AIAA 80-1056R

Current Status and the Future of Advanced Supersonic Transport Noise

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Noise-control technology developed during the past decade could enable the United States to resume development of an advanced supersonic transport (SST) that will give acceptable levels of noise. Such developments include coannular and nonconcentric nozzles, thermal acoustic shields, and mechanical suppressors to control jet noise, the primary source of SST noise. Advanced operational procedures during takeoff and landing will reduce SST community noise. However, because the success of noise-suppression devices cannot be predicted with certainty, more noise-control technology must be developed and flight tested to ensure that SST jet and turbomachinery noise can meet community-noise standards of the future.

Nomenclature

a_0 = speed of sound
A_p = primary flow area
A_s = secondary flow area
C_V = nozzle coefficient
dB = decibels = $20 \log_{10}(p_0/p_{\text{ref}})$
PNLW = an angle weighting of perceived noise level (PNL) to estimate the effectiveness of a suppression device on an airplane flyover, $10 \log_{10}$

$$\sum_{\theta=90\,deg}^{\theta=160\,deg} 10 \left[\frac{\text{PNL}(\theta) - 10\log_{10}\sin^2\theta}{10}\right]$$

T_{TP} = total temperature, primary stream
V_A = aircraft/airstream velocity
V_j = jet velocity
V_P = primary jet velocity
V_s = secondary jet velocity

I. Introduction

WHEN the U.S. supersonic transport (SST) program was canceled in 1971, the available noise-control technology left substantial room for improvement. The SSTs at that time also had a significant challenge in meeting FAA noise certification requirements, established in 1969 as 108 effective perceived noise in decibels EPNdB in Part 36 of the Federal Aviation Regulations. One of the principal objections to SSTs in the United States was the potentially unacceptable noise during takeoff and landing. Figure 1 compares the noise predicted for an SST (750,000-lb gross weight) with the noise rule levels for a subsonic aircraft of equal weight for the 1971 era. The same comparison is made in Fig. 1 for 1981 after 10 yr of noise-control technology, showing the improvements that have been accomplished and the additional noise reduction for an SST that is still required to provide a competitive aircraft for the mid-1990's. The lower noise levels are the result of replacing turbojet engines with variable-cycle bypass engines, using advanced operational procedures, and developing nacelle acoustic treatment.

Current and near-future SST designs are forecast to have a lower noise fall-off rate to the distant community than today's subsonic, wide-body, commercial aircraft. This is attributed, in part, to the low-frequency-dominated noise spectrum that SST engines will generate, that will not attenuate as rapidly with distance as the more broadband high-frequency-dominated noise spectrum of today's high-bypass-ratio turbofan engines. This shows the need to 1) reconsider criteria for optimum noise reduction to meet community-noise requirements at distant, as well as close, locations and 2) further develop suitable noise-control devices, particularly for the jet, which is the principal noise source requiring additional control.

Since 1971, NASA has sustained the supersonic cruise research (SCR) program to develop the technology associated with nonmilitary applications of supersonic airplanes. By keeping its technology current with that of other countries, the United States maintains the option for future development of an advanced U.S. SST and re-entry to the SST market without incurring an excessive lag in technical competence.

To maximize aircraft performance yet lower SST noise to meet expected domestic and international community-noise requirements, SCR has applied appropriate subsonic noise-control technology developed in the past decade by 1) adapting advanced technology data and noise-control experience for subsonic aircraft to the SST, 2) investigating innovative noise-control concepts for application to the SST, and 3) conducting limited static, wind tunnel, and flight tests to evaluate noise-control devices and considering potential flight testing with scaled flight vehicles.

II. Noise Control Today

The main sources of advanced SST engine noise are 1) the low-frequency jet noise generated by takeoff power and 2) the inlet turbomachinery noise at takeoff cutback power and landing approach power. These problems have been studied to develop specific noise-control devices, as well as reduce noise by changing airplane operational procedures.

Jet Noise

The higher jet velocity (high noise) turbojets developed over a decade ago are no longer considered for SST application because they do not provide the wide spectrum of airplane performance that includes subsonic and supersonic cruise legs. Instead, current candidate engines have a variable cycle that permits operation, in effect, as different engine types, depending on the segment of the flight profile being flown—for example, as a turbofan during takeoff and subsonic legs and as a turbojet during supersonic cruise. Such current candidate

Presented as Paper 80-1056 at the AIAA 6th Aeroacoustics Conference, Hartford, Conn., June 4-6, 1980; submitted July 18, 1980; revision received Jan. 30, 1981.

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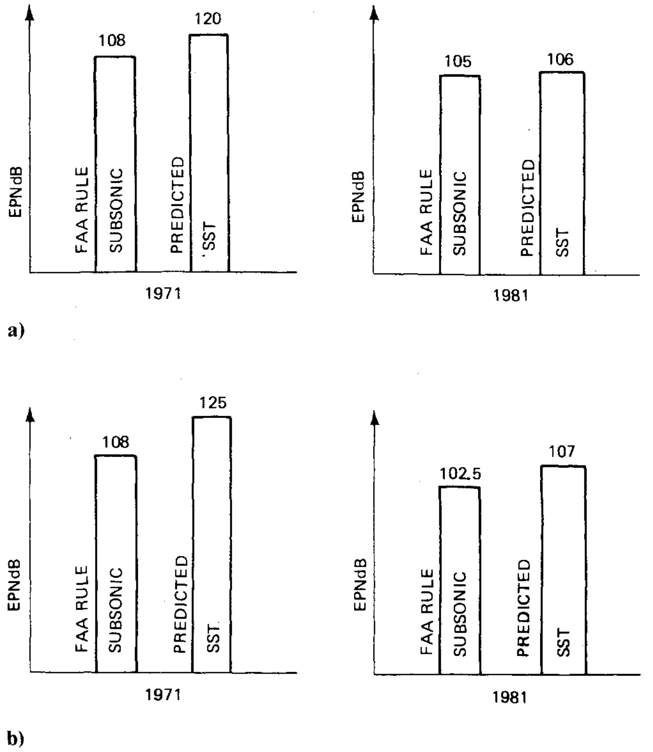


Fig. 1 Progress in SST community noise: a) community flyover noise and b) sideline noise.

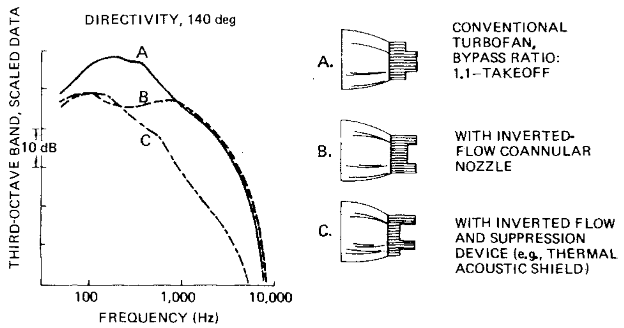


Fig. 2 Progress in jet-noise reduction technology.

engines include variable-bypass engines, as well as duct-burning turbofans. The latter demonstrated inverted velocity profiles (usually called "coannular jets") that reduce jet noise. As a result of the changes in engine cycle, many methods have been evaluated that help to reduce engine jet noise, particularly jet mixing noise and shock-cell noise. Model tests and some large-scale engine studies have been performed with coannular nozzles, ejector suppressors, mechanical suppressors, and other methods for suppressing jet noise.

Coannular Nozzles

In static tests at the Boeing acoustics laboratory anechoic large test chamber, modification of jet-stream velocity profiles modified the level of jet noise generated. Figure 2 shows[1] sound-pressure-level (SPL) spectra scaled to that perceived at a distance of 1500 ft. For a coannular nozzle with an inverted-turbofan velocity profile (Fig. 2b), the high-velocity jet surrounding the low-velocity fan flow generated less noise than a conventional-flow turbofan (Fig. 2a). Furthermore, even less noise was generated by a nozzle configuration representing a variable-cycle engine with an inverted velocity profile and a suppression device such as a thermal acoustic shield (Fig. 2c).

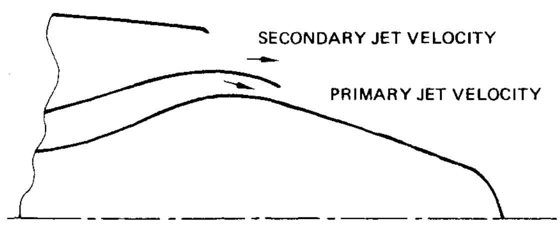


Fig. 3 General Electric coannular nozzle.

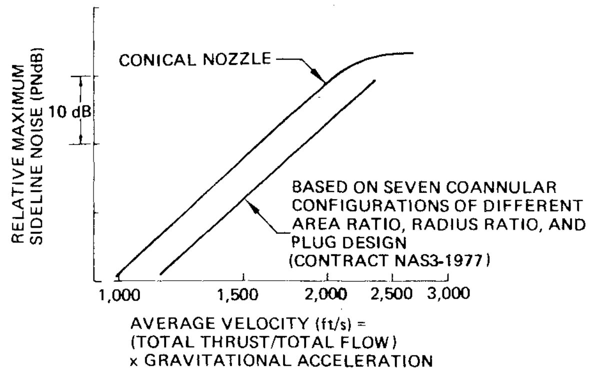


Fig. 4 General Electric correlation of coannular nozzle and maximum perceived noise level.

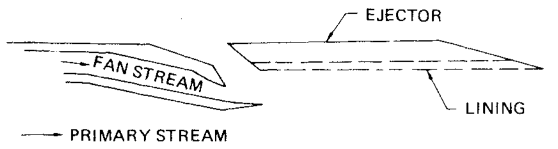


Fig. 5 Pratt & Whitney coannular-nozzle ejector suppressor.

As part of a jet-noise suppression program funded by the FAA and the Department of Transportation, General Electric developed a coannular-plug nozzle configuration to investigate 1) the outer nozzle radius ratio, 2) the location of the inner flow/outer flow interaction, 3) the amount of inner flow, and 4) the characteristic dimension of the inner flow (Fig. 3).[2] Based on model tests under static conditions, the perceived noise level in decibels (PNdB) at a distance of 2400 ft was 5-6 dB less with a coannular nozzle than with a conical reference nozzle (Fig. 4) when PNdB was normalized for jet density and thrust (ideal).[2]

Lined Ejector Nozzles

Lined ejectors have also been used in conjunction with coannular nozzles to form ejector suppressors. When Pratt & Whitney Aircraft tested this configuration (Fig. 5), the effective perceived noise was about 8 dB below the noise level predicted for a fully mixed conventional nozzle (Fig. 6).

Mechanical Suppressors

Tubes, slots, perforated plates, and fixed or retractable mechanical suppressors have been investigated to 1) transfer the acoustic energy generated by jet turbulence from a low-frequency to a high-frequency regime where noise attenuation is more tractable using acoustic linings and 2) increase the mixing process of the jet turbulence with the surrounding atmosphere to minimize the generation of acoustic energy.[2-4] Figure 7 shows the predicted reductions in sideline noise using a coannular nozzle or a conventional nozzle with a mechanical suppressor (McDonnell Douglas Corporation), compared with a simple conventional unsuppressed nozzle, which was the noisiest.[2] Figure 8 shows the variation of jet-noise suppression obtained in a flight test scaled to SST engine size with relative jet velocity.[5]

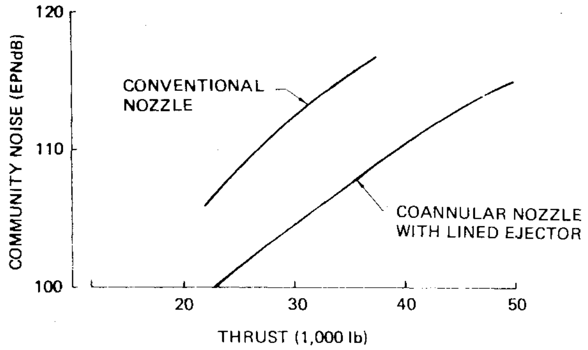
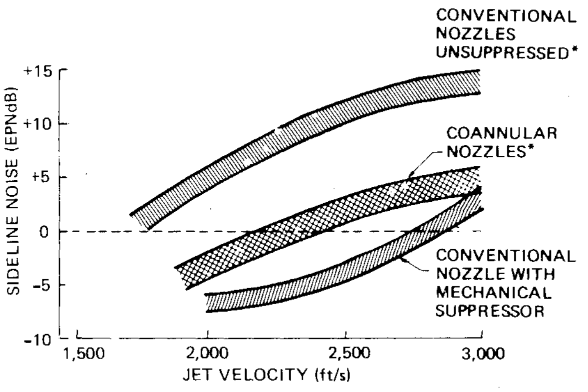


Fig. 6 Pratt & Whitney suppression results, jet noise only.



*ENGINE MANUFACTURER ESTIMATES

Fig. 7 Noise suppression by different nozzle configurations relative to FAR Part 36.

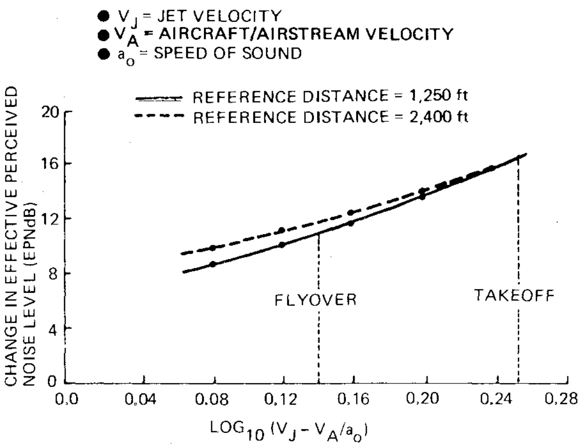


Fig. 8 Variation of noise suppression scaled to SST engine size with relative jet velocity.

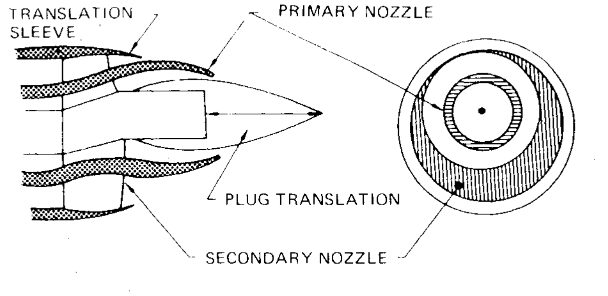
Other Devices

Additional control devices currently under study include nonconcentric nozzles, thermal acoustic shields, and exhaust duct zone-burning.

Nonconcentric or asymmetric coannular nozzles are being studied with a coplanar or offset exit plane and with or without a plug (Fig. 9). Model tests by The Boeing Company showed that a nonconcentric coplanar nozzle produced less noise than a conventional-bypass baseline nozzle (Fig. 10). In these results, an angle weighting of the perceived noise level (PNLW) estimates the effectiveness of a suppression device on an airplane flyover. The extrapolated noise of the nonconcentric nozzle was 5-10 dB lower (PNLW) than for the coannular nozzle; both nozzles were operated with a conventional velocity profile. The optimum noise attenuation occurred at a velocity ratio near 0.7 (Fig. 11). Figure 11 also shows the decrease in attenuation due to forward-flight effects close to the optimum attenuation. The reduction in effectiveness due to flight relative velocity is similar to a reduction in velocity ratio, which suggests that this concept can be optimized for flight operation.

Since Cowan and Crouch[6] summarized early work on the concept of thermal acoustic shielding, a heated, low-velocity shroud wrapped around the lower surface of a jet (Fig. 12) has been studied as a way to reduce jet noise radiated to an observer on the ground. Shielding jets have asymmetric properties, so thermal acoustic shields partially reflect and refract[7] the acoustic energy generated by the propulsion engine. Based on model tests by The Boeing Company, data extrapolated to 1500 ft in Fig. 13 show jet-noise reduction using a thermal acoustic shield in conjunction with a fully inverted coannular nozzle, as well as with a conventional bypass jet.

Another concept being considered, afterburners in the lower part of the bypass duct of a turbofan engine, will



● AREAS AND OFFSET NOT TO SCALE

Fig. 9 Offset variable nozzle concept.

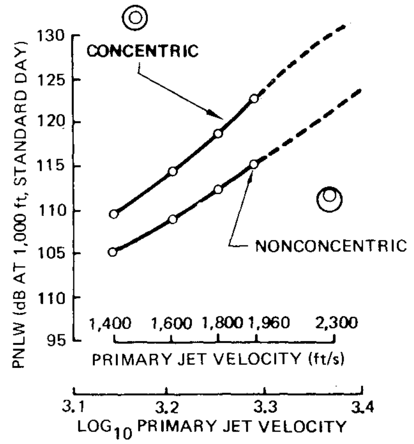
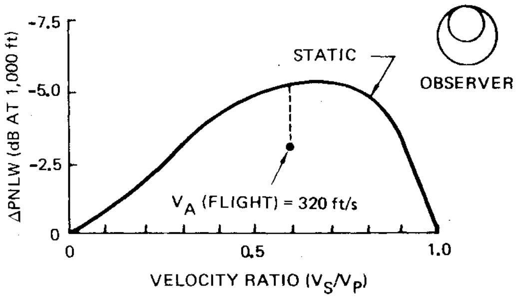


Fig. 10 Noise reduction with nonconcentric nozzles.



● SECONDARY FLOW AREA/PRIMARY FLOW AREA = 0.8
● V_P = PRIMARY JET VELOCITY = 1,600 ft/s
● V_S = SECONDARY JET VELOCITY
● V_A = AIRCRAFT/AIRSTREAM VELOCITY
● T_{TP} = TOTAL TEMPERATURE, PRIMARY STREAM = 1,000°F

Fig. 11 Velocity ratio effect.

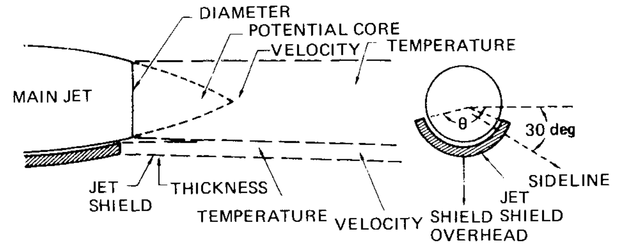


Fig. 12 Thermal acoustic shield.

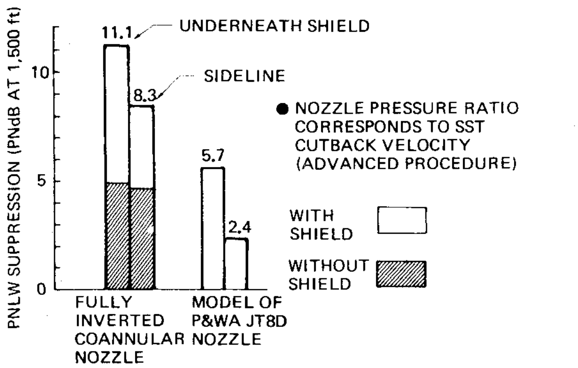


Fig. 13 Noise reduction using a thermal acoustic shield with different nozzles.

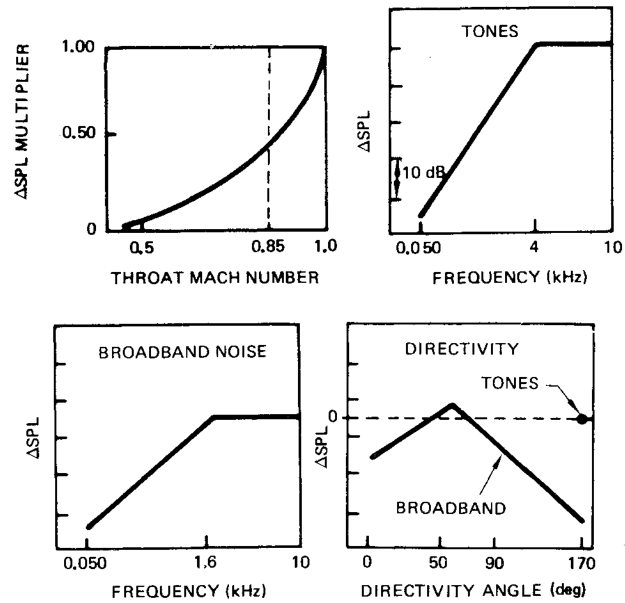


Fig. 14 Inlet attenuation effects used in estimating SST turbomachinery noise.

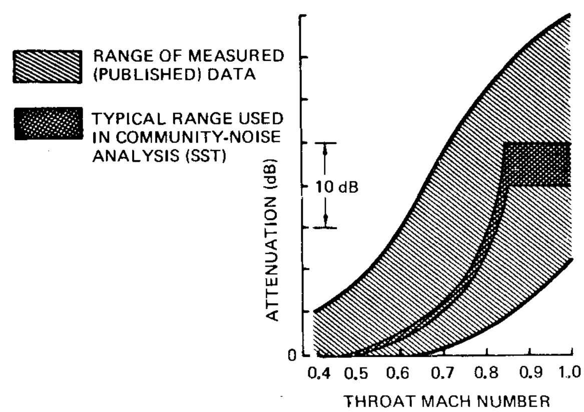


Fig. 15 Measured attenuation of turbomachinery noise.

provide a hot thermal acoustic shield, as well as thrust augmentation. Noise radiated by the primary jet is reduced by the afterburner stream in a manner similar to that of a thermal acoustic shield. The optimal balance between shielding and augmentation still must be determined.

Turbomachinery Noise

Although jet noise is usually considered the major SST engine noise problem, the measures to reduce it make turbomachinery noise important to consider. The principal source of turbomachinery noise is the inlet multistage fan, which may have a noisy design to accommodate performance constraints. For supersonic flight, an SST engine has a nacelle inlet designed to control the airflow velocity within it. The complexities of this control severely limit areas suitable for installing conventional acoustic linings. Conversely, however, the velocity control means that inlet fan noise can be reduced by using the nacelle as a sonic inlet. This method has had some success, but the influence of inlet auxiliary air intakes (takeoff doors) has not been investigated sufficiently to ensure that this acoustic flanking path will not be a severe problem. Also, adequate mass flow through the inlet must be provided during approach and landing operations to ensure an adequate velocity at the throat of the sonic inlet. A variable-cycle engine can facilitate sonic inlet control on approach by ensuring adequate mass flow through the engine.

The attenuation of turbomachinery noise radiating from a sonic inlet is principally determined by the Mach number at the throat. However, less than sonic velocity at the throat can be effective in reducing engine noise. Methods have been developed to determine the acoustic attenuation of discrete tones and broadband noise as a function of throat Mach number (Fig. 14). The effect of the throat Mach number is determined by a multiplier of the change in sound pressure level (ΔSPL). The ΔSPL multiplier is then used to estimate the attenuation of tones and broadband noise as a function of frequency and radiation directivity.

Data on attenuation as a function of throat Mach number are determined empirically. However, published data on sonic inlet noise suppression range widely (Fig. 15), indicating the need for more precise information on the sound attenuation characteristics of sonic inlets for both static and flight conditions. The attenuation range in Fig. 15 is a conglomerate of overall sound pressure levels, fan-compressor discrete tones, and limited measurements of bandwidth; the narrower range typically is used to analyze SST community noise. Recent test results obtained with a high-speed flight vehicle[8] fall in the narrower (shaded) range shown in Fig. 15.

Turbomachinery noise from exhaust ducts is more controllable with conventional acoustic linings and therefore will not be discussed further.

III. Solutions to Current Problems

The main methods for solving current SST noise problems are 1) combining suppression devices such as those shown in Fig. 2 and 2) developing advanced operational procedures to fly aircraft in the quietest mode. Hardware development and flight validation are needed to provide parametric design data for SST-type engines and to thoroughly examine the effects on thrust loss. In addition, shock-cell noise remains a prime noise source that must be controlled by new technology.

Composite Suppression Schemes

Combining two suppression devices that are complementary can be very effective—for example (as shown in Fig. 2), an inverted velocity profile that reduces low-frequency noise, plus a thermal acoustic shield that reduces high-frequency noise. Thermal acoustic shields also work well with suppressors, and these two devices could be even more effective with an inverted velocity profile. An area needing

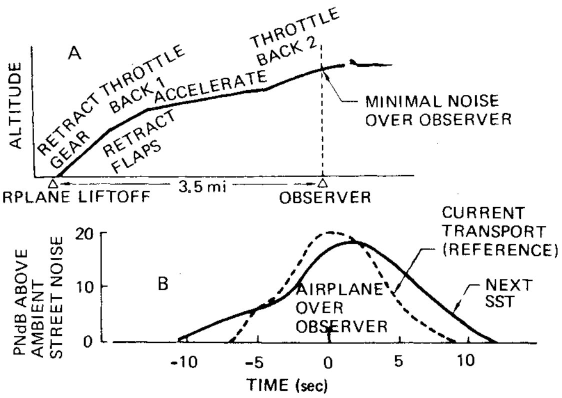


Fig. 16 Operational procedure to reduce SST takeoff noise to that of current long-range, wide-body airplane.

further study is the combination of devices that individually may not be optimal, but that together may be even more effective than combinations of individually optimal devices.

Advanced Operational Procedures

Advanced operational procedures, such as engine thrust and airplane flap management during takeoff, substantially affect the noise generated by an aircraft. Such advanced operational procedures can tailor the flightpath to minimize noise over the observer (Fig. 16). Preliminary studies[1,11] indicate that using such procedures for future SSTs (Fig. 17) could reduce substantially noise at some critical community locations. The advanced procedures use computer-controlled continuous modulation in flap and throttle positions during takeoff and climbout, procedures that would reduce SST noise comparable to that of a current long-range, wide-body subsonic aircraft (Fig. 16b). Some simpler advanced procedures have been adopted successfully by airlines today, for subsonic airplanes as well as for the Concorde SST. Regulatory rules must allow for use of these procedures.

Hardware Development and Flight Validation

A stumbling block for many noise-control concepts is the development of flight hardware that can withstand the rigors of airline service. For example, suppressors on an SST must be retractable from the gas stream for supersonic flight, but such hardware has yet to be developed.

Experience such as with the Concorde SST has shown the gap that often occurs between demonstration of a noise-reduction concept in ground tests and implementation on an airplane. Flight testing is essential before any noise-reduction concept, however attractive, can be considered viable.

Prediction-to-Demonstration Uncertainties

Flight tests designed to demonstrate noise compliance have shown that predicted noise values cannot be achieved with high certainty. The uncertainties are due to the statistical accumulation of uncontrollable (and unpredictable) variations in the chain between predicting noise performance and producing noise values from a flight demonstration for certification purposes.

The statistical uncertainty can be subdivided into measurement uncertainty and prediction uncertainty, each with its own elements. Because most noise predictions are derived from measured data bases, the measurement uncertainty also affects predictions. The net result of the uncertainties can be described by a statistical standard deviation for the state of the art for the particular airplane design considered.

The design and demonstration tolerances required to certify or guarantee noise levels from nominal noise estimates depend on the airplane design. The tolerances do not simply depend on noise but are a function of overall airplane performance and how this can be traded off in the associated risks. The

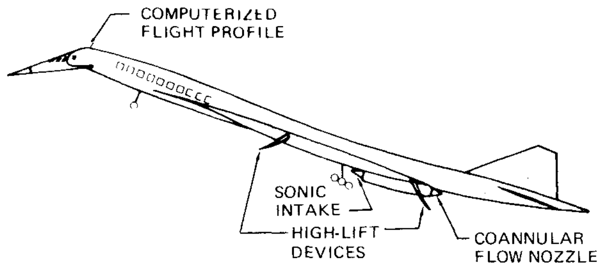


Fig. 17 The next SST, from Ref. 1.

major risk is to invest billions of dollars in an aircraft that is undeliverable for failure to pass certification. As a guide to understanding the process, a confidence level of 80% (an 80% certainty that certification would be achieved using all allowances) requires a tolerance approximately equal to the standard deviation of uncertainty. The Boeing Company uses a qualifying statement in connection with nominal estimates (see Table 1) to ensure that readers understand the limitations of such values. All publishers of noise predictions should add such a qualifier.

It should be noted that nothing in the preceding discussion is peculiar to supersonic aircraft; that is, the same uncertainties exist between predicting noise performance and producing noise values from a flight demonstration for certification purposes for both subsonic and supersonic aircraft. The small data base and limited experience with SSTs do, however, dictate a need for greater margins than is the case with subsonic airplane types.

Jet Shock-Cell Noise Control

The presence of shock-cell patterns in a supersonic jet flow results in shock-associated noise. Turbulence convected downstream results in intense noise generated when the turbulence passes through the cells. Noise is radiated from the cells as a relatively broadband noise (shock-cell noise). In addition, an aeroacoustic feedback mechanism between the radiated noise, nozzle lip, convected turbulence cells, and shock cells gives rise to high-intensity discrete tones (screech noise).

Recent and current ongoing work on shock-associated noise was reported at a NASA shock noise workshop.[9] While control of discrete screech noise was resolved in the early 1950s,[10] control of broadband shock-cell noise requires further work. Screech noise can be eliminated by simple methods such as roughening the nozzle lip (notching) or adding tabs to the nozzle periphery to break the feedback loop.

Broadband shock-cell noise is reduced by some suppression devices such as coannular (inverted flow) nozzles, plug nozzles, and mechanical suppressors. Thermal acoustic shields have demonstrated a modest reduction in static tests. Convergent-divergent nozzles have been demonstrated to eliminate shock-cell noise under laboratory conditions and are under active study and test for broader application.[9]

IV. Current SST Noise Estimates

The current, nominal noise estimates in Table 1 are for an advanced-design SST with delta wings and duct-burning turbofan engines with an inverted-velocity-profile jet. The engine air intakes are fitted with translating centerbody-type sonic inlets operated in a noise-suppression mode over the community. Other noise components, such as engine core noise, turbine noise, and airframe noise, are included in the estimate. (This is a reason why these levels are higher than those shown (Fig. 23) in Ref. 11.) The takeoff noise and sideline noise are for an advanced procedure flight as described previously. The approach noise is for a decelerating

Table 1 Nominal[a] noise estimates for an advanced SST design

Operation	Noise level, EPNdB
Takeoff	106
Sideline	107
Approach	104

[a]Nominal estimates shown—appropriate design and demonstration tolerances required for certifiable/guarantee levels.

approach when the engine is operated at very low power part of the time; low approach noise can be achieved if the engine induces sufficient airflow to achieve the noise-suppression mode of the air inlet.

Note that the sideline (2150 ft) noise level estimated in Table 1 occurs 13,000 ft from brake release, inside the boundary of most airports. At 21,300 ft from brake release, the point where many wide-body airplanes register maximum sideline noise, the nominal predicted SST noise is 97 EPNdB, which is about the same as the noise of a subsonic wide body. As discussed earlier, these noise estimates require the appropriate design and demonstration tolerances.

V. Concluding Remarks

The jet is the principal noise source requiring additional control if community acceptability is to increase. This can be done with more extensive work on mechanical noise-control devices such as coannular and nonconcentric nozzles, thermal acoustic shields, and mechanical suppressors.

Also, advanced operational procedures offer a means of substantially minimizing community noise of both SST and subsonic aircraft without incurring penalties during cruise. These objectives require experimental studies and, in some cases, flight testing to reliably evaluate the noise-control devices and systems being developed. Noise reduction concepts should be further developed to achieve the noise control required for a successful, advanced, second-generation SST. Much needs to be done, but the outlook is promising.

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