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Upper Surface Blowing Noise of the NASA Ames Quiet Short-Haul Research Aircraft

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An experimental study of the propulsive-lift noise of the NASA Ames quiet short-haul research aircraft (QSRA) is described. Comparisons are made of measured QSRA flyover noise and model propulsive-lift noise data available in references. Developmental tests of trailing-edge treatments were conducted using sawtooth-shaped and porous USB flap trailing-edge extensions. Small-scale parametric tests were conducted to determine noise reduction/design relationships. Full-scale static runup and flight tests were conducted with the QSRA to evaluate edge treatments under flight conditions. QSRA flight and published model propulsive-lift noise data have similar characteristics. Noise reductions of 2-3 dB were achieved over a wide range of frequency and directivity angles in static and flight tests of the QSRA. These noise reductions appeared to be limited by a source other than the trailing edge.

Introduction

IN January 1974, NASA began the quiet short-haul research aircraft (QSRA) project as the culmination of 20 years of research in powered-lift STOL aircraft. The object was a low-cost, versatile, quiet jet research aircraft with STOL performance. The powered-lift system selected for the QSRA was a four-engine, upper surface blowing (USB) concept, with the objective of yielding high-lift coefficients and very low sideline noise levels. The QSRA aircraft, which was built by the Boeing Commercial Airplane Company and first flew on July 6, 1978, is shown configured for a STOL approach in Fig. 1. One of the primary goals of the QSRA program was to have a 90-EPNdB community noise impact area of not more than 1 square mile for a 150,000-lb gross weight commercial transport airplane based on QSRA-generated technology. This low-noise-level objective was considered vital for public acceptance of propulsive lift, or any other airplanes in small community airports.

The noise levels of the QSRA were measured, extrapolated, and compared to program goals. The maximum effective perceived noise level (EPNL) measured at the 500-ft sideline at takeoff was 93.5 EPNdB; during landing, it was 89 EPNdB and the goal was 90 EPNdB.

The measured community noise impact area was larger than the program goal, but the latter was derived early in the program, using static model data. The primary basis of the jet/flap interaction noise estimate was Ref. 1, which included an assumption of substantial noise reduction with flight speed. However, more recent and extensive model testing reported in Refs. 2 and 3 indicates that flight effects may not provide any noise reduction.

Comparisons of QSRA flyover noise spectral shape, directivities, and dependencies on jet velocity with edge noise characteristics published in Ref. 2 provided excellent agreement. Static tests conducted with the QSRA, in which USB wing surface fluctuating pressures were correlated with radiated noise, confirmed edge interaction noise as a prominent component.

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Based on results of these early QSRA acoustic tests, a joint NASA/Boeing program was initiated, which had a goal of reducing QSRA community noise levels by 2-3 dB, primarily by decreasing the jet/flap interaction noise. Studies of powered-lift flap noise by Boeing and other investigators have shown that sawtoothed or serrated trailing-edge and porous-edge treatments have significantly lower jet/edge interaction far-field noise levels. In order to develop candidate treatments for full-scale static testing, small-scale tests were performed by Boeing, using a flat plate model, with nozzle-to-trailing-edge spacing ratio similar to the QSRA propulsion nozzle and flap system. Four serrated treatments and one porous treatment were statically tested on one of the outboard USB flaps of the QSRA on September 1979. Results of the static test indicated a 2-2.5-dB reduction in far-field noise. Although several of the treatments worked equally well, a single serrated treatment seemed more practical and was flight tested in early 1980.

Objective of Tests

Initial flight tests were conducted to determine general community noise characteristics of the QSRA. Subsequent testing was conducted to investigate the source of USB noise, its characteristics, and the means of reduction of that prominent component.

Description of Tests

Flight Tests

The QSRA was flight tested for airport community noise on three occasions—July 25, 1978, at Skagit County Airport, Burlington, Wash., and January 16 and 18, 1979, and again on March 20, 1980, at Crows Landing Airfield, Calif. In all tests, noise levels were measured along the flightpath and at two sideline locations. The microphone positioned on the concrete runway surface under the flightpath had an effective distance from microphone diaphragm to surface of 1 cm. The major ground reflection interference in the noise spectra was found to be above 5 kHz. The two sideline microphones were positioned about 13 m above the ground surface. The major ground reflection distortion in noise spectra measured at those microphones occurred below 50 Hz.

About 40 flight passes were conducted at variable altitudes, thrusts, airspeeds, and USB flap deflections. Tests were also conducted with and without vortex generators (small vanes) attached at the USB surface of the wings. Flyover noise data

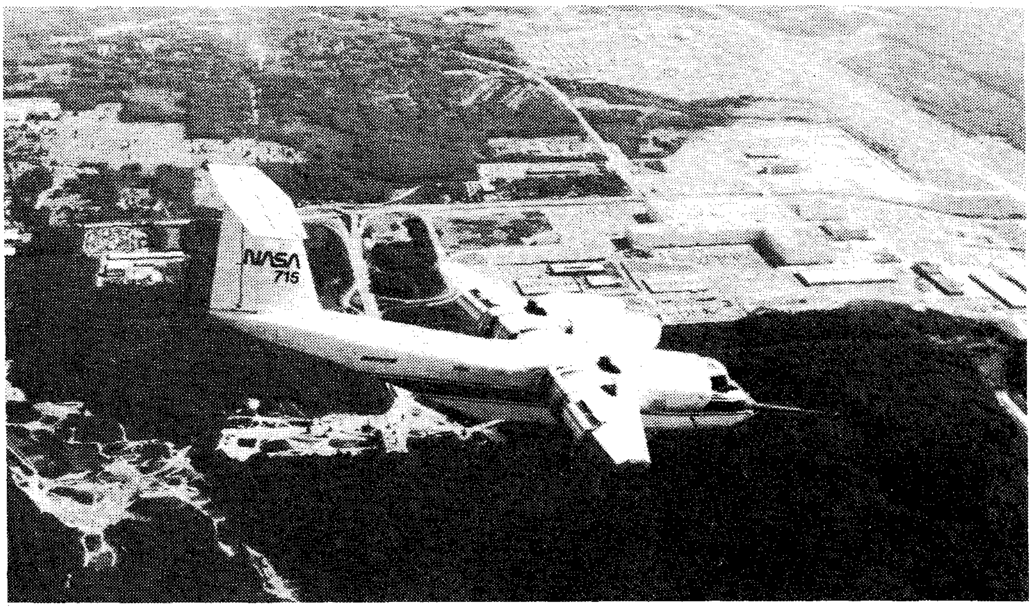


Fig. 1 The QSRA.

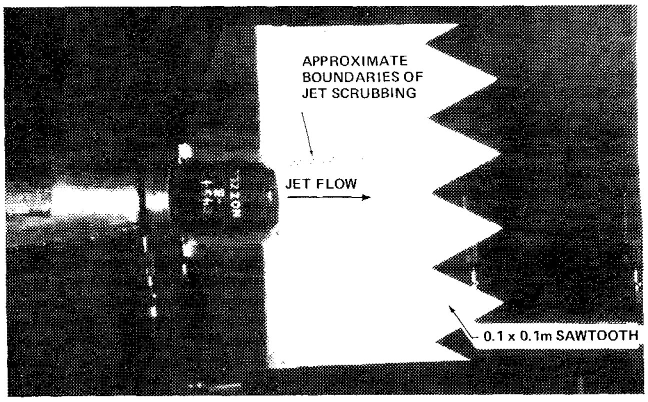


Fig. 2 Jet nozzle and test plate.

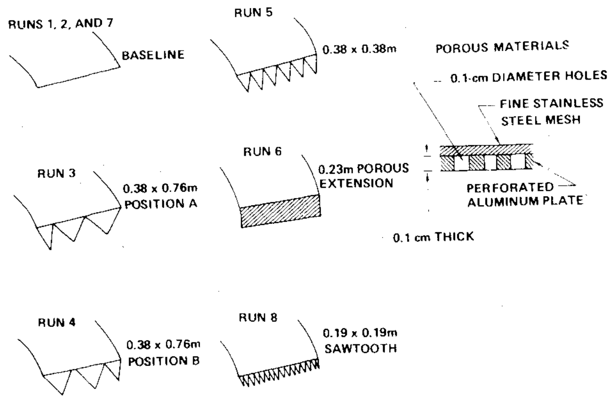


Fig. 3 Test configurations and sequence.

were reduced to overall sound pressure level (OASPL), perceived noise level (PNL), and ⅓-octave band SPL's tabulated with time, propagation distance, and radiation angle.

Model Tests

Small-scale tests were conducted in a quiet-air facility in the Boeing Noise Technology laboratory, as shown in Fig. 2. In these tests, acoustically muffled cold air was exhausted through a D-shaped nozzle of about 30-cm^2 area. The jet was exhausted over a flat plate, with the distance from the nozzle to the edge of 20 cm. The ratio of that separation distance to the effective diameter of the model nozzle was similar to that of the QSRA. Radiated-edge noise levels were measured when sawtooth-shaped edge extensions were attached to the trailing edge of the plate. A matrix of sawtooth geometries and various treatment porosity values was tested to determine design criteria for application to full-scale testing on the QSRA.

Static Tests

Static testing was conducted on the QSRA (in ground runups) at Moffett Field, Calif. Noise source diagnostic tests were conducted in January 1979. Dynamic (acoustic) pressure transducers were mounted on the USB surface of the wing, and a microphone was placed on the ground below the wing (3.4 m from the trailing edge). Signals from the transducers were analyzed to obtain cross-correlation for verifying the presence of jet/edge interaction noise in the radiated noise field.

Ground runup tests were conducted in September 1979. Each of the four sawtooth configurations and the porous treatment configuration shown in Fig. 3 were consecutively attached to the trailing edge of one USB flap. Noise levels were recorded at four locations on the concrete runup pad along a line under the only operating engine. ⅓-octave band spectra plots were overlaid to reveal the effects of the trailing-edge treatments.

Flyover Noise Characteristics

QSRA flyover noise data were found to be essentially free of turbomachinery (fan and turbine) tones, yet they generally exceeded preflight predictions. A typical spectrum of measured peak flyover noise is presented in Fig. 4. Also included in that figure are predictions of the fan, jet, and engine core noise component and total noise spectra. No prediction of jet/edge interaction noise is included. The predictions are, in effect, projections of the high-bypass-ratio engine noise flight test data base of conventional Boeing airplanes.

Recently, many experimental studies of USB flap jet/edge interaction noise have been performed. Some extensive and comprehensive tests were done at Lockheed under a NASA contract[2] and United Technologies Research Center.[3] In those references, noise spectral shapes, directivities, and velocity dependencies of the noise measured in the model tests were formulated to be projected for full-scale predictions.

Predictions were made for the QSRA (using Ref. 2) and results are superimposed on measured QSRA data in Figs. 5-7. The quantity V_j is chosen to be representative of an average

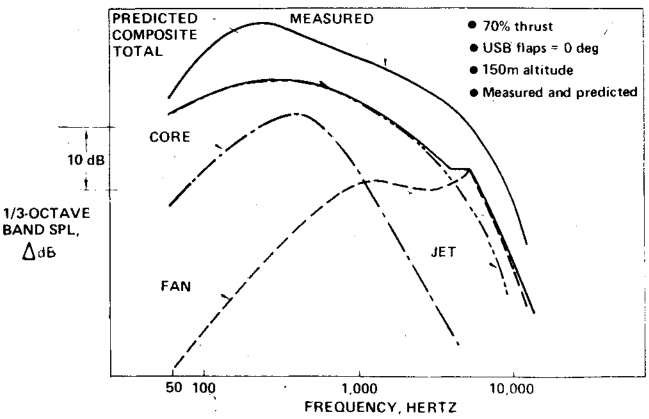


Fig. 4 QSRA community noise peak flyover spectra.

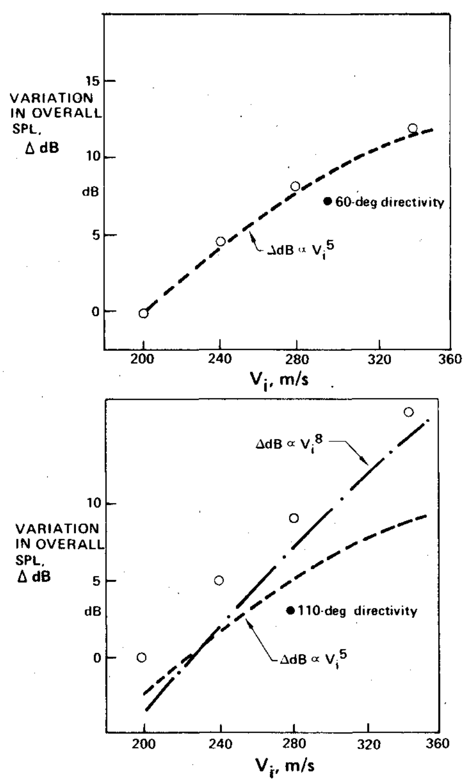


Fig. 5 Normalization of noise for jet velocity effects.

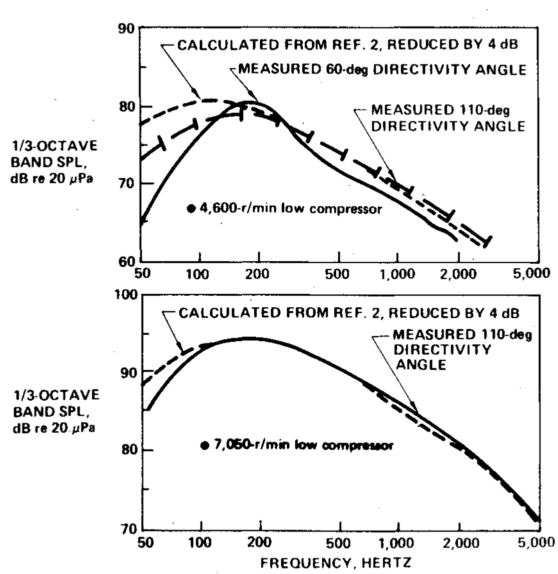


Fig. 6 Comparison of measured noise spectra with extrapolated model jet/edge interaction noise.

exhaust jet velocity, as suggested in Refs. 1-3. In the case of the QSRA, the primary and secondary jets were not mixed. Furthermore, with enhanced jet spreading, the velocity profile at the flap trailing edge could differ greatly from reference model tests. Therefore, a large error in absolute levels of projected noise (on the order of 5 dB) could occur.

It should be noted that the comparisons are of static model data projected to full-scale flight test data. Although no flight effects were included in the projections, the basic features of the data curves are nevertheless very similar.

In Ref. 2, it was noted, and in the comparison it was confirmed, that 1) at low jet velocities, the noise had forward-radiation peak directivity and a fifth power of the jet velocity dependency; and 2) at high jet velocity (approaching Mach 1) the noise behaved like jet noise; i.e., aft-radiation peak directivity and a V^8 dependency. In Ref. 2, these characteristics were suggested to be the result of a dipole source and a quadrupole source, respectively. In Ref. 4, the theory of Goldstein[5] is applied to show that edge noise directivity shifts aft with increasing jet velocity as a consequence of the velocity gradients at the noise source.

Effects of USB Flap Angle-Tip Vortex Noise

The directivity of the QSRA propulsive-lift noise changed dramatically at high USB flap deflection angles. The change was caused by the addition of noise radiated primarily aft and sideways. This addition is shown in the PNL time history presented in Fig. 8. These data were recorded at a 230 m sideline location, during a 150 m altitude pass. The additional noise most likely originated at the flap tips and was associated with the high-lift vortex.

Flight Effects

In 1975, Bhat[1] used a free-jet wind tunnel to show that edge-interaction noise was reduced in simulated flight. In tests described in Ref. 2, also using a free jet, noise reductions were observed only under some conditions, with noise increases sometimes associated with simulated flight conditions. Unfortunately, the conditions of jet spreading and flow attachment at the trailing edge were often unstable and affected by "flight" speed. The greater the USB flap deflection, the greater the sensitivity to flight speed. Thus, a large variation is observed in flight effects in various tests.

Some indication of flight effects is implicit in the QSRA test results. A microphone was installed with the diaphragm flush with the outside of the fuselage under the wing. A continuous recording was made of this microphone output during a static condition, brake release, takeoff roll, and climbout, while the engine fan speed was held constant. USB flaps were retracted during this test condition. Data presented in Fig. 9 represent the static and flight conditions of this sequence. The difference in the noise spectra is typical of results in Refs. 2 and 3. The validity of these measurements is discussed in the next section.

Validity of Semi-Far-Field Measurements

In addition to the measurements cited, which were taken at the side of the fuselage, noise measurements were also taken during static runup tests at locations on the ground below the wing. These data are considered to be valid representations of far-field radiated noise. Evidence to support this assumption is presented in Fig. 10. Spectra from the fuselage microphone are overlaid with flight test spectra from a ground microphone at a time just before the airplane was overhead. The difference in amplitudes of the two microphone locations was a constant 32 dB. The spectral shapes were in excellent agreement. Also, variations with flight conditions such as flap angle and airspeed were the same at both measurement locations. Thus, results of ground microphone measurements in static runup tests, discussed in the following sections, are assumed to represent far-field noise.

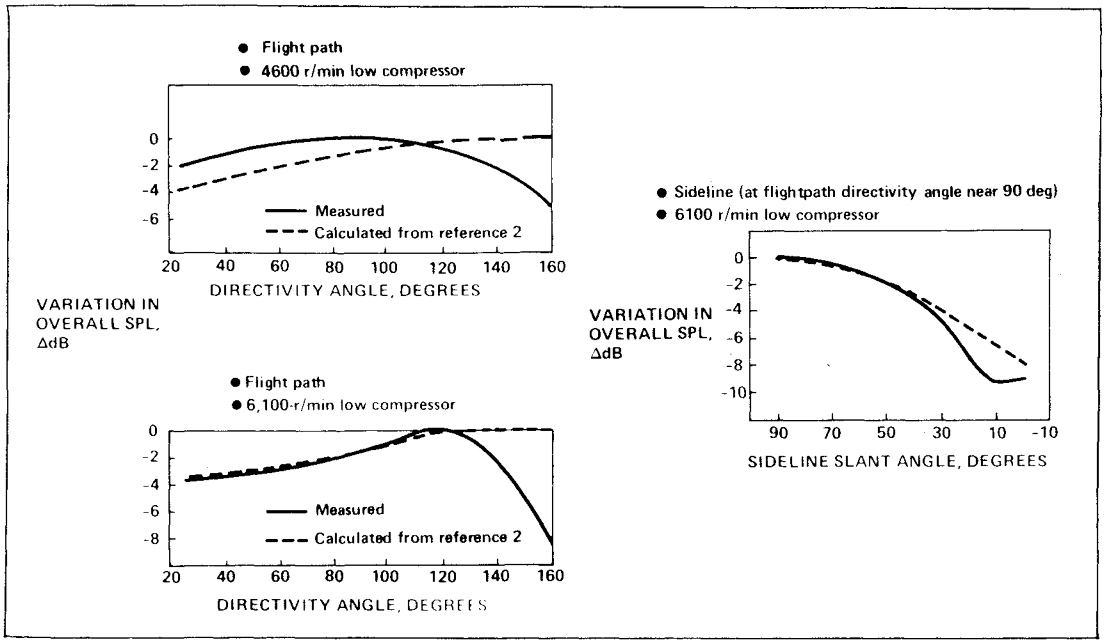


Fig. 7 Comparison of measured noise directivities with extrapolated model jet/edge interaction noise.

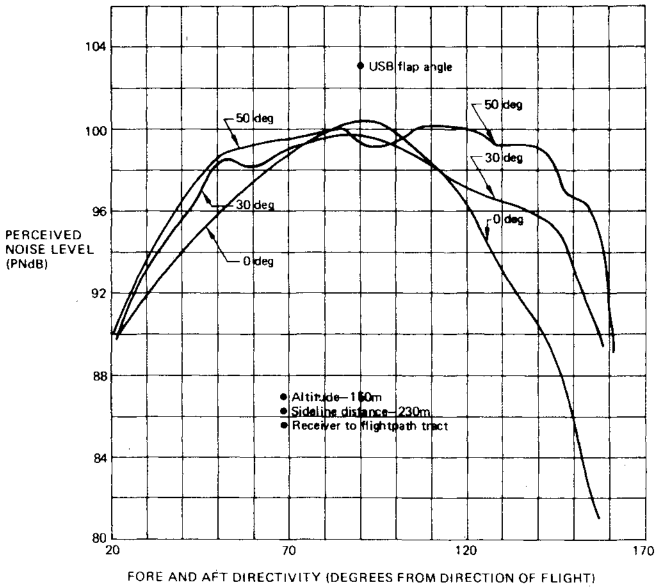
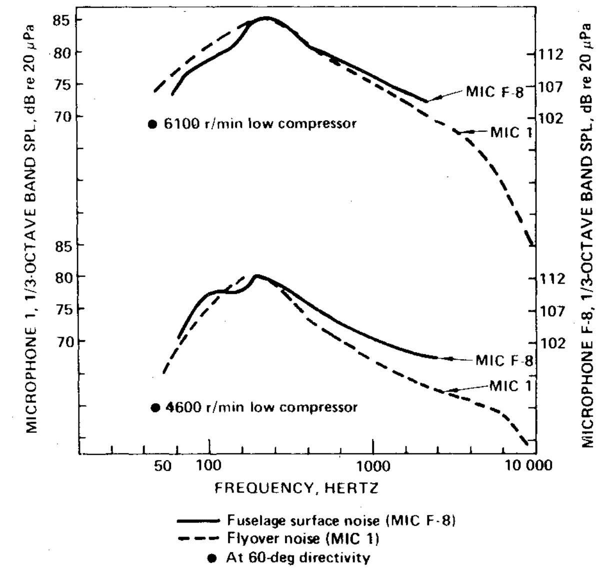


Fig. 8 Effect of USB flap angle on flyby noise.



Note: F-8 was "Doppler" shifted 2/3 of one 1/3-octave band.

Fig. 10 Comparison of noise on fuselage with flyover noise.

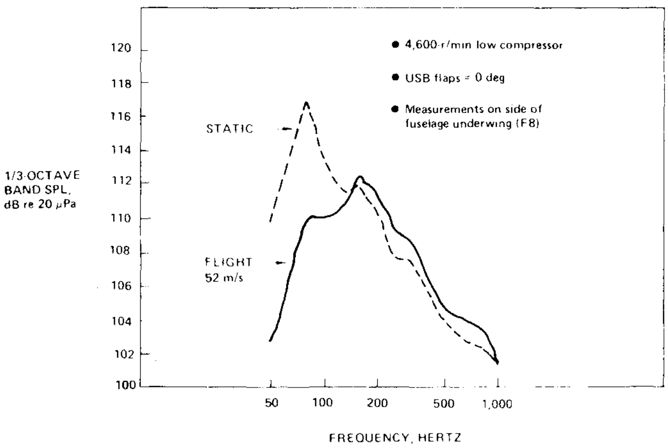


Fig. 9 Fuselage surface noise static and flight conditions.

Source Diagnostic Tests

Ground runup tests were conducted to verify conclusively that jet/edge interaction noise is indeed a prominent component in the total QSRA noise. Three pressure transducers (microphones) were located on the USB flap surface. Two were at the trailing edge, separated by 30 cm, and one was upstream by 30 cm. Each of the surface transducer outputs was cross correlated with each other and the ground microphone.

Correlated signal time delays were observed, which indicated a signal propagation speed of about $0.8V_j$ on the surface and of acoustic velocity between the trailing edge and the ground microphone. This confirms the presence of the jet/edge interaction component. A coherence level of about 0.5 was measured between surface pressure and radiated noise at 50 Hz, as shown in Fig. 11. This indicates a strong dominance of edge noise at that frequency. Quantitative evaluation of contributions at higher frequencies requires

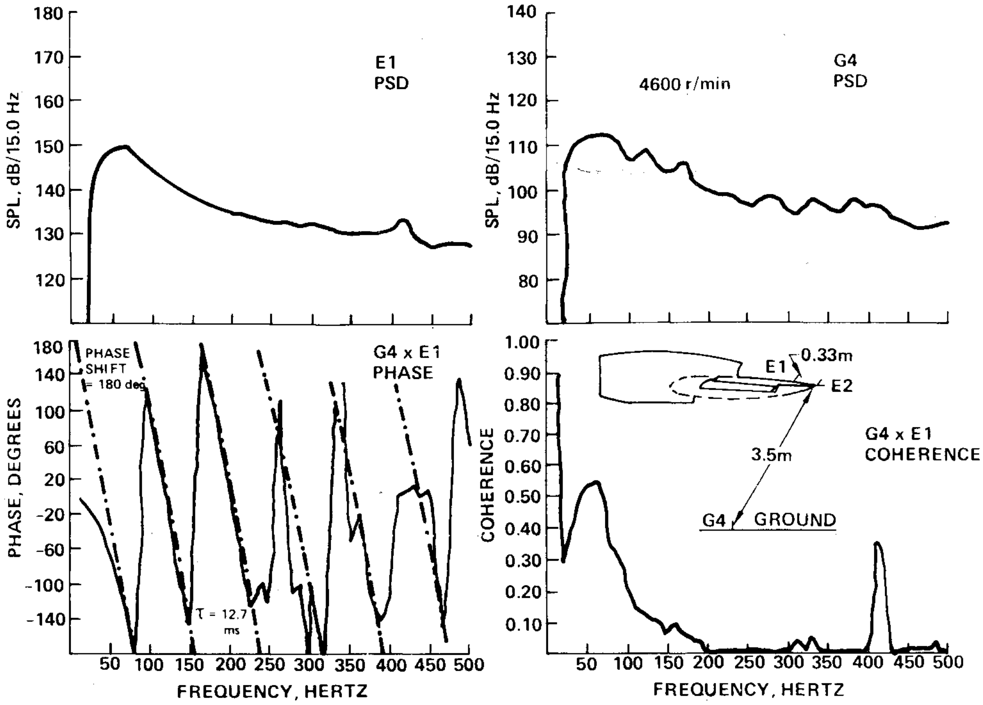


Fig. 11 Coherence and phase of surface pressures and radiated noise.

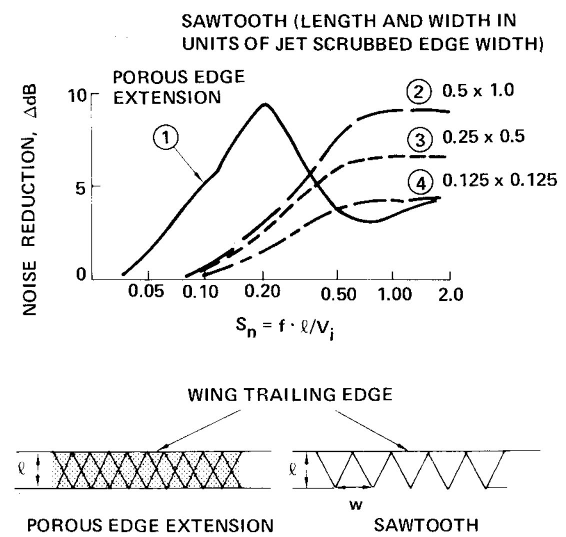


Fig. 12 Normalized small-scale test results.

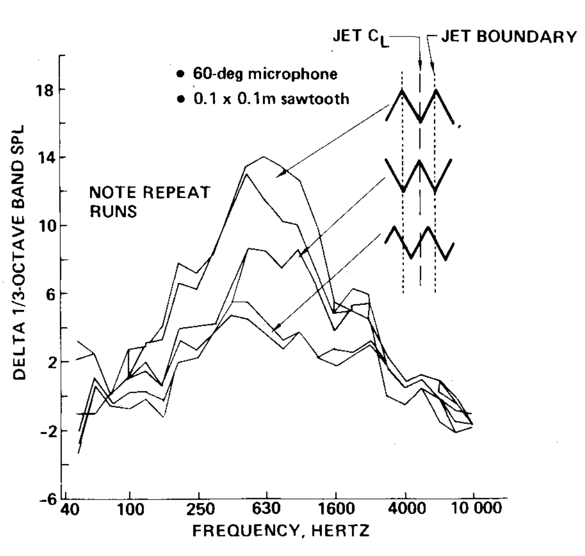
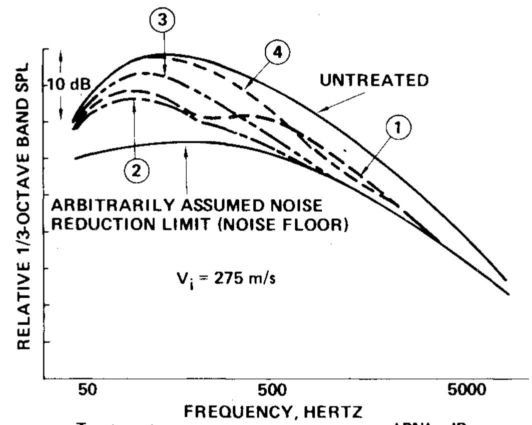


Fig. 13 Effect of sawtooth position on noise reduction spectra.



Treatment	ΔPNL, dB
① 0.23m porous edge extension	5
② 0.76m (ℓ) x 1.5m (w) sawtooth	6
③ 0.38 x 0.76m sawtooth	5
④ 0.19 x 0.19m sawtooth	2

Fig. 14 Ranking of estimated effects of QSRA USB trailing-edge treatments.

determination of the spanwise correlation length, which was not accomplished. [The signal from one transducer represents a source area related to the correlation area of the signal. The total edge noise is the composite of all the constituent, independent (uncorrelated) source areas.]

The large coherence values at low frequencies indicate that large-scale turbulence interacts with the trailing edge to create the predominant noise at those frequencies in static test cases. It is this component that is greatly reduced by flight effects. The higher frequency edge-noise components have much smaller correlation lengths and are not reduced by flight effects.

Small-Scale Noise Reduction Tests

Small-scale tests were conducted of a jet emitting from a D-shaped nozzle scrubbing a flat plate, with an edge downstream at a distance roughly scaled to the QSRA (on the basis of the nozzle size). The edge extended beyond the scrubbed region by over one jet diameter. Radiated edge noise was

Fig. 15 Static test of QSRA USB edge treatment.

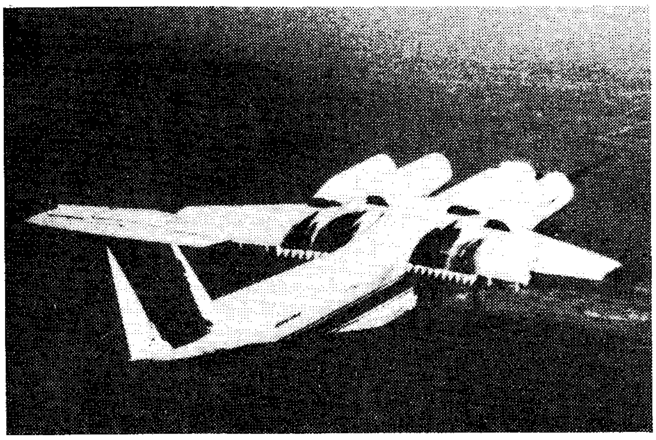


Fig. 16 The QSRA with sawtooth-shaped USB trailing-edge acoustic treatment.

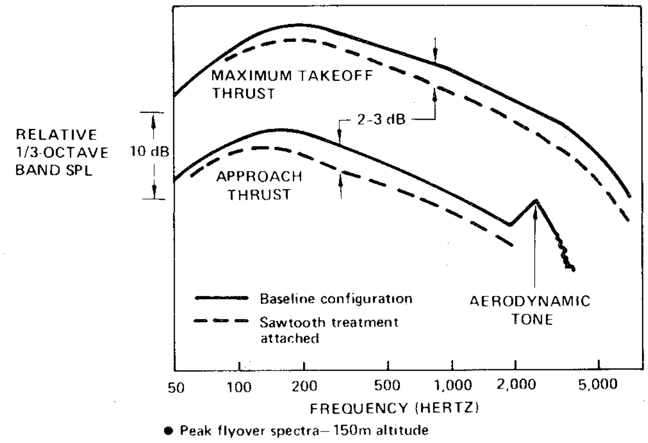


Fig. 17 Measured effect of QSRA USB flap edge treatment in flight test.

measured when jet velocities were set in the range from 60 to 300 m/s. Noise reduction spectra were determined in tests of a matrix of sawtooth-shaped edge extensions where the number, length, width, and sweep angle of the teeth varied, and of a porous edge extension where porosity was varied. Normalized results are presented in Fig. 12.

The increase in noise reduction with increased size of the sawteeth shown in Fig. 12 was found to be dependent on the transverse location of the tooth pattern relative to the jet. Lateral repositioning of the tooth patterns, by one-half the width of a tooth in some cases, changed noise reductions (ΔdB) by a factor of two! A sample of this change is shown in Fig. 13. This indicates a noise-reduction mechanism in addition to the one described by Filler in Ref. 6, where the noise is a function of the cosine of the sweep angle of the teeth. It appears that the two-dimensional distribution of the edge "source" sets up a local source interference pattern that severely affects radiated noise levels. This appears with the sawtooth concept as well as with porous edge extensions, as described in Ref. 7.

An estimation of effects of four edge-treatment designs on QSRA noise, based on the small-scale tests, is presented in Fig. 14. This evaluation is complicated by the unknown proportion of edge noise in the total QSRA noise. In this analysis, the noise reduction limit, or nonedge noise "noise floor" was assumed to be representative of midthrust conditions at overhead angles of radiation. Because of its unwieldy size and only slightly higher anticipated noise reduction, the large sawtooth (configuration 2 in Fig. 14) was not tested full scale.

Full-Scale QSRA Edge Noise Reduction Tests

Ground runup tests were conducted of a baseline configuration and three edge-treatment designs selected from the small-scale test matrix. One configuration and the test setup is shown in Fig. 15. Noise was measured along the ground under the engine at distances of about 3 to 4 m from the flap trailing edge. Test conditions ranged from idle to maximum takeoff thrust.

The levels of noise reduction observed ranged between 2 and 3 dB over the entire noise frequency spectrum at all thrusts. This was less than those in the model test in the frequency range of peak reductions. It was also observed that all treatment configurations tested on the QSRA yielded equal amounts of noise reduction. This indicates that some unaffected component may have presented a noise reduction ceiling in the static tests.

Flight tests were conducted with a 0.38- × 0.38-m sawtooth attached, as shown in Fig. 16. Tests were limited to the USB flap retracted condition. Results, shown in Fig. 17, were essentially identical to those of the static tests. The average reduction in EPNL was 1.5 EPNdB.

Conclusions

1) Jet interaction with flap trailing edges produces the predominant noise component of a USB propulsive-lift airplane when the fan and turbine noise components are reduced by nacelle acoustic linings.

2) An additional source associated with USB is indicated—probably at the flap ends, associated with airfoil tip vortices.

3) The QSRA test results presented have generally confirmed findings of many investigations that were limited to model and/or static test facilities.

4) The USB noise behaves as the classic dipole at low jet velocities and exhibits quadrupole-like properties at jet velocities approaching Mach 1.

5) Noise at frequencies below 150 Hz was caused predominantly by large-scale turbulence, correlated over a large portion of the jet mixing region. This component was reduced dramatically by flight velocity.

6) At frequencies above 150 Hz (at which perceived noise levels were determined) no noise reduction resulted from flight speed.

7) USB flap trailing-edge treatments were effective in reducing propulsive-lift noise by about 1.5 EPNdB; however, noise associated with the flap tip vortices is suspected to have limited the total noise reduction.

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