Some Flight Simulation Experiments on Jet Noise from Supersonic Underexpanded Flows

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Experiments on underexpanded cold jet flows from a convergent nozzle under simulated flight conditions have shown that a large periodic spinning motion of the jet can occur with greatly enhanced broadband noise production. Shadowgraph pictures indicate that this oscillatory jet motion accompanies the generation of random weak shock waves at the source. These waves appear to be generated at the point downstream of the nozzle exit where the shock cells in the jet begin to disappear. The weak shock waves propagate upstream and have been identified to be the cause of enhanced broadband jet noise production in flight. In addition, the results show that the boundary-layer flow conditions over the outside of the primary nozzle (simulating engine cowl flow in flight) influence the production of these random weak shock waves.

Nomenclature

d = primary nozzle exit diameter
P' = pressure fluctuations of radiated jet noise
P_0 = nozzle stagnation pressure
P_∞ = ambient pressure
R $\equiv P_0/P_\infty$, nozzle pressure ratio
X = streamwise coordinate from nozzle exit plane
θ_I = angle measured with respect to the nozzle intake (see insert in Fig. 1)
δ_0 = outer boundary-layer thickness at the nozzle exit plane

I. Introduction

IN recent years, there has been a growing interest in the effects of forward flight on various components of aircraft engine noise sources, viz., jet noise, fan noise, core noise, etc. The effect of flight on the modification of these noise sources has been more intriguing than was anticipated. One of these effects is that of forward aircraft velocity on jet noise from slightly underexpanded supersonic nozzle flows that one encounters with high-thrust engines at their maximum power settings.

Ffowcs-Williams et al.[1] report the influence of forward aircraft velocity on the annoying component of excess jet noise that is referred to as "jet crackle." It was surprising to find that this noise peaks in the forward quadrant during flight whereas, in the static case, this crackling noise is a maximum near the jet axis. In Ref. 1, it is explained that for a static jet, the "jet crackle" noise is produced as a consequence of local coalescence of the compression waves at the source in the jet. The authors of Ref. 1 did not expect "jet crackle" to occur under flight conditions during which the convective Mach number of the eddies responsible for local compression waves could be subsonic relative to the ambient flow (depending upon flight Mach number). Under flight conditions, the noise signal in the far field (which resembles the static engine "jet crackle" noise signal) was concluded to result from nonlinear propagation effects instead of from a local steepening of compression waves at the source. Unfortunately, no detailed and systematic investigation of the underexpanded jet flowfield in flight has been made in the past to verify the preceding assertions.

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However, several investigators have studied the structure of freejets and the radiated noise from underexpanded jet flows exhausting into an ambient atmosphere.[2-13] Such jet flows are known to radiate almost periodic pressure fluctuations in the far field, which are attributed to a feedback phenomenon in the jet flow, referred to as "jet screech." In particular, Powell studied the flow structure experimentally and concluded that the jet radiation from underexpanded convergent nozzle flows depends strongly on the structure of the boundary layer at the nozzle exit.[7-9] His results clearly demonstrated the importance of the jet turbulent mixing layer on the development of the shock-cells and, consequently, in the generation of the radiated noise, from an underexpanded jet flow. The experimental results of Lassiter and Hubbard[5] on the elimination of screech tones from jets of choked nozzles further confirm Powell's results. These results strongly indicate that the initial flow conditions at the nozzle exit plane in flight can have an important role in the production of jet noise from underexpanded jet flows. Previous experimental investigation of subsonic jets has demonstrated the influence of the engine cowl boundary-layer flow on the radiated jet noise from aircraft in flight.[14] Very little experimental information is available, however, on the manner in which these initial flow conditions in flight influence the shock-cell structure and the radiated noise from supersonic underexpanded jet flows.

Hay and Rose have also reported shock-associated noise measurements obtained under flight conditions.[15] They cite some cases of structural damage due to the presence of shock-associated jet noise generation from full-scale engines flying at high altitudes. The results presented in Ref. 15 show considerable increase in the broadband noise spectrum for cruise as compared to take-off. Hay and Rose further emphasize that the shock-cell noise in flight is due to an instability phenomenon and may depend on geometric flow conditions in flight that need further elucidation.

The inherent unstable jet oscillations of the underexpanded jet flows have been reported in the literature by many investigators.[4,10,13] Hammit[4] demonstrated experimentally that, with two-dimensional, split-type jet nozzle flows, "screech tones" were associated with these larger jet oscillations and could be eliminated by stabilizing the jet. Experimental results of Sherman et al.,[10] show that the jet screech tones were associated with periodic jet oscillations along with the periodic shock-cell oscillations. Experiments showing the manner in which the flow velocity influences the oscillating shock-cell jet flow will be of great assistance in understanding the shock-cell noise, as discussed by Hay and Rose[15] and as reported by Ffowcs-Williams et al.[1]

In the past,[16] the effect of forward flight on shock-associated noise has been thought to be a well-understood classical problem. The increased jet noise from supersonic underexpanded flows was thought to result from forward arc amplification of sound intensity due to forward aircraft velocity. However, the structure of the jet mixing layer due to the presence of engine cowl boundary-layer flow in flight will be modified[14] and will result in modification of jet noise sources.

Analytical studies by Lighthill,[17] Ribner,[18] and others[19,20] have demonstrated the importance of the interaction of the jet mixing layer turbulence, organized vortex structures, etc., with shock waves in the production of jet noise. The present experimental investigation has been undertaken to study how the forward flight velocity of an aircraft affects the shock-cell jet structure and the way in which the forward flight modifies the jet noise sources. It is anticipated that these results will advance the understanding of supersonic jet flow noise in flight.

II. Experimental Arrangements, Instrumentation, and Measurements

To obtain additional insight into the mechanism of jet noise sources from slightly underexpanded jet flows in flight, simulation experiments were performed in an anechoic chamber. The experimental setup basically consisted of a 1.27-cm-diam primary convergent nozzle in a 12.7-cm-diam free-jet flow. The nozzle pressure could be varied up to a value of approximately $R \equiv P_0/P_\infty \simeq 5$ where P_0 is the upstream stagnation pressure and P_∞ is the ambient pressure. A free-jet velocity as high as 200 m/s could be attained. The outer boundary layer could be altered by placing symmetric rings of various sizes at different locations from the nozzle exit plane around the outside of the primary nozzle. In the following writeup, the words outer flow and flight simulation velocity have been used synonomously. Both refer to the flight simulation velocity of an aircraft.

Both near- and far-field pressure measurements were made with 0.32-cm and 1.27-cm-diam microphones. The microphones were located 100-170 jet diameters from the primary nozzle exit. The noise data in these measurements have been normalized to 100 jet diameters. The signal was analyzed on a digital real-time spectrum analyzer to determine the frequency constituents of the radiated jet noise signal. In analyzing the present noise measurements, no corrections have been made due to sound propagation through the shear layer of the outer jet which simulated the forward aircraft velocity.

Observations of the jet structure were made by taking shadowgraph and high-speed Schlieren motion pictures. The primary nozzle flow was seeded with CO_2 gas to visualize the subsonic part of the jet flow which existed downstream of the shock-cell jet flow region. A high-intensity spark source of flash duration of approximately 1.0 μs was utilized for the shadowgraph pictures. A two-mirror Schlieren system was used in which the camera triggered the spark light source and Schlieren motion pictures could be taken at a framing rate as high as 7000 frames/s. The exposure time of each frame was of the order of 0.3 μs, which was short enough to "freeze" the high-speed jet flowfield.

III. Experimental Results and Discussion

Flight Effects on Jet Noise

There have been numerous measurements of far-field radiated jet noise from both cold and hot underexpanded jet flows in the past.[2-13] For cold jets, as the pressure ratio is increased above the critical pressure ratio for convergent nozzle flows, i.e., $R \gtrsim 2.0$, the radiated noise is dominated by periodic pressure fluctuations, referred to as "jet screech." The jet screech noise contributes significantly to the radiated noise spectrum in the forward quadrant, i.e., $\theta_I \lesssim 90$ deg. Typical noise distribution from static underexpanded jet flows (without the outer flow) for pressure ratios $R = 2.1$ and 3.7 are indicated in Fig. 1. As discussed later, the spectra of the radiated noise without outer flow was dominated by screech tones.

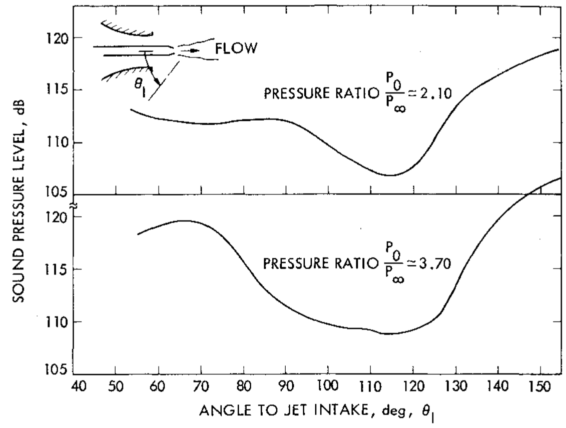


Fig. 1 Measured far-field sound pressure distribution without forward simulation velocity.

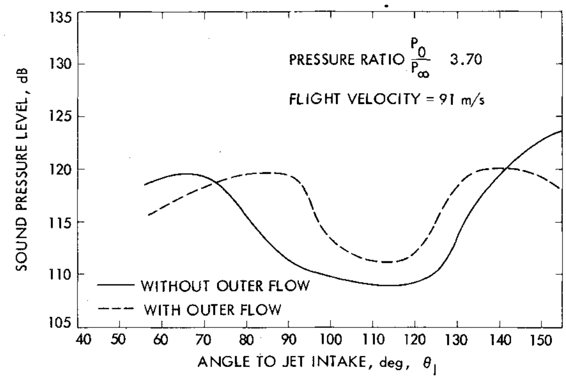


Fig. 2 Effect of forward simulation velocity on shock-associated noise.

It was surprising, however, that the simulated forward flight velocity had a pronounced effect on the radiated noise field, as shown in Figs. 2 and 3. There was a significant increase in noise in the forward quadrant at the higher outer flow velocity. Both of these measurements were made with a fixed nozzle pressure ratio of $R \simeq 3.70$ and at two forward outer flow conditions of 91 and 173 m/s, respectively. Similar trends in radiated in-flight jet noise were observed at other nozzle pressure ratios when compared with the static jet flow noise.

The observed increase in shock-associated jet noise in simulated flight as compared to the case without outer flow has, in the past, been thought to result from the forward arc amplification of the sound intensity ($\theta_I \lesssim 90$ deg) by assuming the source strength to remain unaffected by the forward flight velocity.[16] A suggested correction factor to account for this amplification is $(1 - M_a \cos\theta_I)^{-4}$ where M_a is the flight Mach number. At $\theta_I = 90$ deg, the suggested correction vanishes and cannot explain the increased jet noise observed in this region, as observed in Figs. 2 and 3.

Information on the noise spectrum in the near field also produces significant information on the understanding of the observed results discussed so far. Figure 4 shows the spectra at a distance of 3 jet diameters from the centerline of the primary jet, as well as the oscilloscope pressure traces for an outer flow velocity of 200 m/s. These measurements were obtained at $\theta_I = 90$ deg, for which the nozzle pressure ratio was kept constant at $R \simeq 2.5$. Similar results were obtained at

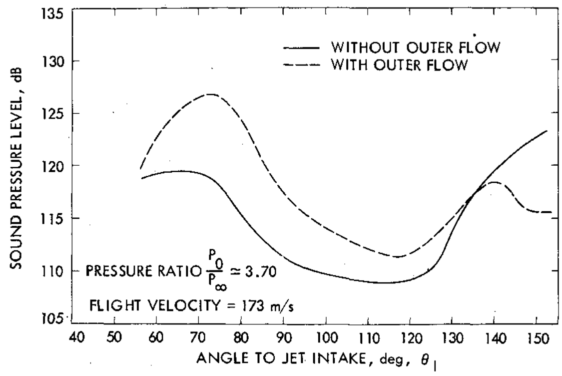


Fig. 3 Effect of forward simulation velocity on shock-associated noise.

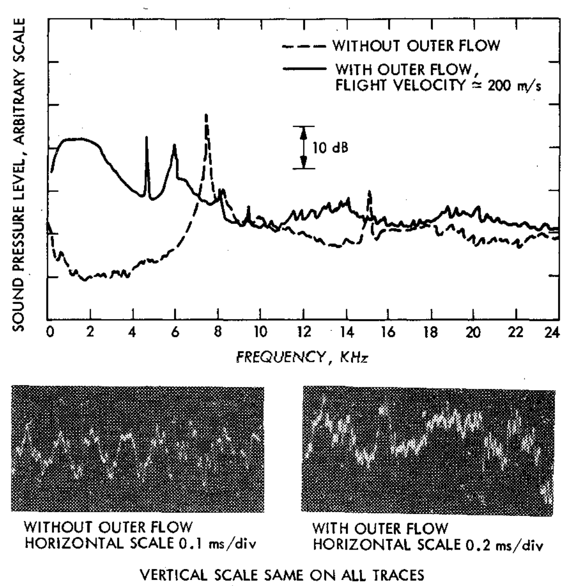


Fig. 4 Influence of forward flight velocity on near-field jet noise spectrum at $\theta_I = 90$ deg at $R \simeq 2.50$.

other outer flow velocities and nozzle pressure ratios within $2.5 \leqq R \leqq 5$. Without outer flow, the near-field jet noise is dominated by jet screech tones. The spectrum, however, changed considerably with outer flow. The screech tones were still present, but, when compared with a noise measurement without outer flow, significant radiated noise was contributed by relatively low-frequency broadband noise, as indicated in Fig. 4. The oscilloscope trace with an outer flight velocity of 200 m/s in Fig. 4 also shows random sharp peaks. It should be noted that the horizontal scales of the two oscilloscope pressure traces are not identical in Fig. 4. One should be aware of the fact that the noise measurements by the outer flow only, simulating the forward flight in the near and far field, showed not to be the cause of this increased broadband noise, as indicated in Fig. 4.

Flowfield

It has been found in this investigation that there are significant changes in jet structure that occur whenever an outer flow is added to an underexpanded supersonic jet to simulate forward aircraft velocity. An example is shown in the shadowgraph pictures in Fig. 5 for a nozzle pressure ratio of 3.70 over a range of outer velocities. First, it is apparent that the jet spread rate decreased when the outer flow was introduced. This decrease in the rate of jet spreading was accompanied with a modification of the shock-cells. Under certain flow configurations, the number of shock-cells observed was also increased when an outer flow was imposed

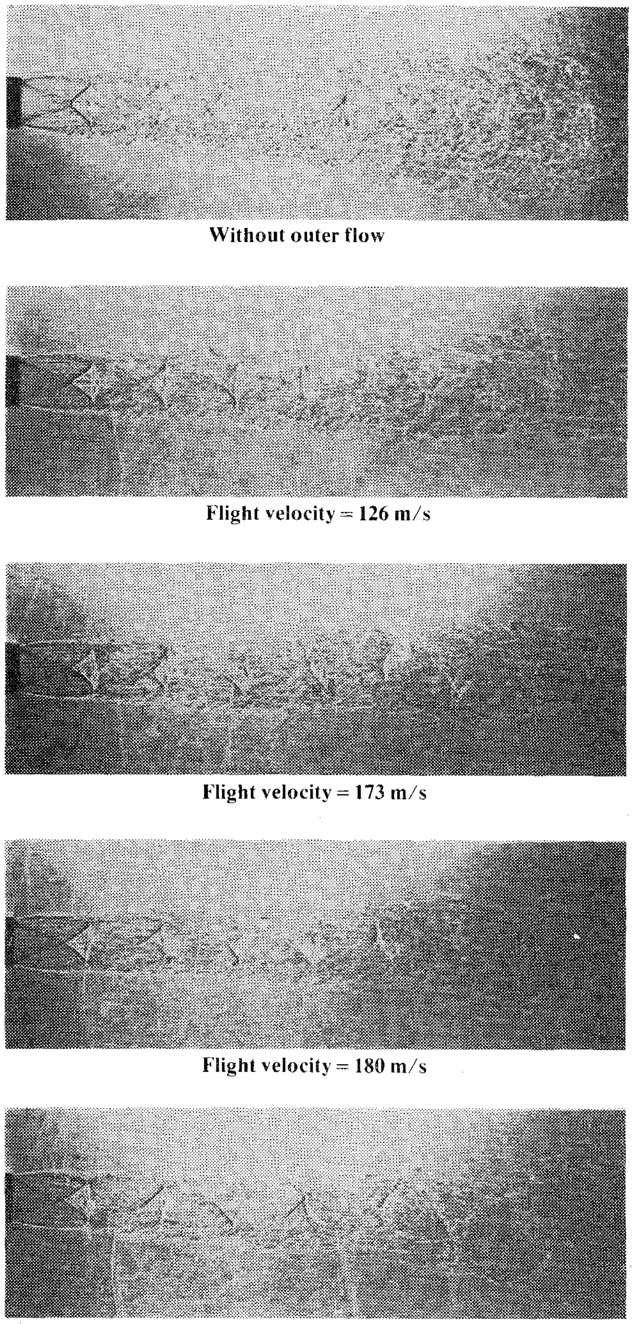
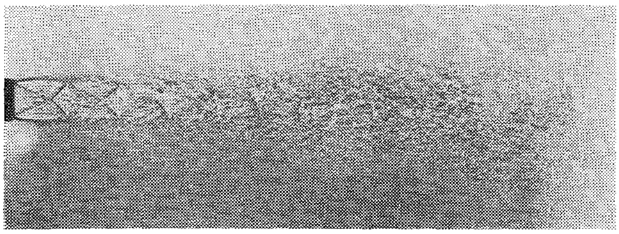
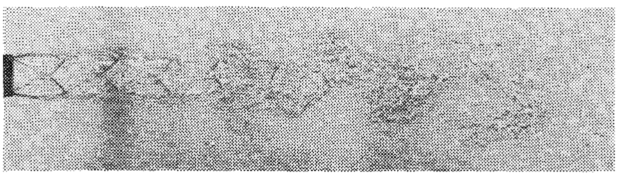


Fig. 5 Shadowgraphs showing the influence of flight velocity on jet structure at $R = 3.70$.

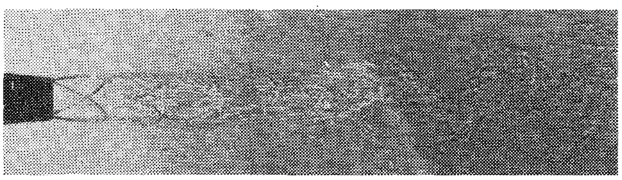
around the jet. These shadowgraphs in Fig. 5, however, also show random weak shock waves surrounding the primary jet at various axial locations. It can be seen that these weak shock waves increase in strength with increasing outer flow velocity. This assertion is made on the basis of shock waves observed as increasingly dark lines in these shadowgraphs. This in turn is related to increased density and pressure jumps across these waves. Furthermore, these weak shock waves are not spaced at equal distances in any given photograph. High-speed Schlieren motion pictures of this jet flow configuration show that these random weak shock waves originated where the jet first became completely subsonic. In Fig. 5, this location was near the end of the fifth shock-cell. Here, compression waves appear to form by the interaction of the outer flow and the unsteady jet oscillations. These compression waves propagate upstream toward the nozzle and seem to coalesce and form weak shock waves. It is inferred from the noise measurements



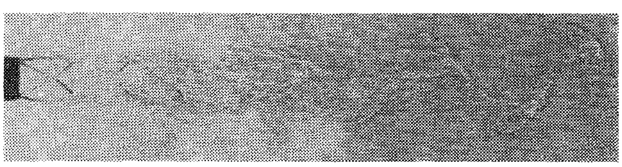
Without outer flow



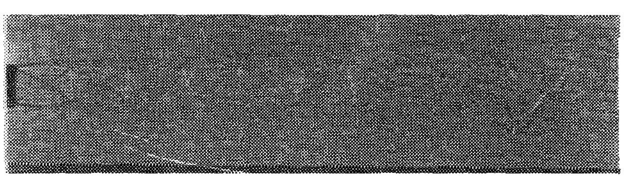
Flight velocity = 100 m/s



Flight velocity = 150 m/s



Flight velocity = 175 m/s



Flight velocity = 200 m/s

Fig. 6 Shadowgraphs showing the influence of flight velocity on jet structure at $R \simeq 3.50$.

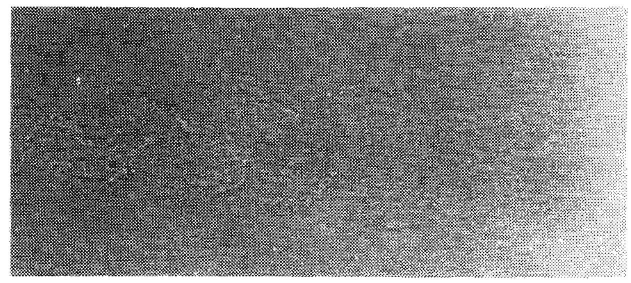
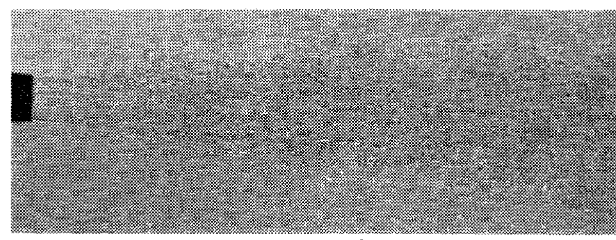
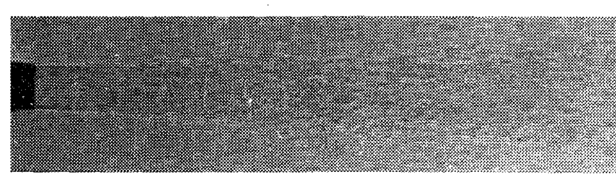


Fig. 7 Jet flowfield between $9 \leq x/d \leq 24$ at $R \simeq 3.50$ and a flight velocity of 150 m/s.



Without outer flow



With outer flow; flight velocity = 173 m/s

Fig. 8 Influence of forward flight on jet structure at $R \simeq 2.50$.

taken with these flows that the increased broadband noise spectrum, as shown in Fig. 4, was contributed largely by these weak shock waves. In Fig. 4, the random peaks in the oscilloscope trace taken with the outer flow on may have been caused by the generation of these weak shock waves from the jet flow.

At the higher outer flow velocities of 180 and 196 m/s, the photographs of Fig. 5 also show large spinning jet oscillations downstream of the region where these random weak shock waves are generated, i.e., downstream of the fifth shock-cell. Similar photographs at nozzle pressure ratios of 3.50 are shown in Fig. 6. The spinning jet oscillations are more evident in these figures in the subsonic portion of the jets because of the larger field of view. This oscillatory jet motion with the outer flow on lasted as far as 20 diameters from the nozzle exit. The portion of the region farther downstream is shown in Fig. 7. At first it was believed that these strong oscillations might have been caused by some vibration of the hardware or the interaction of the primary nozzle flow with the end of the potential core of the outer flow. Careful examination of the experimental setup, however, indicated that this was highly unlikely; hence, it was concluded that the formation of these oscillations was associated with a complex interaction of the modified jet mixing layer and the shock-cell structure. In fact, Hammit[4] and Westley and Wooley[12,13] have also observed such organized jet motion when their jet exhausted into stationary ambient air. The presence of the boundary layer around the outer part of the primary nozzle modifies the jet mixing such that these oscillations increase drastically in amplitude, leading to the generation of random weak shock wave propagation from the jet. At a lower nozzle pressure ratio of 2.50 (perhaps more typical of engine operation), as shown in Fig. 8, the modification in the shock-cell structure with the outer flow on is also evident. In addition, the random weak shock waves around the jet flow are visible for this condition.

The shadowgraph pictures in Figs. 5, 6, and 8 also show that the outer flow influences the details of the shock-cell themselves. For example, Fig. 5 clearly demonstrates a slow increase in the length of the shock-cells with increasing outer velocity. In these experiments, an increase in the shock-cell length, as much as 17% of its length without the outer flow, was observed. It was surprising to observe that this lengthening of the shock-cell did not modify its radial size. The lengthening of the shock-cell in Fig. 5 was also accompanied by a gradual disappearance of the "Mach disk." As will be discussed in the following section, this shock-cell modification for a given outer flow velocity was greatly influenced by the initial flow conditions around the primary nozzle. These outer flow conditions simulate engine cowl flow in flight.

Influence of the Outer Boundary-Layer Thickness on Jet Noise

In order to determine the manner in which the boundary-layer thickness over the outer surface of its primary nozzle influences the underexpanded jet flow development, a symmetrical ring was placed more than 10 jet diameters upstream of the nozzle exit to modify the boundary layer. In these tests, the outer freestream velocity was kept constant. Typical results are shown in Fig. 9 for a case in which the boundary-layer thickness δ_0/d was increased by ap-

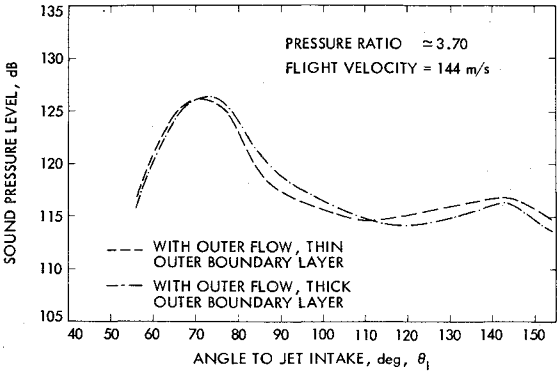


Fig. 9 Effect of outer boundary-layer flow on jet noise in flight.

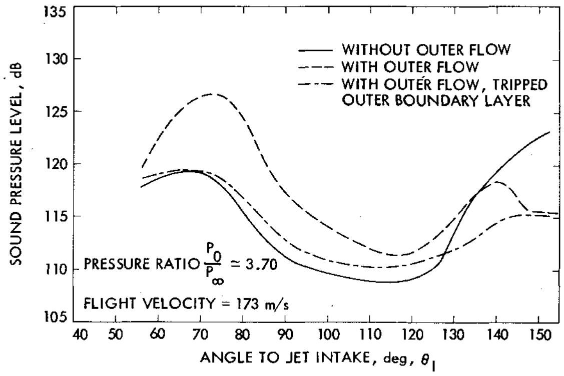


Fig. 10 Effect of tripping the outer boundary layer on jet noise in flight.

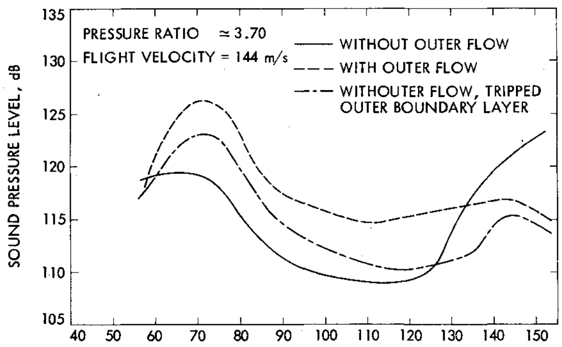


Fig. 11 Effect of tripping the outer boundary layer on jet noise in flight.

proximately 5%. The initial boundary-layer thickness without the ring was estimated to be around 7-10% of the nozzle exit diameter. The results in Fig. 9 show a weak dependence of the boundary-layer thickness of radiation of noise. Corresponding shadowgraphs showed little change in the jet structure when the boundary-layer thickness on the primary nozzle was altered.

Reduction of Noise from Underexpanded Jet Flows in Flight

The experimental results discussed previously indicated that, for a given nozzle pressure ratio, the strength of the random weak shock waves outside the jet increased with an increase of the outer flow velocity (cf., Fig. 5). With an increasing outer flow, the shadowgraphs in Fig. 5 show a reduction in the growth of the jet mixing layer. Based on these results, it is believed that this increase in jet noise with outer flow on (cf., Figs. 2 and 3) can be reduced by enhancing the jet mixing. To verify whether this would reduce the noise, simple experiments were performed by placing a symmetric trip ring around the primary nozzle near the exit. To improve the jet spreading rate, the trip ring with a height more than the boundary-layer thickness δ_0 was placed about ¼ to ½ jet diameter upstream of the nozzle exit plane. In the course of this investigation, it was found that the effectiveness of this trip ring in enhancing jet mixing layer growth depended upon its height and location. An effective ring was one with a height more than the boundary-layer thickness and that it should be located as close as possible to the nozzle exit plane.

The effect of tripping the boundary-layer flow in this manner produced a reduction in the intensity of the radiated jet noise, as indicated in Figs. 10 and 11. As shown in Fig. 10, most of the excess noise in flight was reduced by the use of a trip ring near the nozzle exit. Similar results were observed with an outer velocity of 144 m/s in Fig. 11.

This reduction in jet noise was accompanied by a marked change in the jet structure, which can be seen in the shadowgraph pictures of Fig. 12. The flow conditions correspond to those of Fig. 10, i.e., a nozzle pressure ratio of 3.70 and an outer flow velocity of 173 m/s. Photographs are shown wihout an outer flow (top), with an outer flow but without a trip ring (center), and with an outer flow with a trip ring (bottom). By tripping the outer flow, one can see that the spread rate of the jet is increased when compared to a non-tripped outer flow. In addition, the strength of the random weak shock waves was diminished by tripping the outer flow and the large jet spinning oscillations were essentially eliminated.

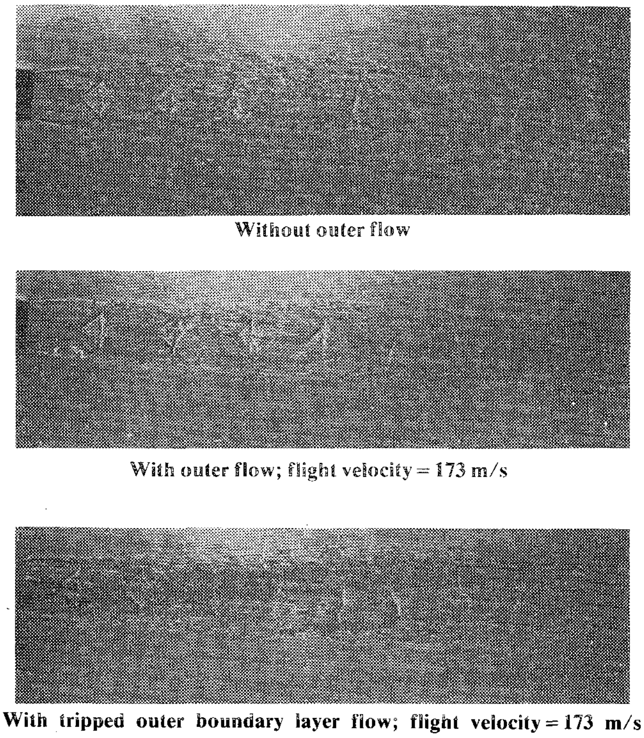


Fig. 12 Shadowgraphs showing the influence of a tripped outer boundary-layer flow on the development of the jet flow at $R \simeq 3.70$.

A sequence of shadowgraph pictures showing the effect of increasing the outer flow velocity on the jet structure for a tripped outer boundary layer at $R \simeq 3.70$ is shown in Fig. 12. These results should be compared with those of an untripped boundary-layer flow shown in Fig. 5. In making this comparison, it should be recalled that the length of the shock-cell structure for an untripped outer flow tends to increase with an increase of the outer flow velocity (cf., Figs. 5 and 6). For a tripped outer flow, the effect of increasing the outer flow velocity, however, is the opposite, i.e., length of the shock-

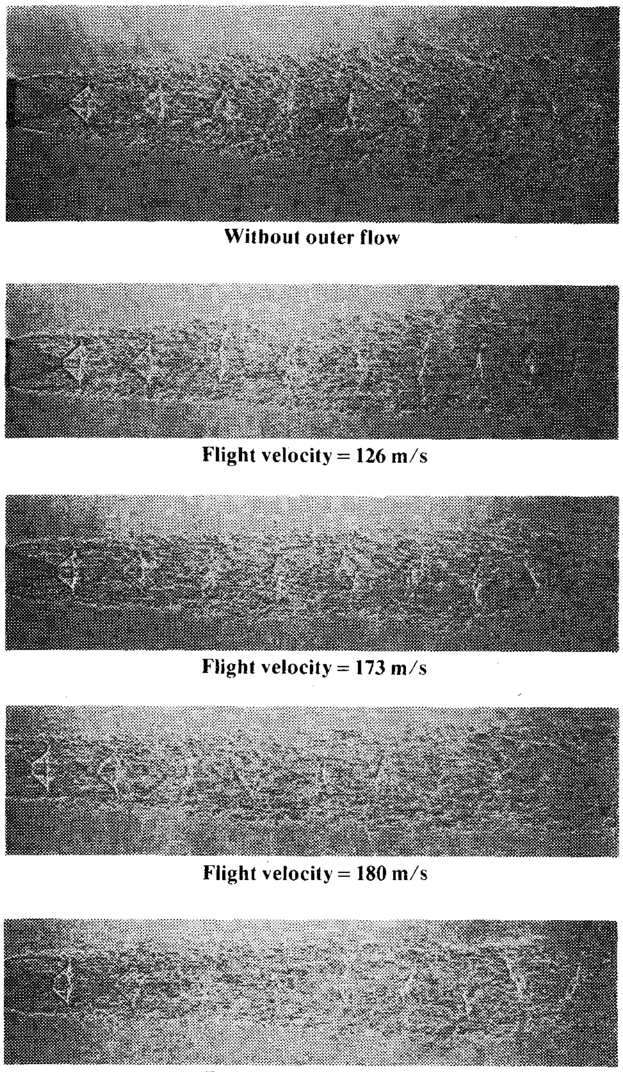


Fig. 13 Shadowgraphs showing the effect of flight simulation velocity with a tripped outer boundary-layer flow on jet structure at $R \simeq 3.70$.

cell region, as indicated in Fig. 12, is shortened. Also, the "Mach disk" seems to increase in strength and diameter with increasing outer flow velocity when the boundary layer is tripped (Fig. 13).

Present study showed that the influence of tripping the outer flow, which resulted in a modification of the jet shear layer, did not always result in a reduction of the radiated jet noise, as shown in Figs. 10 and 11. Present study also asserts the importance of the initial flow conditions of the outer boundary layer (simulating engine cowl flow in flight) at nozzle exit in modifying the jet noise sources in flight. Future detailed experiments are needed to elucidate the manner in which the supersonic, underexpanded jet shear flow gets modified in flight.

IV. Summary and Conclusions

The experimental results for simulated in-flight conditions demonstrate the importance of the initial outer flow conditions at the nozzle exit in the development of the jet flowfield for a supersonic underexpanded jet. It has also been shown that alteration of the outer flowfield near the nozzle exit can significantly modify the radiated jet noise. A correction in the amplification factor for sound intensity, assuming that the source strength is unchanged by flight, as suggested in Ref. 16, does not adequately account for the modifications in the sound sources, as observed in the present experiments. The present observations clearly showed that in simulated flight conditions, large, spinning jet oscillations are imparted to the subsonic part of the jet flow, after the shock-cell structure diminishes. The radiated noise from such oscillations of the subsonic part of the cold jet may not be the dominant overall noise source, but if such oscillations exist from underexpanded hot jet flows in flight, the subsonic part, which will be supersonic for certain jet flow regions with respect to the ambient air, may result in a significantly increased jet noise. The jet noise radiated from such an oscillating hot subsonic jet in flight may even offset the flight benefit due to reduced relative velocity in flight. Results of the present investigation also indicate that, by enhanced mixing of the primary jet flow with the outer flow, most of this oscillating jet behavior and, hence, the propagation of the associated random directional weak shock waves to the far field can be eliminated.

It is important to note that the excess noise measured from a supersonic underexpanded jet flow with outer flow present (cf., Figs. 2 and 3) pertains to a source that is associated with the modification of the shock-cell structure and its interaction with the jet mixing layer. This interaction produces excess jet noise and is believed to be closely related to the source of "jet crackle" noise as studied by Ffowcs-Williams et al.[1] The evidence of this, in terms of pressure signal traces, are the random sharp peaks in the near field observed with the outer flow on, shown in Fig. 4. It is suggested that the cause of "jet crackle" may be due to the formation of random compression wave fronts at the source, rather than nonlinear propagation effects as postulated in Ref. 1. These randomly directed weak shock waves may have been the cause of the high jet crackle noise, as observed in flyover tests and reported in Fig. 9 of Ref. 1.

The main conclusions of the present investigation are:

1) The external flow emanating from the trailing edge of a nozzle critically influences the jet shock structure of an underexpanded supersonic jet and, consequently, also affects the jet noise sources under simulated flight conditions.

2) Large, spinning oscillations of the subsonic part of such an underexpanded jet flow were observed under simulated flight conditions. This motion appears to cause a local steepening of compression waves into random weak shock waves at the source. These weak shock waves are responsible for the excess noise generated by underexpanded jet flows under simulated flight conditions.

3) Enhanced mixing of the outer boundary-layer flow with the primary jet mixing layer can suppress the generation of these random weak shock waves.

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