Recent Advances in the Technology of Aircraft Noise Control

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Continuing research and development programs dealing with the technology of aircraft noise control have yielded recent significant advances. Certain noise sources about which little was known previously have become better understood. Concepts leading to more efficient noise suppression have been defined. This paper surveys recent results from a number of research and development programs active within industry and government. The paper discusses advances relating to the prediction and suppression of noise generated by engine components (fans, compressors, turbines, combustors, and jets). In addition, it discusses recent advances in the understanding of the noise generated by the aerodynamic flow over airframe components.

Introduction

OVER the past 20 years a great deal of effort has been devoted to improving the understanding of the sources of noise radiated from jet aircraft and to the development of effective methods for controlling the noise. These efforts have involved investigators of the engine manufacturers, airframe manufacturers, government agencies, universities, and consultants.

It is the purpose of this paper to summarize recent advances in the technology of aircraft noise control. The following major sources of noise are discussed: 1) the fan stages on turbofan engines (compressor stages on turbojet engines), 2) jet noise from the exhaust jets of the primary, or secondary (fan), nozzles, 3) the combustion and turbine stages of an engine, and 4) pressure fluctuations in the unsteady airflows around the various components of an airplane during landing approach (nonpropulsive noise sources).

Fan Noise

Early fan noise research identified the unsteady airflow due to blade or vane wakes impinging upon downstream bladerows as the major source of fan noise and suggested design practices that should result in reduced noise. Several of these design features (such as elimination of inlet guide vanes, selection of rotor-blade and stator-vane number, and large spacing between rotor blades and stator vanes) were utilized in the second generation of turbofan engines – the high-bypass-ratio engines such as the JT9D, CF6, and RB211. Incorporation of these design features was intended to minimize the amplitude of the fundamental blade-passage-frequency tones at subsonic rotor-blade-tip Mach numbers where the acoustical energy would theoretically decay (i.e., the various modes of vibration would be "cutoff").

However, it was observed during early ground static tests that the fundamental blade-passage-frequency tone that should have been cutoff was somehow still being produced and radiated to the far field. The explanation of this phenomenon was that fan-noise sources other than the rotor-stator interaction sound field were responsible for the tone at blade passage frequency. These sources include 1) the sound field generated by the interaction with the rotor of inflow distortion and turbulence frequently present during ground static testing and 2) the rotor-alone sound field. Distortion and turbulence under static conditions can result from an unsteady vortex originating at the ground and entering the inlet, from initial turbulence in the ingested atmospheric air, and from ingestion of crosswinds.

Evidence now indicates that placing the engine in its natural environment, flying with the airplane, causes the fan noise to be substantially reduced compared to noise produced by the same engine on the ground (Ref. 1).

Differences Between Ground and Flight Noise Levels

In order to compare flight data with ground static data, it is necessary to adjust the static data to account for factors such as the number of engines, aircraft flight path, airspeed, atmospheric absorption, Doppler shift, and acoustic path lengths. Figures 1 and 2 compare adjusted static data with flight data at the same fan rotor speed. Figure 1 compares tone-corrected perceived noise levels (PNLT) and Fig. 2 compares ⅓-octave-band spectra at a typical angle for inlet noise for a DC-10 airplane powered by General Electric CF6-6 engines. The PNLT plot indicates that the flight data are about 4 PNdB lower than the adjusted static data. The spectral comparisons indicate that the primary cause of the PNLT difference is a difference of about 8 dB in the level of the fundamental blade-passage-frequency tone.

An investigation of the statistical coherence of the pressure/time signal can help in understanding the generation of noise at fan-blade-passage frequencies under static and flight conditions. Rotor-alone and rotor-stator noise is produced by a periodic source and hence is highly coherent. Turbulence-induced noise, on the other hand, is a random source and hence is incoherent even though the sound energy may be concentrated in a narrow bandwidth.

One indication of the statistical character of a signal is the shape of the probability density function (PDF). The PDF of a random signal, such as turbulence-induced noise, has the shape of a normal or Gaussian curve. The PDF of a periodic signal, on the other hand, has two cusps with a central trough resembling the letter U. In a recent Douglas test described in Ref. 2, a DC-10 airplane with CF6-6 engines was instrumented with high-response microphones mounted on the inlet and fan exhaust duct walls to study the effect of forward motion on fan noise generation. The results indicated that, for fan rotor speeds below cutoff, the level of the fan blade-

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Index category: Aircraft Noise, Aerodynamics; Aircraft Noise, Power Plant.

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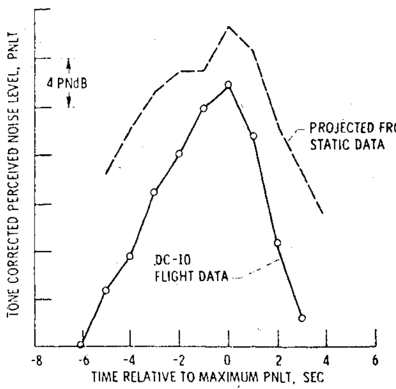

Fig. 1 Comparison of flight and projected static PNLT histories for CF-6 engine at approach condition (2579 RPM). [1]

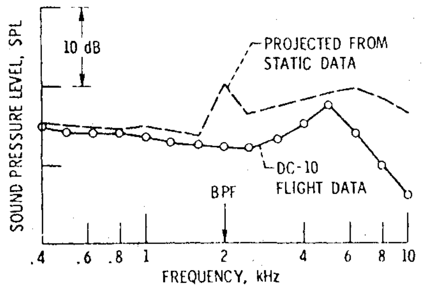

Fig. 2 Comparison of flight and projected static inlet sound pressure spectra for CF6-6 engine at approach condition (2579 RPM); 70° inlet angle. [1]

passage-frequency tone in the inlet was reduced by as much as 8 dB below the corresponding level under static condition. Figure 3a shows that at low approach power settings, the shape of the PDF exhibited a Gaussian distribution under static test conditions, indicating that the fundamental blade-passage-frequency tone was a narrow-band random signal and was, therefore, generated by an unsteady source (i.e., turbulence-induced noise). In flight, however, Fig. 3b shows that the PDF has the characteristic shape of a nearly periodic signal with some random amplitude modulation. This result indicates that the fundamental blade-passage-frequency tone was generated by a nearly periodic source such as the rotor-alone or the rotor-stator interaction sound field.

The results of this test program indicate that during forward motion at approach power settings, the fan inlet tone at blade-passage-frequency decays (i.e., is cutoff) in the inlet and should not effectively propagate to the far field. During static testing, however, unsteady inflow and atmospheric turbulence interact with the fan rotor to produce noise in propagating modes.

Effect of Spinning Modes on Duct Linear Attenuation

The theoretical calculation of duct liner attenuation is a complex problem which is greatly simplified by the assumption of axisymmetric sound fields. As a result, much of the early theoretical work adopted this assumption in spite of evidence indicating that, in most cases, the sound energy generated by a typical fan stage resides in higher-order spinning modes. Recent theoretical work has shown that spinning-mode number is an important parameter to be considered. Figure 4 shows the maximum attenuation that can be achieved from an acoustic liner designed to achieve the theoretical maximum sound absorption as a function of nondimensionalized frequency for various spinning-mode numbers. As can be seen from the figure, high-order spinning modes are more highly attenuated than the axisymmetric mode ($M=0$). The result of assuming all the sound energy is in the axisymmetric mode is to underestimate the attenuation, if, in fact, the energy is all contained in the high-order spinning modes. Note also that an analysis based on the least-attenuated-mode approach would yield noise reduction estimates considerably lower than analyses that take spinning modes into account. The seven experimental data points shown in Fig. 4, which represent data from fans with most of the energy in spinning modes, substantiate the theoretical prediction of greater attenuation for sound fields with spinning modes.

In past studies where large amounts of noise reduction were required, nacelle acoustical treatment designs often included acoustically treated inlet rings or vanes and acoustically treated splitters in the fan-discharge ducts. With the new understanding of flight effects on fan-noise generation and the effectiveness of duct wall treatment alone in attenuating spinning modes, the required inlet noise reduction frequently can be achieved today with wall treatment only.

Jet Noise

The most pervasive source of noise around commercial airports today is the turbulent jet-exhaust stream exiting into the atmosphere as airplanes take off and climb out. Recent studies conducted by industry and government investigators have indicated promising areas of improvement in the areas of predicting and suppressing jet noise.

Studies of jet noise stem primarily from work conducted in England in the early 1950s. M. J. Lighthill, Ref. 3, developed a theoretical description of the generation of jet noise by the convected turbulent fluctuations of density and velocity. Lighthill's formulation is still the basis for studies of jet noise generation. Experimental studies of jet noise generation and suppression began with the model-scale work of A. Powell, Ref. 4, and the model-scale and full-scale work of F. Greatrex at Rolls Royce, Ref. 5. In 1954 and 1955, with the advent of the first generation of jet transports powered by turbojet engines, Pratt & Whitney Aircraft, Douglas Aircraft Company, The Boeing Airplane Company and the General Electric Company began comprehensive programs to develop exhaust nozzle modifications that would reduce the magnitude of the jet noise exposure with minimum loss in performance. These studies led to the development of the 21-tube and 9-tube nozzles on the JT3C, JT4A, and RCO-12-powered Boeing 707s, the 8-lobe daisy nozzle and ejector/reverser on JT3C, JT4A, and RCO-12-powered Douglas DC-8s, and the 8-lobe nozzle on the CJ-805-powered Convair 880 (Refs. 6 and 7). The development of the JT3D and JT8D low-bypass-ratio turbofan engines further alleviated the jet noise problem by achieving lower jet velocities at the same thrust. The development of high-bypass-ratio turbofan engines for the new wide-bodied transports continued the trend toward lower jet noise levels by basic engine design.

Although various analytical and empirical noise-prediction techniques had been developed in the late 1950s, the implementation of the U.S. supersonic transport program in 1962 led to the development of a jet-noise prediction method under the auspices of the Society of Automotive Engineers (SAE) (Ref. 8). Recently, efforts have been initiated by the SAE to incorporate additional information in order to improve and extend the prediction method to cover a wider range of jet velocities than the original version of AIR 876 and to incorporate additional spectral and directivity data as well as the effects of forward motion. The revised version is currently being circulated for review and approval.

Turbojet Engines

The development of the Concorde supersonic transport and the proposed development of the U.S. supersonic transport in the 1960s also led to considerable additional research efforts to develop viable jet-noise suppression systems for turbojet engines. This work, at Rolls Royce and SNECMA, and, as reported in Ref. 9, at the General Electric Company and The Boeing Company, consisted of various analytical studies, model-scale tests, and full-scale engine tests directed at reducing the noise from jets with exhaust velocities between 1300 and 3250 fps (400 and 990 m/sec). Reference 9 covers a multitude of concepts for reducing jet noise in this velocity regime, and no attempt will be made here to redescribe this work.

In the velocity region between 650 and 1300 fps (200 and 400 m/sec), there have been many studies related to reducing jet noise. As reported in Ref. 10, for application to STOL transports using lower-surface-blown flaps, mixer nozzles and acoustically lined ejectors are potential devices to reduce blown-flap noise as well as the jet noise during climbout after the flaps have been retracted.

The work reported in Ref. 10 encompassed detailed studies of 6-tube and 8-lobe mixer nozzles. A single ejector was used with a 6-tube nozzle. Individual ejectors were used around each lobe on the 8-lobe nozzle. The tests covered velocities on the order of 800 fps (250 m/sec). The use of an acoustically lined ejector was noted to reduce high-frequency noise and to increase low-frequency noise when compared to the noise of the 6-tube nozzle alone. Also, it was noted that the noise-reduction benefit associated with forward motion with the mixer nozzle was less when the ejector was placed downstream of the nozzle compared to the acoustic benefit obtained with forward speed for the mixer nozzle alone.

Although a large number of suppressor designs for turbojet engines have been evaluated, including families comprising systematic parametric variations of assumed important variables, a coherent analysis or design procedure has not yet been evolved. The systematic categorization and study of the large amount of data now available may reveal some patterns not yet evident and may suggest a clearer indication of what understanding is missing.

JT8D Refan

For some turbofan engines, jet noise during takeoff may be reduced by replacing the two-fan stages with a larger single-stage fan. This larger fan extracts more energy from the turbine, which reduces the jet velocity and hence the jet noise at the same thrust. As described in Ref. 11, the new front fan, or refan, has been developed mostly for the JT8D engine. Ground testing has been conducted by The Boeing Company for B727/B737 applications and flight tests have been conducted by the Douglas Aircraft Company on a DC-9 airplane.

Figure 5 shows a comparison of the cross section of the JT8D-109 refanned engine with that of the standard JT8D-9 engine. Engine modifications are concentrated in the fan section, except for two new low-pressure-compressor stages and the blades in the last stage of the low-pressure turbine.

Estimates of flyover perceived noise levels derived from sound pressure levels measured around an engine test stand are shown in Figure 6 as a function of static thrust. At its rated static thrust of 16,600 lb (74 kN), the JT8D-109 is estimated to be significantly quieter than the JT8D-9 at its rated static thrust of 14,500 lb (65 kN). Flyover noise tests conducted by Douglas with refanned engines installed on a DC-9-30 airplane confirmed that the refanned engine did indeed produce significantly less jet noise at takeoff and at approach power settings. Detailed analyses of the data obtained during the tests are currently underway.

High-Bypass-Ratio Turbofan Engines

Although the high-bypass-ratio turbofan engine has led to markedly lower jet noise levels, the noise of these engines at takeoff power tends to be dominated by jet noise because of the acoustically treated, low-noise fan designs used. Hence, reductions in the takeoff noise of high-bypass-ratio turbofans engines will require further reductions in jet noise. Current jet noise predictions indicate that limited reductions can be achieved simply by further increases in bypass ratio. The jet noise suppressor concepts for turbojets discussed in Ref. 9 were generally found to be ineffective at the low jet velocities typical of high-bypass-ratio turbofans [approximately 1500 fps (460 m/sec)]. Industry and government organizations have recently intensified efforts directed toward the challenging task of developing effective and efficient concepts for the reduction of jet noise from such engines.

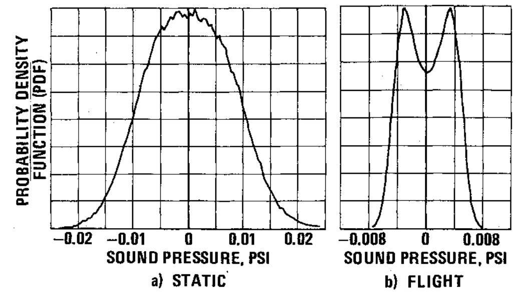

Fig. 3 PDF of fan inlet noise, bandpassed at fundamental blade-passage-frequency ± 10 Hz, at approach fan speed.

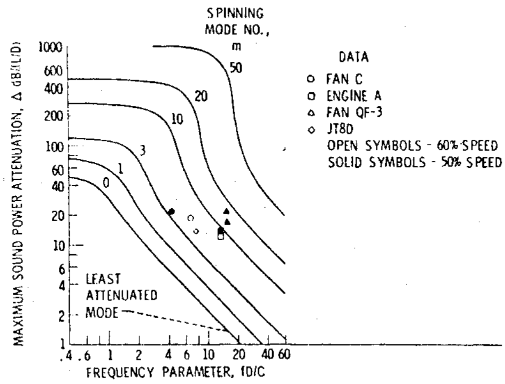

Fig. 4 Effect of spinning mode number on theoretical maximum sound attenuation in soft walled circular duct with no mean flow.

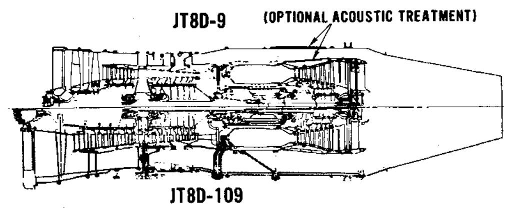

Fig. 5 Comparison of JT8D-9 and JT8D-109 engine cross sections.[10]

Core and Turbine Noise

Recent studies have indicated that noise reductions for future transport aircraft could be limited by several noise sources that have received little attention in earlier noise research programs: core engine noise, turbine noise and non-propulsive noise. Figure 7 shows the component noise source distribution for a typical high-bypass-ratio turbofan engine. Notice that reduction in jet and fan noise levels would not be effective in reducing the total noise level unless accompanied by a corresponding reduction in core, turbine, and non-propulsive noise.

Investigators have previously recognized that, at low jet exhaust velocities [e.g, below 1000 fps (300 m/sec)], the dependence of jet engine noise on jet velocity deviated from the V^8 power law predicted by Lighthill. Figure 8a shows typical overall sound pressure level (OASPL) data for a full-scale engine test. The line labeled "predicted jet noise" is the Lighthill V^8 law. For jet velocities above 100 fps (300 m/sec) the measured levels follow the predicted trend, but for jet velocities below 1000 fps (300 m/sec) the measured levels fall off less rapidly than the eighth-power law would predict in-

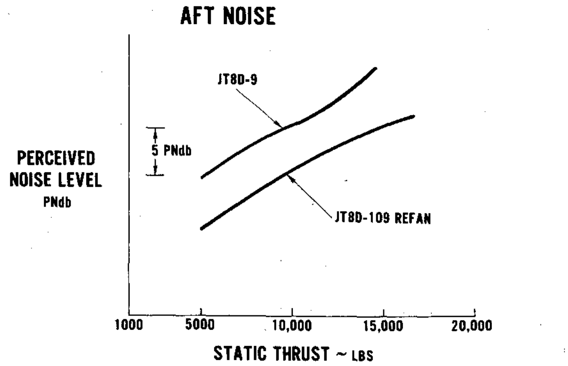

Fig. 6 Predicted peak sideline noise levels in aft quadrant for JT8D-9 and JT8D-109.[10]

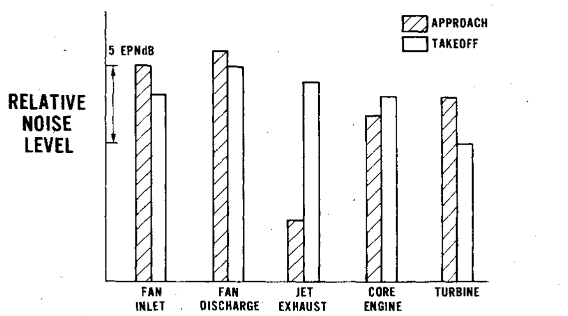

Fig. 7 Typical high-bypass-ratio engine component noise distribution.

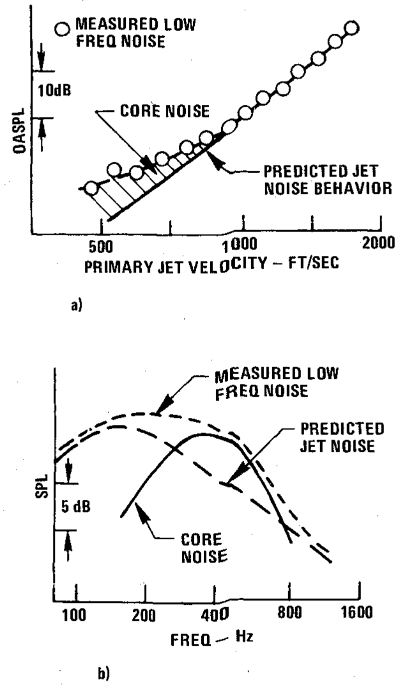

Fig. 8 Definition and characteristics of core engine noise.[12] a) Characteristics of core noise. b) Definition of core noise.

dicating a potential source of "excessive noise" – excess in the sense of being more than predicted by an extension of the V^8 line. It is postulated that this excess noise is caused by noise sources internal to the engine as opposed to jet noise which is caused by noise sources downstream of the nozzle. Hence the name "core noise" seemed to be the natural terminology since the core of the engine contained the sources. As shown in Figure 8b, core noise differs from jet noise in its spectral characteristics as well as its velocity dependence.

Core noise may be inferred by deducting jet and nonpropulsive noise from measured low-frequency engine noise. In recent analyses of measured flight spectra for Douglas airplanes powered by high-bypass-ratio engines, it has been indicated that nonpropulsive noise dominates the low-frequency spectrum at idle power and jet noise dominates at takeoff power. At intermediate powers, the sum of jet and nonpropulsive noise predictions underestimate the measured spectra by about 8 dB. Thus, it is indicated that, at intermediate powers, the low-frequency noise of high-bypass-engine-powered airplanes is internally generated core noise.

Core noise is believed to include noise from several sources as follows. 1) Unsteady pressures accompanying combustion in the burner. 2) Velocity and temperature fluctuations generated within the burner and interacting with the rotors and stators of the turbine stages. 3) Noise generated at the exhaust struts downstream of the final turbine stage due to turbulence and/or swirl in the exhaust flow. 4) Noise generated at the nozzle tip due to fluctuating forces imposed on the medium surrounding the nozzle.

Current Core Noise Research

Reference 12 discusses an experimental research program in which the experimental configuration consisted of a JT3D engine with the fan inlet extensively suppressed and the fan exhaust flow diverted out of the core noise radiation field (Fig. 9).

In these experiments, it was determined that internally generated low-frequency core noise is radiated to the far field. This result was demonstrated by cross-correlating the signals from internal microphones with the signal from far-field microphones. It has also been indicated that the frequency of

Table 1 Summary of published core engine noise prediction systems

	Discusses					
Authors	OAPWL	OASPL	Directivity	Spectra	Relevant parameters	Sources of data
Smith		X	X	X	Jet velocity, nozzle diameter	Turbojet and low BPR turbofan engines
Motsinger	X		X	X	Engine flowrate, combustor temperature rise, compressor pressure ratio, combustor inlet temperature	Combustor rig and GE TF39 and T64 engines
Gerend, et al		X	X	X	Combustor exit temperature, turbine pressure ratio, corrected weight flow	Several high-and low-bypass-ratio turbofan engines
Grande	X				Combustor temperature rise, corrected weight flow, combustor pressure, combustor geometry parameters	Combustor noise model, P&WA JT8D and JT9D engines

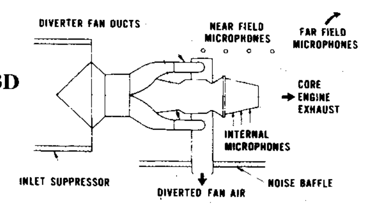

Fig. 9 Schematic of basic JT3D test configuration. [12]

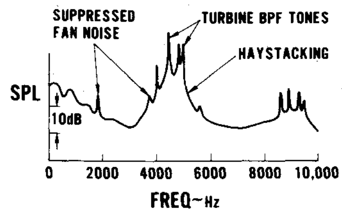

Fig. 10 Spectral characteristics of turbine noise (JT9D engine at typical aircraft approach power). [12]

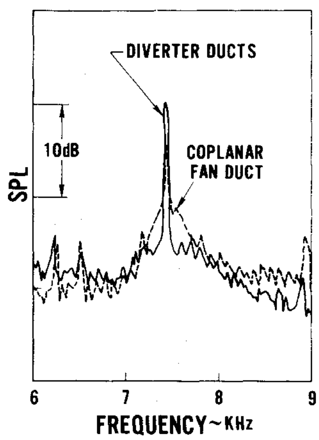

Fig. 11 Effect of fan duct configuration on JT3D turbine noise spectra. [12]

the peak sound pressure level does not shift with engine operating conditions, in contrast with the trends indicated by currently published correlations (Table 1). It appears that none of the current preliminary correlations is universally applicable to all engine designs of interest. More research is needed to determine the accuracy and applicability of current or newly proposed correlations.

Future reductions in core noise may be achievable through modifications in the source mechanisms or through the application of acoustically absorptive duct liners. Effective means for modifying the source mechanisms cannot yet be specified because of the present limited understanding of the mechanisms. Moderate reductions of core noise through the use of acoustic liners are cited in Ref. 12. Large liner thicknesses were required owing to the low frequencies of core noise.

Turbine Noise

Unlike core noise, turbine noise is easy to discriminate from other noise sources because it is dominated by high-frequency tones related to turbine blade passage. Figure 10 shows a typical turbine noise spectrum. In addition to the blade passage frequency tones, there is significant energy in a broad-band "haystack" centered at turbine blade passage frequency. Experimental research at P&WA has verified that haystack noise is due to an interaction of the fluctuating pressures associated with the turbine tone at blade passage frequency and the turbulence in the boundary between the exhaust jet and the ambient air. Figure 11 shows a comparison of data taken using a standard turbofan engine and the same engine with the fan exhaust flow diverted away from the primary nozzle. With the fan flow diverted the shear layer between the primary jet and the ambient air is much thinner than it would be if the fan were not diverted. The diverted, thin-

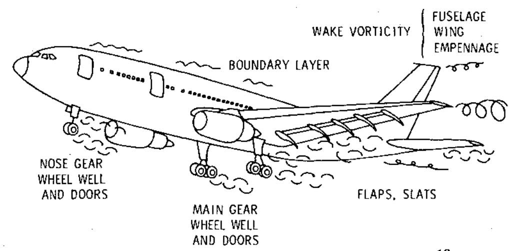

Fig. 12 Nonpropulsive noise sources. [19]

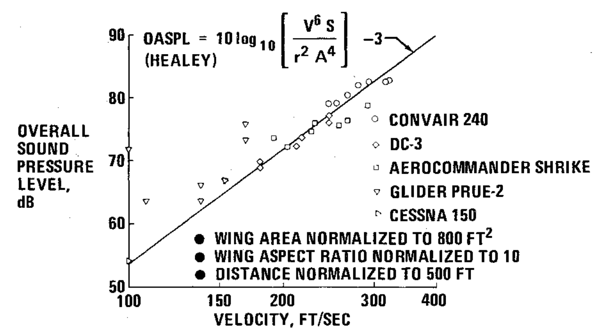

Fig. 13 Correlation of measured OASPL with empirical equation (clean configurations).

shear-layer configuration gives less haystack noise and higher turbine blade-passage-frequency tone noise.

Current methods for predicting turbine noise are based primarily on empirical correlations of test data. Pratt & Whitney Aircraft has recently formulated a correlation based on data from tests of JT3D, JT8D, and JT9D engines (Ref. 12). Future, more accurate predictions will require improved modeling of the generating mechanisms.

Recent studies have suggested that turbine noise may be reduced by increased spacing between the rotors and stators. It has also been suggested that the interaction of rotor or stator wakes with downstream stages may be a major source of discrete tones, in which case selection of the proper number of rotor blades and stator vanes could reduce the noise by causing "cutoff" of the acoustic spinning modes. Acoustically absorptive liners can also be used to augment turbine noise reduction achieved at the source.

Nonpropulsive Noise

References 13 and 14 were among the first to point out that aircraft nonpropulsive noise is expected to become a major noise source during approach. The sources that contribute to nonpropulsive noise during approach are illustrated in Fig. 12 and are discussed in detail in Refs. 13-15.

The major contributors to nonpropulsive noise are the turbulent boundary layer; flow over extended landing gear, wheelwell doors and covers; flow over extended flaps and slats; and wake vorticity from wing and fuselage. When an airplane is aerodynamically clean the major noise source is thought to be the interaction between the turbulent wing wake and the wing surface, creating fluctuating lift and drag forces over the entire wing surface (generating low-frequency noise), and creating small-scale pressure fluctuations at the trailing edge (generating high-frequency noise). When the configuration is aerodynamically dirty with gear and flaps extended, the dominant noise sources depend on the local flow about the protuberances. Separated flows around landing gears and wheelwell covers can dominate for some configurations.

Prediction of Nonpropulsive Noise

Prediction of nonpropulsive noise has only recently been attempted for actual aircraft, previous attempts being confined to airfoils. An empirical equation for predicting nonpropulsive noise for clean aircraft was reported by Gibson, Ref. 13, and updated by Healy, Ref. 16. The method is based on flyover data from five aircraft with power off. The assumption was made that the dominant noise source is a dipole resulting from fluctuating forces in the direction parallel to the lift vector. The result for the maximum value of the far-field overall sound pressure level (OASPL) directly under the aircraft is

$$\text{OASPL} = 10 \quad \log_{10} \frac{V^6 S}{r^2 A^4} \tag{1}$$

where V is airspeed, S is wing area, r is distance from the airplane to the observer, A is the wing aspect ratio, and K_1 is a dimensional constant.

The sixth-power dependency on velocity and the inverse square dependency on distance result from the assumption of a dipole source and are confirmed by observation. The functional dependence of S and A and the value of the constant K_1 have been determined from experimental data. The equation fits the available measured data quite well, Figure 13, and was used (Ref. 17) to predict the measured maximum OASPL for one configuration of the C-5A within 0.6 dB. However, large differences between measured and predicted values were obtained, Ref. 18, when Eq. (1) was applied to a delta wing configuration. Subsequently another empirical equation was developed by Hardin, (Ref. 19) from a data base that included the data from which Eq. (1) was developed

$$\text{OASPL} = 10 \quad \log_{10} \frac{V^{4.93} S^{0.72}}{r^{1.62} A^{2.06}} + K_2 \tag{2}$$

The resulting equation reliably predicts OASPLs for airplanes having a wide variety of weight and moderate to high-aspect ratios. The attenuation of noise with distance expressed by Eq. (2) is less than that predicted by the inverse square law ($r^{1.62}$ instead of r^2), indicating near-field properties of the noise. The result might be expected in view of the relatively large scale of the airframe dimensions relative to the approach noise measurement distance of about 400 ft (110 m).

To complete the overall sound pressure level with either method at some point other than on a perpendicular to the flight path, the directivity of a dipole oriented in the lift direction was used. That is, OASPL was multiplied by $\sin^2 \phi$ where ϕ is the angle between the flight path and the vector to the location of the ground observer.

Recent work at Douglas by A. G. Munson has shown that the sound field directivity can be better represented by two dipole sources – one oriented parallel to the lift vector and one parallel to the drag vector. The Douglas analyses also show that it is important to account for the motion of the sources as several investigators have also done (Ref. 20-22). The results for a clean airplane are shown in Fig. 14, with the contribution of each dipole indicated. The strengths of the two dipoles were determined by fitting the theoretical curve to the data represented by the circles. Data represented by the triangle and diamond symbols are for the same configuration but from different microphone locations and different runs. The data were obtained for a DC-10 airplane with the engines at flight idle.

Healy has also given a nondimensional spectrum (Figure 15), based on smoothed spectra from the five aircraft reported in Ref. 16. This spectrum, together with Eq. (1), or Eq. (2), can be used to predict the spectral content of the peak noise for clean aircraft.

To account for additional noise generated by flow over flaps, extended landing gear and other protuberances in the landing configuration, Healy and Hardin suggest that the OASPL predicted for clean configurations be increased by 5 to 6 dB. This factor was found to predict the landing configuration noise reasonably accurately for at least the aircraft

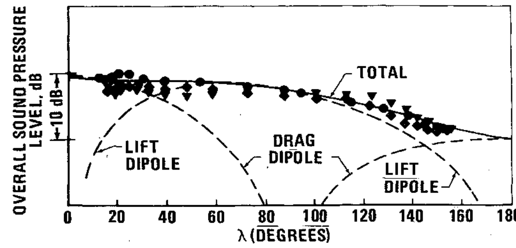

Fig. 14 Comparison of two dipole directivity model with DC-10 flyover data.

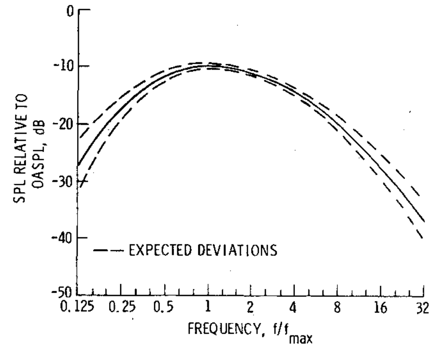

Fig.15 Nondimensional nonpropulsive noise spectrum. [19]

studied. Revell, Ref. 23, has proposed an alternative method that predicts nonpropulsive noise for any airplane configuration whose drag parameters are known. He assumes that nonpropulsive noise is a byproduct of mechanical energy dissipated by drag. His analysis leads to an equation similar to Eq. (1) for the peak OASPL.

A different approach, that might be called the component approach, is to predict the noise generated by each component of the aircraft, e.g., wings, flaps, struts, wheelwells, pylons, and engine nacelles, and combine the separate contributions to predict the noise of the complete aircraft. A beginning has been made in this direction – see for example Ref. 24 – but much work remains to be done before a prediction technique relying purely on a theoretical knowledge of component noise can be developed.

The ability of the present semi-empirical method to predict nonpropulsive noise at the approach location and under the conditions of the FAR Part 36 is illustrated in Fig. 16. Certified approach noise levels of several airplanes are compared with the Part 36 requirement. The solid symbols represent predictions for the same airplanes made with Hardin's correlation for the OASPL and the spectrum of Fig. 15 and thus are for clean configurations. If 5 or 6 dB are added to account for the additional noise generated by the aerodynamically dirty landing configuration, the predicted values would fall approximately within the shaded region. Thus, the prediction scheme gives values approximately 10 EPNdB below the current Part 36 requirements. It is also reported in Ref. 23 that Revell's technique predicts nonpropulsive noise levels about 10 EPNdB below Part 36 requirements. These predictions are in good agreement with the nonpropulsive noise levels indicated by Boeing 727 and 747 tests.[25]

If technology could be developed to reduce engine noise by 5 to 6 EPNdB below the Part 36 approach noise levels shown in Fig. 16 for current advanced-technology jet transports, then the level of nonpropulsive noise would be comparable to the level of the engine noise. To get full benefit from applications of future technology to reduce engine noise, corresponding reductions in nonpropulsive noise would have to be achieved. Since approximately 5 to 6 EPNdB of the level of nonpropulsive noise may be due to unsteady flow around flaps, landing gear, wheelwells, etc., a reduction of that order

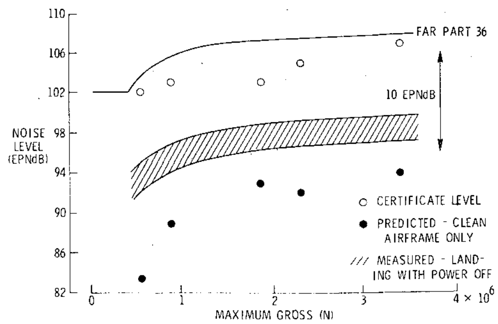

Fig. 16 Approach noise of current aircraft.[19]

of magnitude might be achieved by "cleaning up" the landing configuration.

Concluding Remarks

This survey of recent advances in the technology of aircraft noise control has briefly discussed the following achievements.

1) Theoretical studies together with analyses of ground static and flight data have shown that the levels of noise propagating forward from the fans of high-bypass-ratio engines under flight conditions are less than previously predicted. The recognition of this fact, together with the realization that inlet duct wall treatment alone (without treated concentric ring vanes) is more effective than previously predicted, can lead in many cases to the use of simple inlet designs capable of satisfying inlet noise requirements without acoustically treated rings.

2) Recent experimental programs have expanded the information available on jet noise characteristics, especially statically, and have stimulated the development of improved jet-noise prediction methods. However, greater emphasis must be directed toward understanding the effect of forward motion on jet noise before a viable jet-noise prediction technique can become a reality.

3) An extensive data bank on a variety of jet-noise suppressor concepts has been acquired. Continuing analysis of the data may suggest some patterns in suppression phenomena not yet evident. When combined with data now being gathered with various techniques simulating inflight effects, analyses of these data will provide a clearer indication of the understanding that is now missing.

4) Two noise sources that may limit future noise reduction efforts have been identified: low-frequency core noise generated internally and propagated out the exhaust nozzle, and nonpropulsive noise generated by the aerodynamic flow over airframe elements. Preliminary definitions of the levels, spectra, and directivity of these sources have been suggested on the basis of ground and flight data. Preliminary concepts for their control have also been suggested.

5) Improved correlations of turbine noise have been substantiated by experimental data. It has been shown that the shear layers of the engine exhaust jet flow can significantly affect the propagation of turbine noise to the far field.

These contributions have enhanced our ability to design more efficient noise control methods and to plan further productive research efforts.

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