig. 6 Effect of outer boundary-layer flow on jet noise in flight.

primary jet velocity V_J was 253 m/sec and the outer flow velocity $V_l = 20$ m/sec. The noise due to outer flow was only 85 dB or less at all angles θ_l. The jet noise in these measurements has been normalized to one meter from the nozzle exit. The results in Fig. 5 show a reduction in radiated noise at all angles with forward velocity. The jet noise increased for the same flight velocity $V_l = 20$ m/sec for a thick outer boundary-layer flow as compared to a thin one. Though the increase is only half a dB, it was very consistent at all angles θ_l.

In the above experiments, the initial boundary layer was quite thick, i.e., δ/d at nozzle exit was approximately 0.2. With a primary nozzle of shorter length, the initial outer flow boundary-layer thickness was reduced to $\delta/D \simeq 0.07$ at nozzle exit with $V_l \simeq 50$ m/sec.

Figure 6 shows the effect of outer boundary-layer flow on the radiated noise level using the short nozzle mentioned above. The primary jet velocity $V_J = 315$ m/sec with outer flight velocity $V_l = 84$ m/sec, which gave an outer boundary-layer thickness δ/d at nozzle exit of about 0.05. The effect of thickening the boundary layer on jet noise close to $\theta_l = 90°$ was significant as compared to the previous set of experimental data where there was initially a relatively thick initial boundary layer (Fig. 5). Close to the jet axis, radiated noise was not altered much by a change in the initial boundary-layer thickness.

The influence of forward velocity on noise spectrum at $\theta_l = 90°$ and $\theta_l = 150°$ are shown in Figs. 7 and 8, respectively. The jet velocity V_J was 330 m/sec with velocity ratio $V_l/V_J = 0.3$. Results in Fig. 7 show a reduction of overall sound pressure level of about 2.5 dB when there was a change from static to flight condition. The spectrum is almost identical with and without the outer flow at $\theta_l = 90°$. The spectrum close to jet axis, however, is significantly altered by the forward velocity. There was a reduction of approximately 8 dB in the overall sound pressure level at $\theta_l = 150°$ with a shift of noise spectrum to lower frequencies as shown in Fig. 8. The

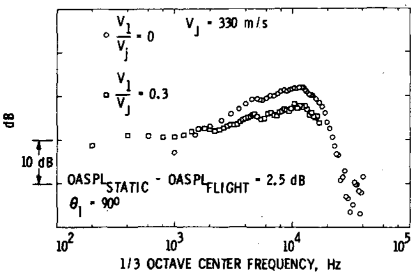

Fig. 7 Effect of forward flight velocity on jet noise spectrum at $\theta_l = 90°$.

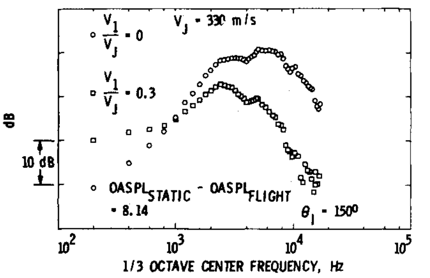

Fig. 8 Effect of forward flight velocity on jet noise spectrum at $\theta_l = 150°$.

measurements at other jet velocities and different flight simulation velocities also showed the same trend in the noise behavior.

Relation of Outer Boundary-Layer Flow to Radiated Noise

Interferences Drawn from Some Results Compared with Existing Models

The aforementioned results show that initial boundary-layer flow plays an important role in turbulence generated noise under flight conditions. Scarcely any change in the noise spectrum was observed close to $\theta_l = 90°$ and in the forward quadrant with forward velocity. The spectrum for $\theta_l \simeq 90°$ contains comparatively high frequency noise than the spectrum close to jet axis, i.e., $\theta_l \simeq 150°$.

The high-frequency jet noise that is generated close to the nozzle exit is not sensed close to the jet axis because of sound refraction effects through the jet flow. Frequency scales with the shear-layer thickness, i.e., the smaller the shear-layer thickness the higher the frequency, and vice versa. Small reduction in jet noise and its spectrum close to $\theta_l = 90°$, and in the forward quadrant in flight as compared to $\theta_l \simeq 150°$, strongly suggests that high-frequency jet noise sources (which lie close to the nozzle exit) are not altered much with forward velocity. As shown in Fig. 9, it seems more appropriate to assume that the noise sources close to the nozzle exit scale with $V_J - V_{\min}$ or approximately as V_J instead of $V_J - V_l$ as has been assumed in existing prediction models. The effect of outer boundary-layer flow on the development of the initial jet flow in Fig. 9 has been exaggerated to demonstrate this fact. The dip in the mean velocity profile close to the nozzle exit is due to a deficit of momentum in the boundary-layer flows on two sides of the primary nozzle. Their effect may last a few jet diameters (Fig. 4) before a reduction (due to flight velocity) in shearing stresses in the mixing layer is fully accomplished.

Figure 10 shows the velocity ratio V_0/V_J, $(V_0 - V_l)/V_J$ and $(V_0 - V_{\min})/V_J$ as a function of downstream distance x/d with $V_J = 330$ m/sec and $V_l = 84$ m/sec. As one would expect the effect of the outer flow increases the length of the potential core. The dip in the mean velocity profile $(V_0 - V_{\min})/V_J$ as shown in Fig. 10 is a function of initial flow conditions, e.g., the ratio of outer flow boundary-layer

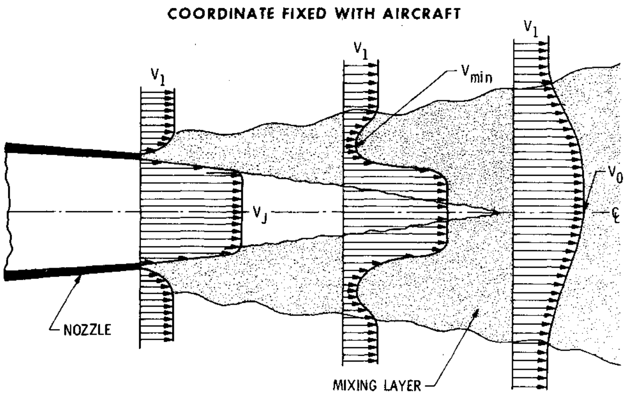

Fig. 9 Axisymmetric mixing layer in flight.

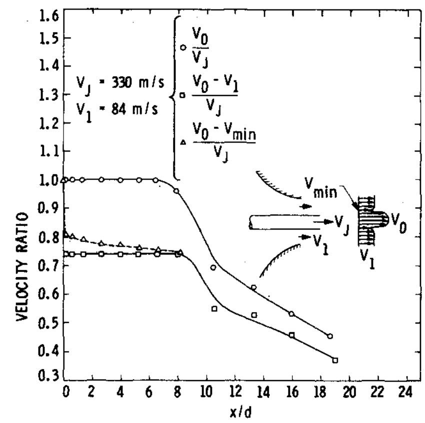

Fig. 10 Influence of forward flight velocity on the development of jet flow.

thickness to jet diameter, angle of attack of the aircraft, presence of any external body, etc. These effects of the initial flow conditions on the mean velocity profile, and consequently the jet noise, have not been taken into account in the prediction model to be discussed in the next section.

In the prediction model that follows, a correction to the jet noise source has been suggested. The results from this modified jet noise prediction in flight have then been compared with the flight results.

Modification of Prediction Model for Jet Noise Source Strength in Flight

According to the Ffowcs-Williams[1] and Ribner[2] analyses, the overall sound pressure level from a static turbulent jet is given by

$$(\mathrm{OASPL})_{\mathrm{static}} = 10\log_{10}\{V_J^8[(1+M_c\cos\theta_l)^2 + \alpha^2 M_c^2]^{-5/2}\} + \mathrm{const} \tag{5}$$

where V_J = jet velocity, $M_c \simeq 0.65\, V_J/a_0$, and $\alpha \simeq 0.3$.

For the far-field jet noise in forward flight, Ffowcs-Williams concludes that the turbulence generated noise scales with relative velocity $V_{\mathrm{rel}} = V_J - V_l$, where V_l is forward jet velocity. After making corrections due to the moving noise source under flight conditions, the overall sound pressure level from a turbulent jet in flight is given as:

$$(\mathrm{OASPL})_{\mathrm{flight}} = 10\log_{10}\left\{V_{\mathrm{rel}}^8\left(\frac{V_J}{V_{\mathrm{rel}}}\right) \times [(1+M_c'\cos\theta_l)^2 + \alpha^2 M_c'^2]^{-5/2} \times (1 - M_a\cos\theta_l)^{-1}\right\} + \mathrm{const} \tag{6}$$

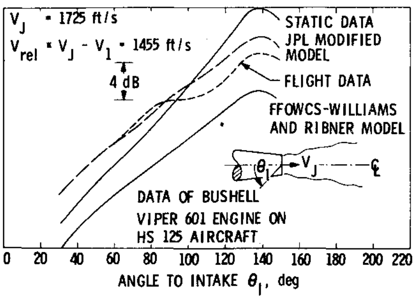

Fig. 11 Comparison with predictions of jet noise under static and flight conditions, $V_J = 1725$ fps, $V_I = 270$ fps.

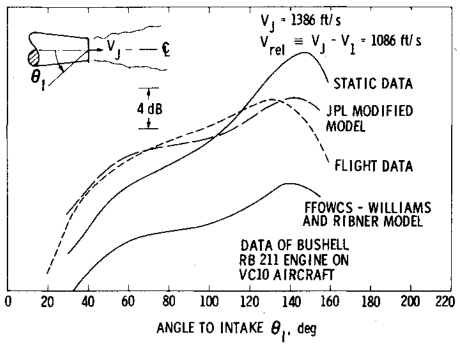

Fig. 12 Comparison with predictions of jet noise under static and flight conditions, $V_J = 1386$ fps, $V_I = 300$ fps.

where $M_c' = 0.65\ V_{\rm rel}/a_0$ and $M_a = V_I/a_0$.

In Eq. (6), the term $(V_J/V_{\rm rel})$ is due to the elongation of the noise generating turbulent jet volume caused by the reduced shear in flight, which scales with relative jet velocity. Both flight and wind tunnel simulation measurements show that Eq. (6) overestimates the reduction in jet noise in flight. The present study suggests that due to a shielding effect by the outer boundary-layer flow, the turbulence generated, and consequently the radiated noise in the initial few jet diameters downstream of the nozzle exit, do not scale with the relative velocity. Instead, it appears more appropriate to assume that noise generated from this part of the jet flow from aircraft in flight scales with jet absolute velocity instead of relative velocity. If the correction due to convective velocity and the elongation of the potential core in flight (which was observed as shown in Fig. 10 above) are retained, then the far-field jet noise in flight can be expressed as:

$$
\begin{aligned}
({\rm OASPL})_{\substack{\rm flight\\ \rm (modified)}} &= 10\log_{10}\Bigg\{V_J^8\left(\frac{V_J}{V_{\rm rel}}\right)\\
&\times[(1+M_c'\cos\Theta_I)^2+\alpha^2 M_c'^2]^{-5/2}\\
&\times(1-M_a\cos\theta_I)^{-1}\Bigg\}+{\rm const} \qquad (7)
\end{aligned}
$$

The prediction of the radiated noise close to the jet axis by Eq. (7) is not expected to very precise because the noise near the jet axis originates largely from fully developed shear flow. Near the jet axis, the prediction of jet noise in flight by Eq. (6) should be quite good (Figs. 11 and 12). In the following section the flight data has been compared with the predictions as given by Eq. (6) and the modified prediction Eq. (7).

Comparison of Experimental and Theoretical Results

A comparison of the flight data with the Ffowcs-William and Ribner's model and the present predictions is given in Fig. 11. Experimental results in Fig. 11 were taken from Ref. 6. These results were for the Viper 601 engine on the HS 125 aircraft with $V_j = 1725$ fps and $V_{\rm rel} \equiv V_J - V_I = 1455$ fps. The jet noise measurements in these experiments were taken at a thrust level sufficiently high for core noise not to contribute significantly to the radiated noise. The Ffowcs-William and Ribner's model shows an overestimated reduction in jet noise as compared to the flight measurements. Equations (5) and (6) have been employed to compute these results. The results of the present modified prediction method given by Eq. (7) are also shown on Fig. 11. As mentioned earlier, close to $\theta_I = 90°$ and in the forward quadrant, the agreement with flight data is reasonably good. Close to the jet axis, a large reduction in jet noise in flight is expected. This is due to reduced shear in the jet flow region sufficiently downstream of the nozzle exit, which contributes largely to radiated noise close to the jet axis. As one would expect, Eqs. (5) and (7) underestimate the noise reduction in flight near the jet axis.

Figure 12 shows another comparison of the flight data with predictions. The measured results were again taken from Ref. 6. The experiments were conducted on a VC10 aircraft flyover with the RB 211 engine. Agreement with the proposed modified model is good in the forward quadrant and also close to $\Theta_I = 90°$. Again, the present model underestimates the reduction of the far-field noise close to jet axis.

Conclusions

The results of the flight simulation experiments strongly demonstrate the influence of the engine cowl boundary-layer flow on the radiated noise from aircraft in flight. Since this outer jet flow differs from one flight simulation experiment to another and also among various flyover experiments, the influence of the outer flow on jet noise source will be variable. This is probably the main reason for the disparity among various flight noise data, e.g., some do and others do not observe the presence of forward arc lift.[4-8] Furthermore, the reduction of jet noise due to forward velocity may be minimized if there is a separation of the boundary-layer flow on the engine cowl. This may happen for certain airplane engine cowl configurations when the thrust line is at an angle of attack at take-off or landing of the airplane.

A systematic investigation of the influence of outer boundary-layer flow on jet mixing and the radiated noise on full-scale flight experiments is needed to completely evaluate the forward velocity effects on jet noise. This investigation will assist in developing refined methods to predict jet noise in flight. These observations will also help in designing engine flows to achieve relative velocity effects on jet mixing in the shortest possible distance and consequently may lead to quieter aircraft in flight.

From the present investigation, it is concluded that:

1) Flight simulation experiments have shown that the radiated jet noise can be changed for a given flight velocity ratio V_I/V_J by altering the outer boundary-layer flow.

2) With outer flow, close to $\theta_I = 90°$ and in the forward quadrant, reduction in jet noise was observed with insignificant change in the noise spectrum. This noise spectrum in the forward quadrant appeared very much like that of a static jet.

3) Close to the jet axis, with outer flow, comparatively large reduction in jet noise was observed. This significant reduction in jet noise was accompanied by a shift in the noise spectrum to the left, i.e., to the lower frequencies.

4) Close to $\theta_I = 90°$ and in the forward quadrant, the full-scale flyover results correlate well with the modified predictions. Comparison of these predictions with flight results indicates poor agreement close to the jet axis, i.e., $\theta_I \geq 130°$, where measurements agree well with the Ffowcs-Williams and Ribner analyses.

Acknowledgments

This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract NAS7-100, sponsored by the National Aeronautics and Space Administration.

The authors would like to express their gratitude to S. P. Parthasarathy for his helpful suggestions. In addition, the assistance of F. H. Slover, W. Bixler, S. J. Kikkert and D. Feller in fabricating, assembling, and conducting these experiments is greatly appreciated.

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