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Twin-Jet Noise Shielding for a Supersonic Cruise Vehicle

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An engine arrangement for a supersonic cruise vehicle (SCV) has been developed that shows promise for jet noise reduction without the performance penalties associated with mechanical suppressors and engine oversizing. This arrangement, wherein two engines are placed on top of the wing directly above two similarly mounted engines below the wing, can produce 3-5 dB less noise below the aircraft flight path than when four engines are installed under the wing. This noise reduction is due to acoustic shielding of the upper jets by the lower jets. Test data are reviewed to verify this acoustical shielding phenomenon. Engine placement variation and differential throttling, wherein thrust is unloaded from the lower engine and added to the upper engine, are to be explored as means for maximizing the shielding effect.

Introduction: Evolution of Over/Under Engine Arrangement

THE over/under engine concept for a supersonic cruise vehicle (SCV) evolved in the early stages of Lockheed's participation in the NASA-sponsored supersonic technology assessment program initiated in 1972. A supersonic cruise vehicle employing this engine arrangement is pictured in Fig. 1.

Lockheed's first baseline configuration for assessing the impact of potential technology advances on SCV performance, noise, cost, and risk incorporated the conventional four-engine-under arrangement. However, engine placement studies generated considerable interest in the over/under concept.

These early engine placement studies[1] included the engine arrangements shown in Fig. 2. Several conventional and unconventional arrangements were assessed from weight, balance, drag, and engine performance standpoints.

The over/under concept was originally included for flutter alleviation and high-speed roll control enhancement. A single deep support rail for the pair of over/under engines on each side of the airplane provides a stiffer structure with lower weight penalties for flutter with respect to a four-engine-under arrangement. The concept also reduces to a minimum the wing trailing edge cutouts, thereby leaving more of the span available for lateral control devices and/or trailing edge flaps.

The two preferred arrangements are circled in Fig. 2—the four-engine-under and the over/under. Further, it was found that the over/under concept had several advantages, in addition to flutter alleviation and control power augmentation, with respect to the four-engine-under version. These are: 1) weight reduction of the vertical tail, engine support structure, and landing gear; 2) inlet protection from unstart; 3) high lift enhancement; and 4) lateral control power improvement. The spanwise location of the engines moves the thrust vector line for critical engine-out condition inboard by 10%, thus reducing the size of the vertical tail. Engine spanwise location impacts the main landing gear length when either cross-wind landing or scrape angle for rotation and touchdown are considered; inboard movement of the engine results in reduced main gear length. Further, with the over/under nacelle arrangement, the wing isolates one inlet from the other and thus prevents an inlet unstart from propagating to an adjacent inlet. Comparable protection with a four-engine-under aircraft configuration necessitates an aerodynamic fence with attendant weight and drag penalties.

The over/under configuration exhibits differing local Mach numbers for the above wing and below wing inlets which will require different inlet geometry schedules for the inlet-engine controls. Engine access and removal challenges and the need to configure the powerplant to be capable of being mounted in both upright and inverted positions also must be recognized.

It should be noted that no important community noise advantages were cited for the over/under configuration in the early design stages. The only acoustic reference was to potential attenuation of forward-radiated fan noise by shielding of the wing structure.

It was recognized that the sideline and flyover noise characteristics of an SCV of the types discussed above were unsatisfactory for an aircraft sized for optimum mission performance. The primary means for relieving this community noise problem were engine oversizing, allowing partial power takeoff with reduced jet velocities, and the introduction of mechanical suppressors into the exhaust stream. These factors were discussed and the weight penalties and thrust losses were assessed.[2] It is with this environment that recognition of the acoustic jet shielding phenomenon took place in early 1976 at Lockheed.

Twin-Jet Shielding Phenomenon

Static Experimental Data

In late 1975, Lockheed's Supersonic Cruise Research (SCR) program office was made aware of General Electric test data

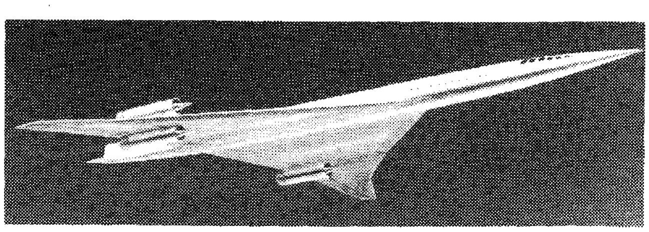

Fig. 1 Supersonic cruise vehicle with over/under engine concept.

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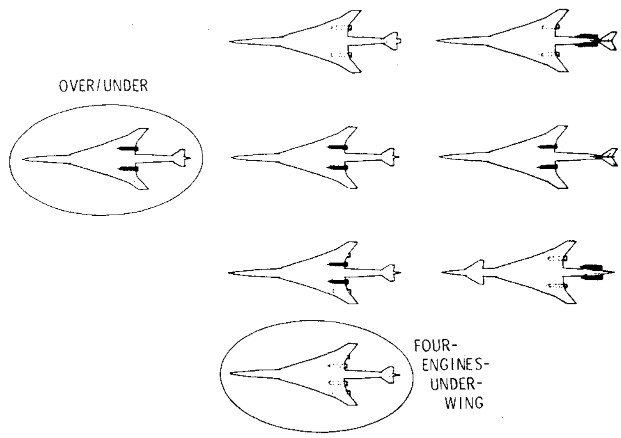


Fig. 2 Engine location study.

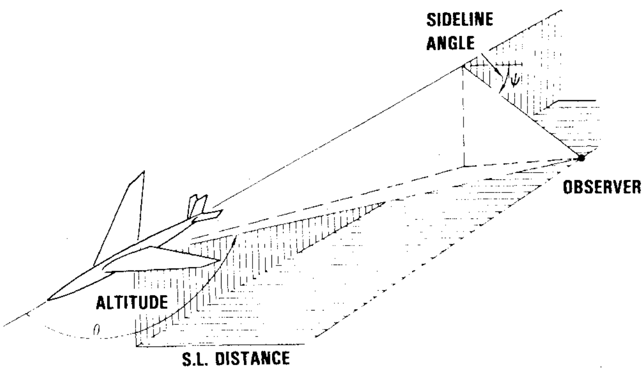


Fig. 3 Geometry for twin-jet noise analyses.

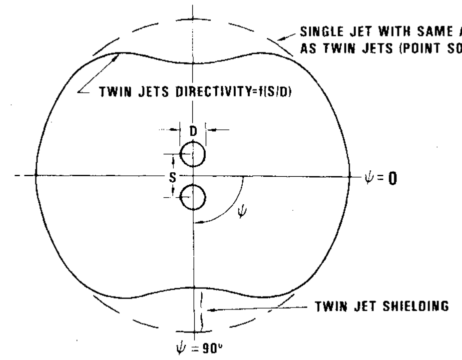


Fig. 4 Circumferential noise directivity of twin-jets.

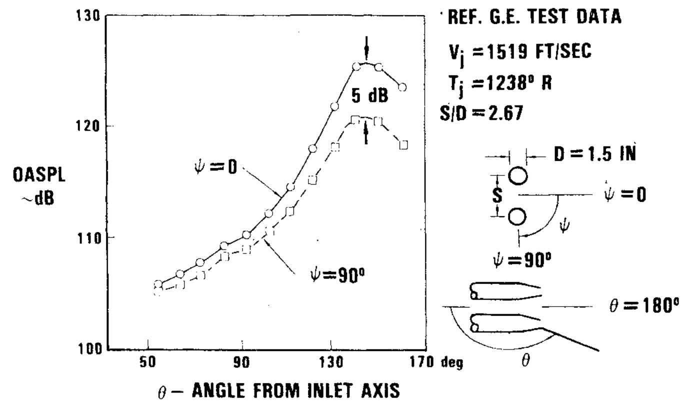


Fig. 5 Twin-jet noise directivity.

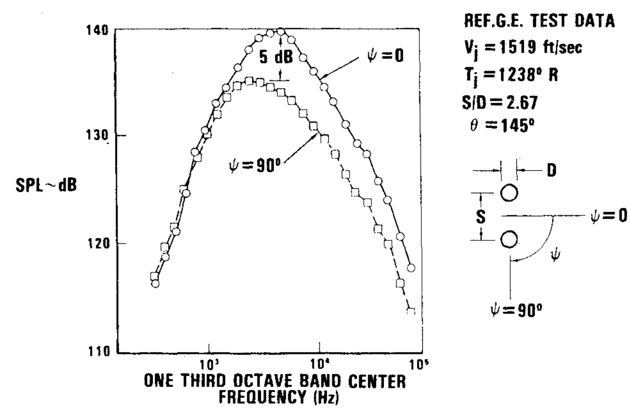


Fig. 6 Twin-jet spectra comparison.

on twin jets during a routine government and industry coordination meeting. Twin jets are two jet exhaust streams in close proximity, i.e., nozzle centerline spacing to diameter ratio (S/D) generally less than 3. These data[3] represented Lockheed's introduction to what is now called the twin-jet shielding effect, an attenuation effect having direct application to the over/under engine arrangement. Literature searches yielded additional data from University of Tennessee[4] and two NASA reports,[5,6] dealing with ground tests of the XB-70 and F-111A aircraft. Summaries of these data are given below. Figure 3 defines the flyover polar directivity angle θ and sideline angle ψ that will be used in discussing the data.

Figure 4 shows a generalized comparison of directivity patterns for a single jet and a twin jet. Along an axis perpendicular to the twin-jet axis ($\psi = 0$), the twin-jet directivity is identical to that of the single jet of equal area. However, the twin-jet directivity is reduced along the twin-jet axis ($\psi = 90$ deg) due to shielding. The particular shape of the twin-jet pattern is a function of S/D.

Twin-jet test data[3] are shown in Figs. 5 and 6. Noise directivity in the flyover plane is shown in Fig. 5. Peak sideline noise is shown to occur approximately 145 deg from the nozzle inlet axis. Noise for $\psi = 90$ deg is approximately 5 dB less than noise at $\psi = 0$. A spectral comparison is shown in Fig. 6 for maximum flyby noise which is considered to occur at $\theta = 145$ deg. Low frequency noise for both $\psi = 0$ and 90 deg has the same magnitude. Peak frequency for $\psi = 0$ is at a higher frequency than noise at $\psi = 90$ deg, and the difference in noise levels is approximately 5 dB.

Test data[4] for circumferential noise directivity of twin jets are compared in Fig. 7 with noise produced by a single jet. For $\psi = 0$ the noise difference is 3 dB, whereas at $\psi = 90$ deg the difference is 1 dB. Data at 0 and 90 deg obtained from other tests indicate that as exhaust velocity increases, noise shielding at $\psi = 90$ deg becomes greater. Therefore, for engines operating with high exhaust velocities, circumferential directivity between a single nozzle and twin jets is expected to be much larger at $\psi = 90$ deg than that shown in Fig. 7 for a 1000 ft/s exhaust velocity. Also, these data are from cold jets and can be expected to be pessimistic as shielding is enhanced by refraction and reflection through temperature gradients.

Nozzle spacing and exhaust velocity effects[3] are shown in Fig. 8. Also, data are compared with single nozzle data where 3 dB have been added to represent the effect of a single nozzle with twice the area of twin jets. As jet velocity is increased from 1006 to 1821 ft/s, the spread in the noise levels for $\psi = 0$ and $\psi = 90$ deg increases from 2 to 5 dB. As the nozzle separation distance S/D increases from 1.5 to 5, the shielding effect is sustained. As the jet velocity is increased from 1519 to 1821 ft/s, noise for $\psi = 0$ becomes greater than single nozzle noise plus 3 dB, but the $\psi = 90$ deg noise is less than noise for one single nozzle.

The twin TF30 engines on a F-111A aircraft are located as shown in Fig. 9. Noise measurements were made for single

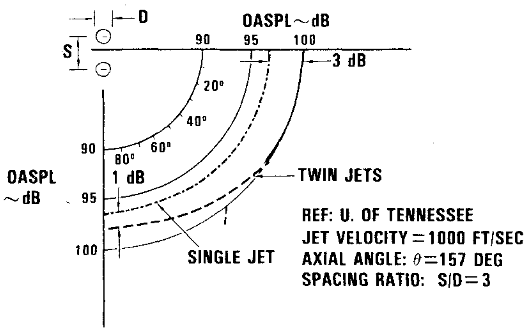


Fig. 7 Twin-jet circumferential directivity.

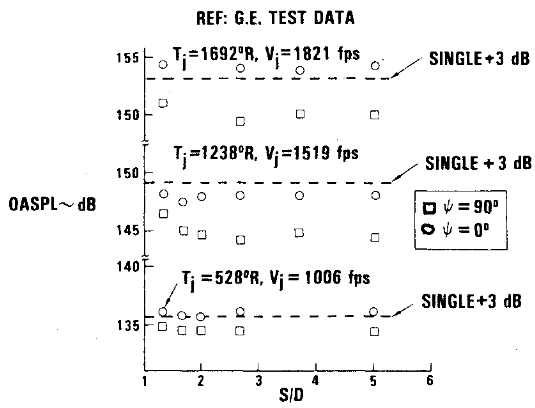
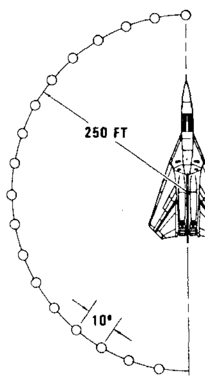


Fig. 8 Twin-jet spacing effect.

Fig. 9 F-111A test.



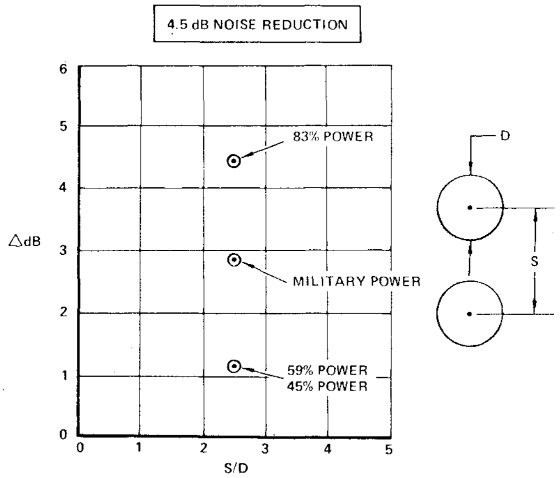


Fig. 10 F-111A test results.

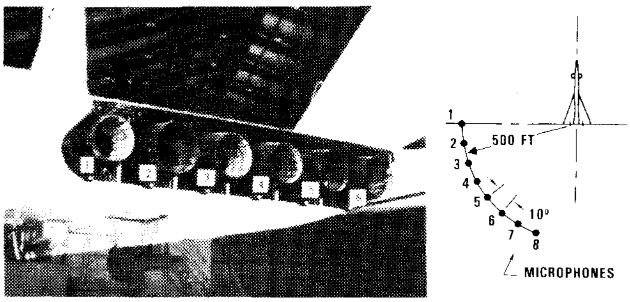


Fig. 11 XB-70 jet noise shielding.

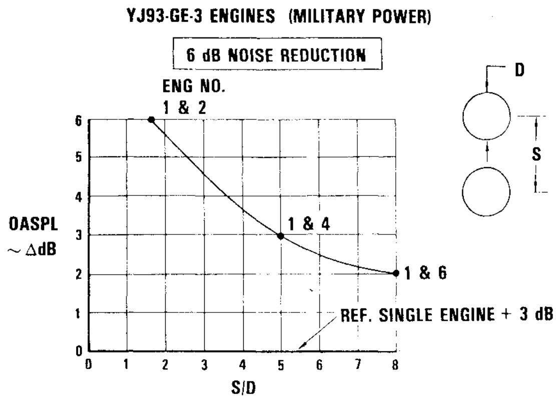


Fig. 12 XB-70 test results.

and two engine operation while the aircraft was parked on the ramp.[6] To evaluate the twin-jet shielding effect, 3 dB was added to single jet noise and measured data for twin jets were subtracted from the results. Tests were conducted for four power settings as shown in Fig. 10. Maximum noise shielding benefits are seen to be approximately 4.5 dB for an 83% rpm setting.

The XB-70 aircraft has six YJ93-GE-3 engines in a row as shown in Fig. 11. Noise measurements made for different combinations of engine positions provide an excellent evaluation of twin-jet directivity effects.[5] The plot in Fig. 12 shows a noise reduction potential of 6 dB for an S/D value of 1.5.

The Caltech Jet Propulsion Laboratory (JPL) was engaged in 1978 to investigate further the acoustic shielding phenomenon analytically for twin-jet coaxial nozzles with inverted velocity profiles. Specifically, the noise generating and shielding mechanisms were to be identified and a prediction method developed. The results of these studies are reported by Parathasarathy.[7] The JPL literature search yielded two additional sources of experimental data on jet shielding—the work of Bhat[8] and Kantola.[9]

Bhat[8] investigated twin jets of unequal velocity and showed that not only can one jet shield another of equal velocity—it can also shield a jet of higher velocity. Data are shown in Fig. 13. In this figure, the perceived noise levels (PNL) of twin circular jets and of the individual jets operating alone are plotted versus the angle with respect to the inlet. The measurements are in a plane containing the two jet axes. In this example the twin jet (two jets operating together) is quieter than the noisy upper jet operating by itself by about 10 dB. The angular average PNL values of the noisy jet and of the twin jet are shown also. The reduction in average power is about 3 dB. The reduction in noise is not caused by a redistribution alone of sound power in the plane of the jets, but must involve a reflection or scattering out of the plane containing the two jet axes. At 90 deg, the shielding is negligible and at large angles it reaches large values. It is suspected that shielding at large angles is so effective because more and more of the oblique rays of sound undergo total reflection at the boundaries of the lower, quieter jet.

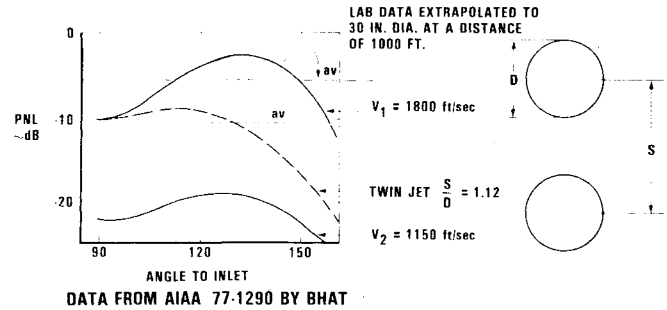


Fig. 13 Twin-jet shielding.

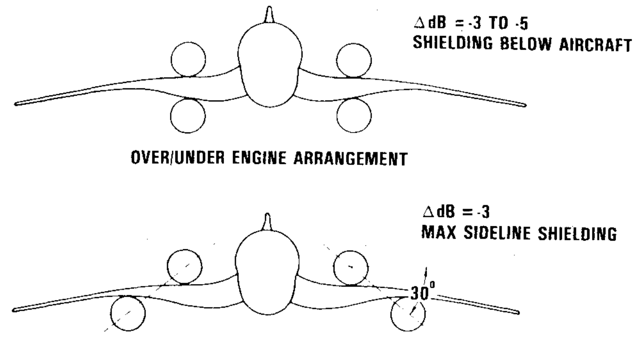


Fig. 14 Engine arrangement shielding benefits.

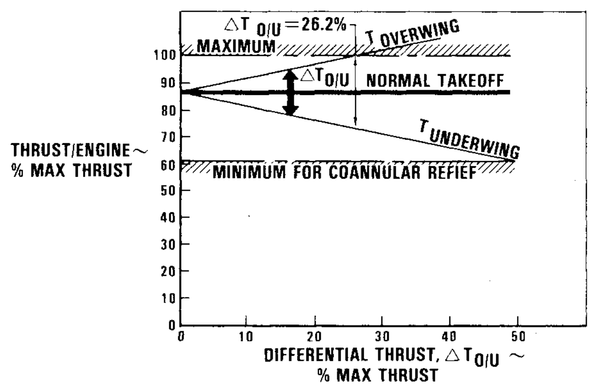


Fig. 15 Differential throttle without cutback.

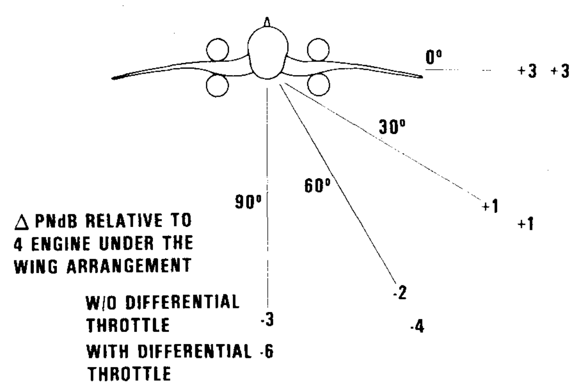


Fig. 16 Twin-jet noise shielding with differential throttle.

Shielding Optimization Possibilities

The twin-jet shielding principle may be exploited to provide additional noise relief for an SCV with an over/under type engine arrangement. Two possibilities are: 1) adjusting the relative engine placement between the upper and lower positions to achieve various lateral displacements and twin-jet cant angles, and 2) increasing the throttle setting of the over-wing engines with respect to the under-wing engines to achieve a differential throttle setting. These additional noise relief possibilities are treated in subsequent paragraphs.

Engine placement can be used to tailor the directivity pattern for the jet noise. In this manner, the acoustic shielding offered by the lower engine for the upper engine can be aimed optimally for the most beneficial impact on community noise. Two arrangements are shown in Fig. 14. Here the basic over/under arrangement is compared with a canted over/under arrangement that has the twin-jet axis inclined 30 deg to the horizontal.

If flyover noise dominates sideline noise, the vertical arrangement with no canting alleviates the flyover noise. If sideline noise dominates, the staggered arrangement would be beneficial. Assuming the elevation angle at the maximum sideline measurement point to be 30 deg, the sideline shielding should provide a noise reduction of at least 3 dB.

As indicated in the above discussion of the twin-jet shielding phenomenon, a quiet jet can shield a noisy jet as well as it can shield a jet with identical size and velocity. This noise reduction method can be applied to the over/under engine installation by increasing the upper engine throttle setting with respect to that of the lower engine.

Some of the practicalities of the differential throttle technique are shown in Fig. 15. The situation here is takeoff at normal power without cutback. Takeoff power does not represent the maximum thrust as the engine is sized for cruise thrust and has unused thrust capability at normal takeoff conditions. In this situation, normal takeoff power is 86.9% of the engine's capacity. On the lower side, the coannular noise relief benefit is lost if thrust is reduced below 60.8% of maximum power. The proper velocity ratios between flow in the core and outer ducts cannot be maintained below this power setting.

As shown in Fig. 15, thrust can be reduced on the lower engine and added to the upper engine until the upper engine is operating at its maximum rating. The lower engine is still maintaining the flow for coannular noise relief. At this point, the total differential thrust between the over and under engines is 26.2% of the maximum thrust or 30.1% of the normal takeoff thrust.

This differential throttle case was investigated.[7] The results are shown in Fig. 16 where over/under noise relief is shown with respect to the four-engine-under case. It is seen that differential throttling produces an additional 3 EPNdB of noise attenuation below the flight path. This effect phases out as elevation angle is decreased, but nowhere does the differential throttle cause any increase in noise levels.

These favorable results suggest combination of differential throttle with advanced operational procedures to maximize the noise relief promise of the over/under engine arrangement. In this manner, flight path shaping, power cutback depth, and throttle schedules can be optimized for best traded takeoff noise levels.

Twin-Engine Exhaust Noise Shielding Flight Tests

A number of existing aircraft types are suitable for flight test evaluation of shielding effects. Beginning in January 1979, Lockheed undertook a joint flight test program with NASA at the Dryden Flight Research Center (DFRC), Edwards AFB, California. Candidate aircraft being considered for tests in the period 1979-80 include the T-38 (or F-5), F-111, F-14, and F-15 aircraft.

A collapsible transportable tower is shown in Fig. 17 which can be used at the NASA DFRC to mount microphones at heights up to 96 ft above the ground. An initial flight test phase was performed during February 1979 to develop procedures for applications of this tower to twin-engine-powered aircraft flyby acoustics studies. The tower was mounted at a perpendicular distance of 200 ft from the

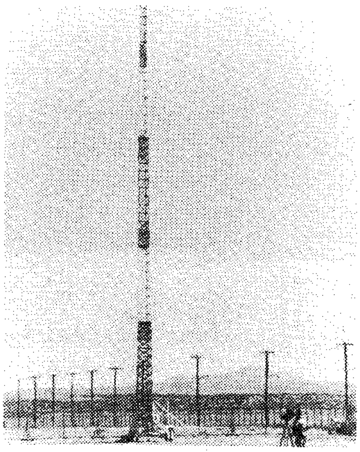


Fig. 17 Ninety-six foot acoustics tower.

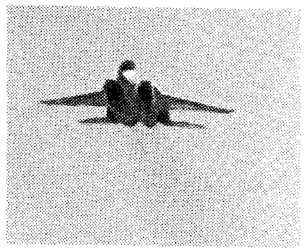


Fig. 18 F-15 aircraft approaching acoustics tower.

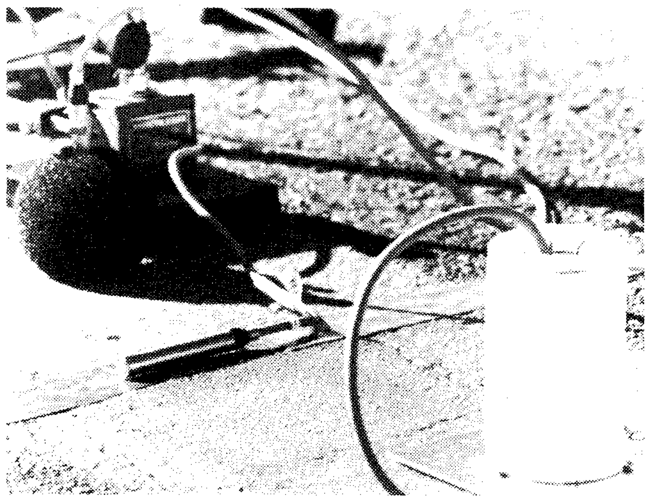


Fig. 19 Ground microphones.

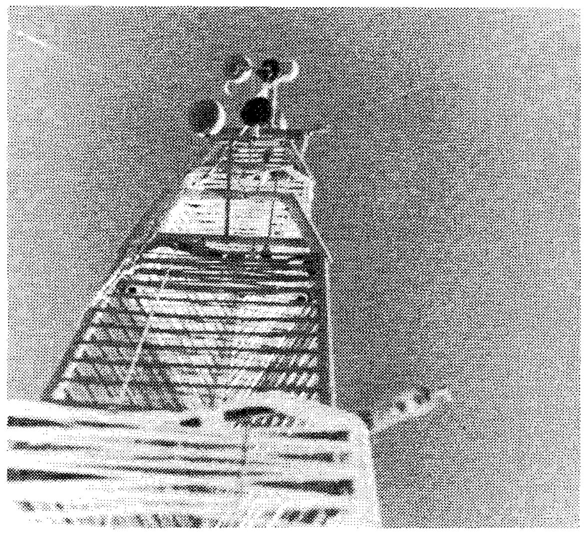


Fig. 20 Tower microphones.

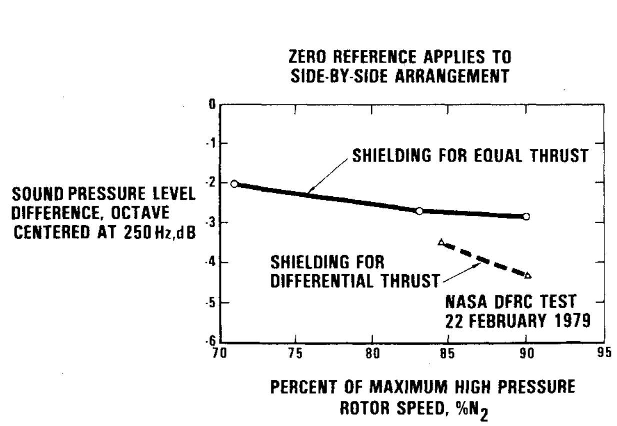


Fig. 21 Preliminary over/under shielding results, F-15 flyby test.

centerline of a taxiway. Practice flights were performed with F-104 and T-38 aircraft to gain experience in operating an aircraft in the vicinity of the acoustics tower under flight path, control surface configuration, attitude, speed, altitude, and engine setting constraints.

On Feb. 22, 1979, an F-15 aircraft, powered by twin P&W F-100 turbofan engines shown in Fig. 18, was flown in a series of 14 passes along the taxiway centerline at altitudes in the range of 100–200 ft above the ground. A set of 20 B&K type 4234 0.5 in. diam microphones was used in a system to acquire tape recorded sounds of the F-15 aircraft. The microphone set was divided into two subsets of 10. One set of 10 microphones and acquisition system was operated by the NASA DFRC and the other set by Lockheed Palmdale flight test personnel. The microphones were placed at 10 locations, consisting of seven ground plane stations and three height positions on the tower as shown in Figs. 19 and 20. Replication was accomplished by placing one NASA and one Lockheed microphone side-by-side at each of the 10 measurement locations.

The test plan required the pilot to operate the F-15 at 230 ± 20 knots indicated airspeed while passing the tower. For the 14 passes, average airspeed was 233 knots, with a standard deviation of 13 knots. The flight passes were all made in the same direction along the taxiway centerline, such that the left-hand engine was always closer to the tower than the right-hand engine. Engine settings for the flights are described here in terms of percent of maximum high pressure rotor speed, percent N_2. Twelve different pairs of left and right engine settings were employed. Three primary engine speed settings were selected to correspond to projected SCV engine landing approach, full takeoff and takeoff cutback power conditions. These three settings are nominally 70% N_2, 90% N_2, and 82% N_2, respectively. A fourth engine setting, referred to as a flight idle, was employed for the right-hand engine in performing 3 of the 14 tower flyby passes.

A motion picture camera with a speed of 8 frames/s was placed on the taxiway centerline opposite the tower. The camera is mounted in a fixture in such a way that the camera axis is directed vertically. At the instant when a frame is exposed to capture an overhead aircraft image, an electrical pulse is transmitted to an acoustics data acquisition tape recorder channel. Subsequent data analyses determine true airspeed, altitude, angle of yaw, and instant of time with respect to tape recorded IRIG "B" time code when the aircraft flew past the tower.

Data processing of the tape recorded microphone signals, optical tracking information, and aircraft onboard performance parameters are being performed currently at NASA DFRC under the direction of F. W. Burcham. For the purpose of this presentation, a simplified procedure was applied to estimate whether the initial F-15 tower flyby tests reveal evidence of shielding benefits. For all 14 flight passes, exhaust noise was maximal in the octave centered at 250 Hz. Sound pressure level time histories were obtained in this octave for two microphones; one at the 96 ft tower height position, and one at the ground plane on the taxiway centerline, 200 ft perpendicular distance from the base of the tower. The maximum 250 Hz octave band sound pressure level was determined for each of the time histories.

The preliminary results summarized in Fig. 21 indicate that over/under shielding on the basis of F-15 flyby measurements has a potential of 2-3 dB for engines of equal thrust. Two differential thrust shielding values are also shown. In one case the engine nearest the tower was at 71% N_2 speed, while the farther engine was at 84% N_2 speed. For the other differential thrust shielding data point, the engine nearest the tower was at 84% N_2 speed and the farther at 90% N_2. This preliminary differential throttling test result suggests that noise reduction for the over/under case has a potential in the range of 3.5-4.5 dB, based upon the initial F-15 flyby test results.

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