Development of Engineering Practices in Jet and Compressor Noise

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The description of jet noise is characterized by the velocity of the jet. There are three major regimes of distinct generation mechanisms. Most work of noise source identification and suppression has been done in the jet velocity region of 1000 to 2000 fps, the region of operation of power plants currently used in most subsonic airplanes. Parametric data are presented showing how a certain level of suppression may be obtained in this midvelocity regime together with a brief discussion of the possibility for suppression at higher and lower efflux velocities. A description of the precise acoustic characteristics of compressor noise is explained, including a discussion of the blade arrangements most effective in producing a reduction of source noise. The achievement of compressor noise suppression is described with reference to the effectiveness of acoustic inlet and fan discharge duct linings, the flow blockage of noise propagation, and finally, a brief description of a novel rotary inlet silencer.

Introduction

THE purpose of this paper is to discuss the development of engineering practices in jet and compressor noise suppression. Modern aircraft propulsion systems are the high bypass ratio turbofan engine and the afterburning turbojet. Each engine type produced a characteristic sound radiation field as indicated in Fig. 1.

The problem of jet noise suppression has existed for quite a few years. It first came up in connection with the development of large turbojet engines during the early 1950's. A considerable amount of work on suppressor nozzle design and development was accomplished by the aircraft and jet engine manufacturers from that time until the end of the decade, at which time the concept of turbofan engines became a reality. These engines relieved the jet noise problem significantly.

Recent events, however, have resulted in renewed effort to tackle the problem of jet noise suppression. It was realized that the high-velocity afterburning engines for the supersonic transport aircraft can create rather high noise levels. Consequently, it is necessary to carry out development programs aimed at suppressing the noise from high-velocity jets.

The establishment of stringent restrictions at major airports in the U.S. and Europe and the simultaneous development of more powerful turbofan jet engines have led to attempts at suppressing the noise from low-velocity jets. This development must, of course, be accompanied by efforts to reduce the compressor and turbine noise in turbofan engines.

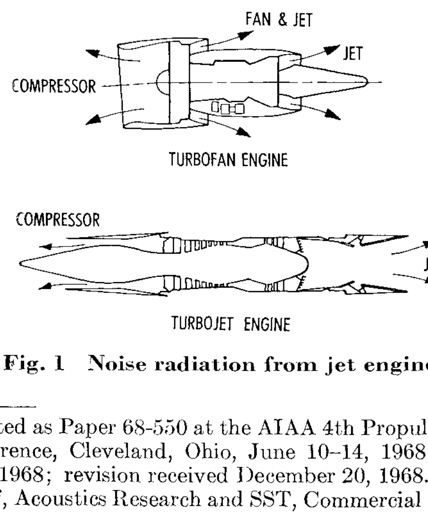

Fig. 1 Noise radiation from jet engines.

Though compressor and turbine noise and the closely related propeller noise have been studied since before World War II, intense studies did not commence until early in this decade. The reason for the interest in compressor noise generation and reduction was the introduction of the ducted fan jet engine, which, besides having augmented compressor noise generation, also reduced jet noise generation.

Jet Noise

Relationship Between Theory and Engineering Practices in Jet Noise

The works of Lighthill, Ribner, Ffowcs Williams, and several others agree that in the jet velocity regimes of subsonic and low supersonic flow, jet noise radiation is dominated by sound generation of convected turbulence in the jet efflux. In this regime, the total sound power emission varies with the eighth power of the flow velocity, (V^8).

At higher supersonic flow, this relationship must necessarily fail, since it is impossible for sound power emission to exceed the available mechanical power of the jet. Therefore the upper limit for jet noise radiation as a function of velocity will approach a third-power relationship at high velocities. Theoretical developments on supersonic jets by Ribner and Ffowcs Williams predict Mach wave radiation from the jet that increases in intensity as the third power of velocity. An additional source of noise is the interaction between turbulence and the stationary shock pattern in supersonic jets. The question of which mechanism dominates the noise radiation will be considered later.

Noise from jets at low flow velocities has been discussed mainly by Ffowcs Williams. Depending on the roughness of the flow upstream of the jet nozzle exit, "dipole" noise generated in this region may overwhelm the "quadrupole" noise up to a nozzle exit velocity of 1000 fps for cold flow. In this regime, the total sound power varies with the sixth power of the flow velocity. As discussed later, this internally generated noise is of interest in the suppression of jet noise from turbofan engines.

To summarize, three separate velocity regimes can be considered in defining the noise generated by turbulent jets. Turbojet engines developed during the 1950's operate in the

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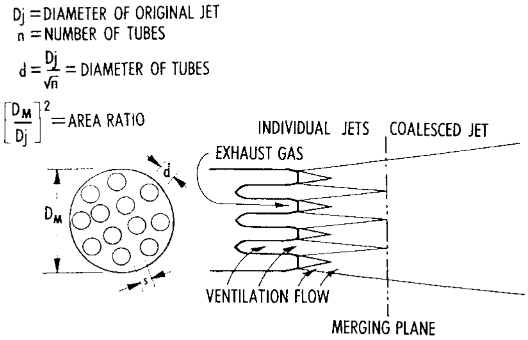

Fig. 2 Schematic of jet flow from multitube nozzle.

velocity regime dominated by V^8 noise. Engines used in current SST designs will operate at supersonic jet exhaust velocities in the transition regime between V^8 and V^3 dominated noise emission. Finally, high bypass ratio turbofan engines currently being developed operate at subsonic jet exhaust velocities just above the regime where V^6 noise becomes appreciable.

Jet noise theories are not yet complete and care must be given in their application toward suppressing the noise from a particular jet engine. For example, consider Lighthill's expression for acoustic power emission from subsonic jets;

$$\text{acoustic power} = K\rho_j{}^2AV^8/\rho_0a_0{}^5$$

Here the only free parameter is the unknown constant K, which depends on the level of turbulence in the jet. Lighthill's power law is consequently of very little help as a guide to the engineer. In order to emphasize this point, further consider application of the formula to a multitube suppressor nozzle with N tubes of equal cross-sectional area. According to arguments by Ribner and Ffowcs Williams, the total noise per unit length is greater by a factor $N^{1/2}$ than the corresponding value for a single jet, which implies that the multiple jet produces as much power in its initial mixing region [of length proportional to $D/(N)^{1/2}$, where D is the jet diameter], as does the single jet in its $N^{1/2}$ times longer mixing region. Since a multiple-nozzle suppressor is known to reduce the jet noise emission, the theory is apparently inadequate in this application (discussed further later in paper).

The lack of clear theoretical guidelines has forced the study of jet noise suppressors to rely on intuition and parametric investigations. Certain design principles have evolved from the almost countless suppressor nozzle configurations that have been tested over the years. None of these principles is well understood or documented, and a number of conflicting explanations of the physical mechanisms involved have been advanced.

Various classes of suppressor nozzles are examined in the following sections. Design principles that have been invoked will be discussed, and an attempt will be made to explain the mechanisms involved in the suppression of the noise.

Developement of Engineering Practices in Jet Noise Reduction

It is convenient to divide the treatment of jet noise into three jet velocity regimes, each characterized by a dominant noise-generating mechanism,[1] when examining jet noise suppression methods, even though the velocity regimes overlap to such an extent that the dividing lines may appear rather artificial.

Jet noise suppression in the V^8 regime

Since pioneering work on jet noise suppression during the 1950's dealt almost exclusively with jets operating in the V^8 regime, it is appropriate to consider this regime first. The discussion is restricted to quadrupole noise generation.

There are several opinions and conflicting experimental work on the location of the prime sources of noise in a jet. The more commonly accepted point of view is that the dominant sources of sound are located in the mixing region. However, it has been recently argued that the transition region leading to the fully developed jet contains the dominant noise sources. Both the experimental and theoretical considerations involved in determining this problem are still under study.

In view of this, it is not possible to reach a definite conclusion as to the location of the dominant sources of noise in the jet. In the following discussion, whenever an attempt is made to explain the mechanisms underlying the design principles, the uncertainty must be kept in mind.

1. Mixing nozzle jet noise suppressors

The name "mixing nozzle" refers to the large class of suppressors that presumably operate on the principle of entraining surrounding air into the jet flow to shorten the mixing region and to reduce the mean velocity gradients. This class includes multitube nozzles and multilobe or corrugated nozzles. In designing mixing nozzles for optimum noise suppression, three main principles apply: a) jet exit geometry, b) ventilation (access of secondary air to individual jet streams), c) flow breakup (number of individual jet streams).

a) Jet Exit Geometry: Parameters of interest in the design of multitube mixing nozzles are shown in Fig. 2 and the discussion is limited to this kind of mixing nozzle, since the arguments may be easily generalized to include multilobe nozzles. One important parameter is the area ratio, which is the area circumscribing the mixing nozzle ratioed to the area of the original jet nozzle. Increasing area ratio leads to an increase in the rate of secondary air mixing. This promotes the development of the self-preserving jet closer to the nozzle exit, so that low-frequency noise suppression results from the shortening of the transition region. A maximum amount of noise suppression occurs when the spacing between the individual nozzle elements approximately equals their diameter, causing the jets to interfere at the end of their mixing regions. This criterion would seem to define an optimum spacing, or area ratio. As the area ratio is increased further, it quickly reaches the point at which the elements are so widely spaced that they behave like individual jets. The sum of their acoustic powers is then equal to that of the single primary jet, so that the only effect is the shift in the characteristic frequency of the noise.

However, the optimum area ratio varies with the geometrical arrangement of the tube elements, increasing with an increasing number of jets and increasing with the jet pressure ratio, as shown in Fig. 3. One reason for this is that as the number of tubes in the suppressor nozzle increases, it becomes more difficult to provide good access of secondary air to the center part of the nozzle. Consequently, when the number

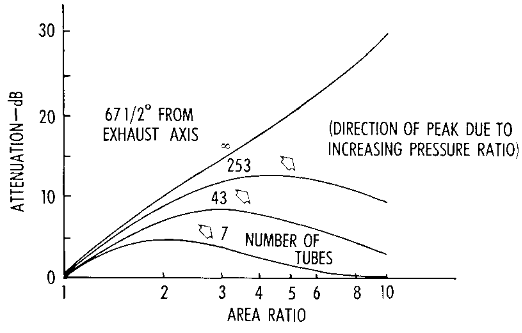

Fig. 3 Variation of SPL suppression of multitube nozzles.

of the tube elements is large, it is necessary to increase the spacing between the elements to a value beyond the optimum in order to provide good ventilation.

b) Ventilation: The effect of ventilation on the noise-suppressing qualities of a multi-element nozzle is not immediately apparent from examination of acoustic data. Depending on the geometry of the suppressor nozzle and the jet pressure ratio, the noise suppression may increase, decrease, or remain unaffected by blocking the secondary air accesses. However, limited tests indicate that at pressure ratios at which the jet is subsonic, suppression of noise of frequency 1000 cps and over depends noticeably on ventilation.

The influence of ventilation becomes clearer when both the acoustic and thrust performances of a suppressor nozzle are considered. Experimental data show that a severe thrust loss is incurred over a wide range of pressure ratios when the ventilation is blocked. Recent investigations by Boeing have shown that part of the sound suppression is associated with this thrust loss.

It appears, therefore, that although the effect of ventilation on sound suppression may be mainly indirect, its effect on the total suppressor nozzle characteristics is of sufficient significance to make proper ventilation a prime requirement in the design of jet noise suppressors.

c) Flow Breakup: Breakup of the flow into a number of individual jet streams by means of multitube or multilobe nozzles has been shown to result in large amounts of jet noise suppression. This result is subject to the condition that the spacing between the individual jet elements be approximately equal to the diameter of circular elements or the width of lobe elements.

The effect of flow breakup is illustrated by considering multitube nozzles of constant area ratio, but with an increasing number of flow tubes. Figure 4 shows the variation in the jet noise spectra. It appears that two main effects result from increasing the number of flow elements. The dominant region in the noise spectrum is seen to shift to higher frequencies with an increase in the number of tubes. This is accompanied by a continuous drop in the high-frequency part of the spectrum. The sound suppression in the low-frequency part of the spectrum appears to be independent of the number of tubes.

d) Total Noise Suppression: Noise reduction mechanisms that cause suppression in the noise spectra can be explained in terms of the location of the dominant sources of noise in the jet. Although uncertainty exists as to the exact location, it may be asserted in general that the high-frequency noise is generated closer to the nozzle and the low-frequency noise farther downstream in the transition region and in the fully developed jet.

It may now be argued that a multi-element jet contains two separate regions where mixing takes place (Fig. 2). One is the mixing region of the elemental jets close to the nozzle exit. These jets coalesce into a single jet flow that possesses a larger scale mixing region. Frequencies of the noise generated in each region scale with the Strouhal number fD/U, where D is the diameter of the elemental jets or of the coalesced jet. Low-frequency noise is generated in the mixing region and the transition region of the coalesced jet. It appears that an increase in the area ratio of the nozzle will have two effects on this noise-generating region. Characteristic frequencies of the noise will be lowered as the area ratio increases. Larger area ratio also leads to a greater rate of mixing with the surrounding air, promoting the full development of the jet closer to the nozzle exit. The consequent shortening of the mixing region and the transition region of the coalesced jet accounts for the suppression of the low-frequency noise.

Characteristic frequencies of the noise generated in the mixing region of the elemental jets will increase as the diameter of the jets is reduced. This accounts for the frequency shift of the dominant part of the spectrum with increasing numbers of flow tubes, as shown in Fig. 4. Suppression of the high-frequency noise is more a matter of conjecture. It is known that increasing the spacing between the elemental jets leads to an increase in the high-frequency noise. It has been suggested that, at some optimum spacing, the secondary air induced between the jet elements causes noise suppression by reducing the mean shear in the jets. This view is partly substantiated by the experimental observation that blocking off the secondary air access increases the high-frequency noise generation. However, as discussed in an earlier section, this effect decreases with increasing flow velocity and apparently does not occur at jet pressure ratios above that at which the flow is choked. Another possible suppression mechanism is the shielding by the circumferential jets of the high-frequency noise generated by the elemental jets in the center of the flow.

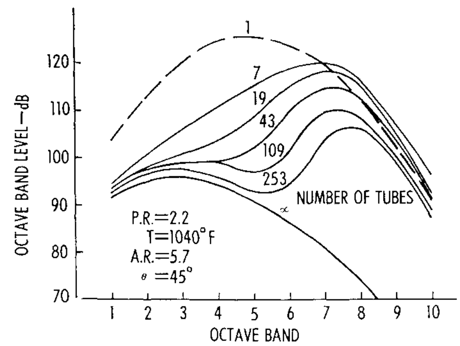

Fig. 4 SPL spectra from multitube nozzles.

2. Other jet noise suppressors

Having considered mixing nozzle suppressors rather thoroughly, it is of interest to discuss briefly suppressor nozzles that rely on separate or additional techniques to achieve a reduction in the acoustic power output.

a) Directional Nozzles: A directional nozzle is a sound suppressor that operates partly or completely on the principle of redirecting the acoustic radiation. It has been determined experimentally that the noise radiation pattern from a slot or rectangular nozzle is elliptical about the jet axis. The significance of the elliptical noise pattern becomes apparent when the requirement of a suppressor is considered in terms of its operational use. Although it is desirable to achieve large noise reductions in all directions and under all operational conditions of an aircraft, the primary aim is to suppress the noise radiated toward the community as the aircraft flies over.

Several investigations into the noise-suppressing qualities of slotted nozzles have been conducted. It has been found that in addition to the considerable noise suppression in the direction normal to the short ends of the nozzle, there is also a reduction in the total acoustic radiation. Tests show that the high-frequency noise is markedly more elliptical than the low-frequency noise, suggesting that the directional effects are mainly limited to the jet mixing region. Due to the shape of the nozzle exit, the jet initially expands considerably more off the short sides than off the long sides of the nozzle. This results in a large flow region of high mean shear that radiates high-frequency noise off the long sides, whereas the low mean shear in the rapidly expanding short side mixing region reduces the high-frequency radiation off the short sides of the jet wake.

b) Ejectors: An ejector system is primarily a flow-augmentation device. The jet discharging from the primary nozzle mixes with the entrained airflow within the cylindrical shroud, resulting in an augmented jet flow of lower velocity. When considering the acoustic power output of a jet to vary as the eighth power of the flow velocity, the ejector system

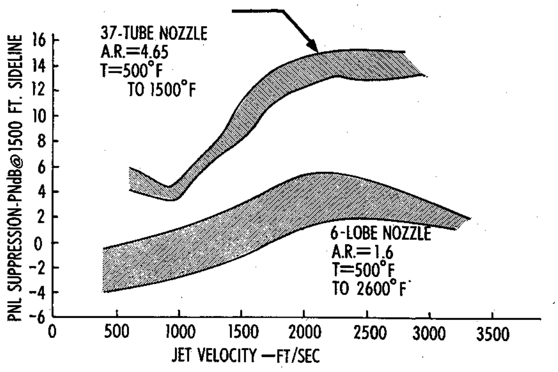

Fig. 5 PNL suppression of 6-lobe Greatrex nozzle and 37-tube Greatrex-ended nozzle.

seems very attractive for the purpose of suppressing jet noise. Investigations have shown, however, that an excessive ejector length is required in order to promote sufficient mixing for a significant noise reduction.

Mixing of primary and secondary air will be increased considerably by using ejectors in combination with mixing nozzles. Ejector length required for satisfactory mixing under these conditions may be reduced to two or three nozzle diameters.

The ejector shroud may also be considered as an acoustic shield, particularly for the high-frequency noise generated close to the nozzle exit. If the shroud is lined with acoustically absorbent material, so that the incident sound is attenuated instead of merely being reflected, a considerable reduction in the high-frequency noise radiation has been shown to result.

Jet noise suppression in the V^3-V^8 transition regime

Two main mechanisms of noise generation are characteristic of high-velocity jet flows. The first is the Mach wave radiation from turbulent eddies convected at supersonic velocities with respect to the speed of sound in the ambient medium. The second mechanism is the generation of sound through the interaction of the turbulence with stationary shock waves that are formed in overexpanded or underexpanded supersonic jets.

Acoustic measurements with jets at high supersonic velocities clearly indicate the dominance of the Mach wave radiation. However, knowledge is very limited for attempting to predict which noise-generating mechanism dominates at low supersonic Mach numbers. The most convincing evidence of the importance of turbulence-shock wave interaction has been found in shadow-graph pictures of supersonic jets, in which strong acoustic radiation is seen to emanate from localized shock regions in the flow. Disregarding the shock-induced noise for the moment, it is clearly evident that there is a velocity of transition at which the quadrupole noise ceases to dominate and Mach wave radiation becomes important. Here it is important to consider Ffowcs Williams' argument that changes in turbulence scales which alleviate the quadrupole mode aggravate the Mach wave case and vice versa.[1] This feature raises the possibility that suppressors known to be good at subsonic speeds might well be very poor at high supersonic speeds.

1. *Mixing nozzle jet noise suppressors*

Results from two sets of tests with scale model mixing nozzle suppressors are next discussed in an attempt to substantiate the arguments of the preceding section.

The first investigation was conducted with a 6-lobe corrugated nozzle of area ratio 1.6. The measured perceived noise level suppression relative to standard nozzle is shown in Fig. 5 as a function of the nozzle exit velocity. Suppression is seen to increase with increasing velocity up to a jet velocity of 2000 to 2500 fps which corresponds to sonic eddy convection with respect to the sound speed of the surrounding air. At higher velocities, the suppression decreases rapidly with increasing jet velocity.

The second set of tests was conducted with a 37-tube suppressor nozzle of area ratio 4.65, in which each elemental tube ended in a corrugated nozzle. Figure 5 shows the measured suppression plotted vs the nozzle exit velocity. It is apparent that, in this case, the high suppression is maintained as the velocity increases beyond 2500 fps.

The improved high-velocity performance of the second suppressor can be explained in the following manner. The large rate of mixing achieved with this configuration results in a rapid decrease from the initial flow velocity. As long as the velocity of the augmented flow remains less than approximately 2500 fps, we may expect the nozzle to maintain its suppression characteristics.

2. *Ejector system suppressors*

In the preceding sections, the emergence of high-speed noise-generating mechanisms at jet velocities of approximately 2500 fps were discussed. It appears that in order to gain any noise suppression from breakup of a high-speed flow, a considerable reduction in the flow velocity must be produced. And as mentioned earlier, the use of ejectors in combination with mixing nozzles greatly increases the mixing of the primary jet and secondary air, resulting in a reduced velocity augmented flow.

High exhaust temperatures of the SST engine makes the use of an ordinary mixing nozzle a complicated engineering problem. The initial suppressors to be used on the SST may consist of retractable devices projecting into the flow from the ejector walls. Figure 6 shows an experimental suppressor configuration with retractable chutes.

Jet noise suppression in the V^6-V^8 transition regime

It has been observed experimentally that with rough flow conditions upstream of the nozzle of a low-velocity jet, the acoustic power generation varies with the sixth power of the jet velocity. This implies that, in addition to the V^8 sources of noise, there exists a noise-generating mechanism of lower power of velocity that dominates the sound field for jet flow of high turbulence and low exit velocity. Ffowcs Williams, in an unpublished paper, discusses several possible mechanisms of dipole noise generation inside the jet nozzle and suggests that the most probable mechanism involves the turbulence in the nozzle exit plane, giving rise to dipole sources that radiate with an acoustic efficiency of

$$\eta_d \sim (\alpha^2/6\pi)\rho_j/\rho_0 M^3$$

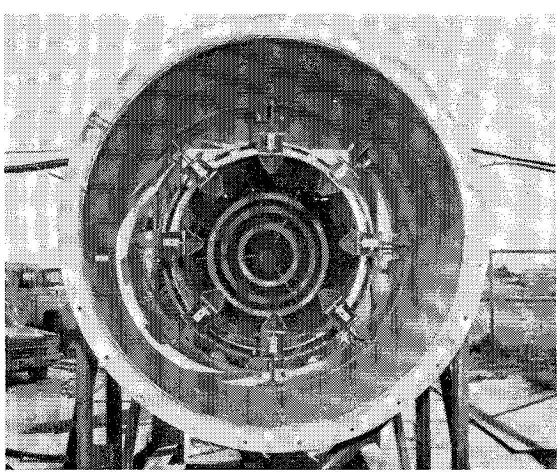

Fig. 6 Experimental ejector-type suppressor.

If we assume the V^8 noise-generating efficiency to be

$$\eta_q \sim 10^{-4}\rho_j/\rho_0 M^5$$

the V^6 noise will dominate the sound field below a jet exit velocity of $20\alpha c_0$. For a 5% turbulence level, this is a speed of 1000 fps. High bypass ratio turbofan engines currently being developed have a primary jet exhaust velocity of approximately 1250 fps, at which speed the calculations show both sources of noise equally important.

However, the preceding calculations are based on order of magnitude estimates only, and could be in error by a considerable factor. Some experimental evidence has been obtained in tests with air jets. Figure 7 shows the increase in the acoustic power emission with jet velocity from a model scale jet under two different upstream flow conditions. The case of smooth upstream flow shows a low noise level which increases as the eighth power of the jet velocity. With highly turbulent flow upstream of the nozzle, the noise level is much higher at low velocities than in the first case, and it increases as the sixth power of the jet velocity.

Further evidence is found in tests with model scale suppressor nozzles. Referring back to the results in the low-velocity region in Fig. 5, noise suppression decreases sharply as jet velocity is lowered, both with the 6-lobe corrugated nozzle and the 37-tube nozzle. For the 6-lobe nozzle, it even shows negative values in the low-velocity region, indicating an increase in the generated noise.

A tentative conclusion from the discussion above is that certain noise-suppression design principles cease to be valid in the low jet velocity regime because the generation of V^6 noise is not significantly affected by conventional noise suppressors. In the case of turbofan engines, this means that the maximum jet noise reduction possible with external suppressors is limited to the difference between the intensities of V^8 noise and V^6 noise.

Compressor Noise

Compressor Noise Generation

A brief description of compressor noise as it is experienced by a listener, and a review of its generating mechanisms is presented next in order to facilitate the discussion of compressor noise reduction.

When a turbofan aircraft passes over a listener on the ground, the listener generally experiences two noise peaks associated with compressor noise. The first peak, which occurs before the aircraft is directly overhead, emanates from sound radiated through the engine inlet; the second peak, which occurs after the aircraft has passed overhead, emanates from sound radiated through the fan exhaust duct (hereafter called the fan duct), Fig. 1. To date, discrete frequency noise has predominated in fan engines. The discrete frequency noise, which is in the kilocycle range, consists of one or two fundamental frequencies that correspond to the blade passing frequencies of the first two compressor stages and their multiple frequencies (harmonics). At a lower noise level, but spread out over a wide frequency range, as the name implies, is the broadband noise. On advanced technology engines, where measures have been taken to reduce the discrete frequency noise, a third kind of noise may also be noted. This is multiple-tone noise, which is discrete frequency noise at multiples of the rotor frequency. It differs from the previously mentioned discrete frequency noise in that the frequencies are numerous and densely spaced, so that the subjective impression is not that of a discrete frequency sound. Multiple-tone noise has only been found to radiate from the inlet and not from the fan duct. Figure 8 shows an assumed spectrum that identifies the three types of compressor noise.

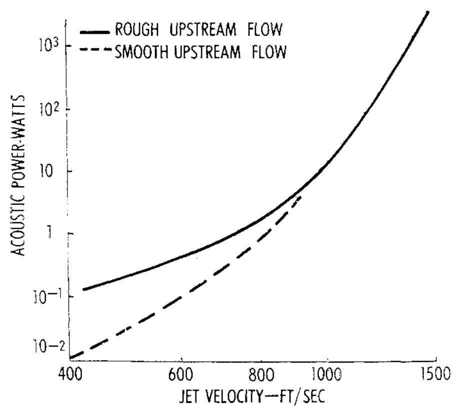

Fig. 7 Influence on acoustic power output of upstream flow conditions.

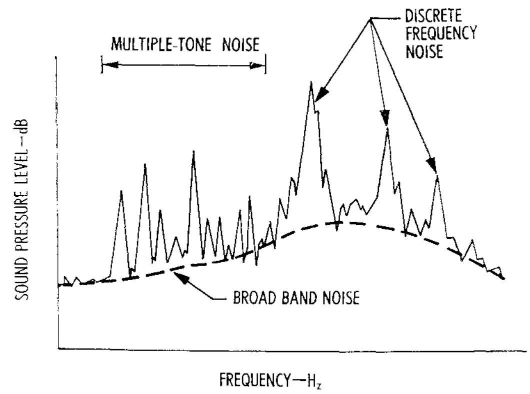

Fig. 8 Types of compressor noise.

Compressor noise is generated by two gross mechanisms: blade lift fluctuations and pressure variations at a fixed point due to the rotation of the pressure and flowfield of individual blades. Pressure variation sound is periodic, that is, discrete in frequency. The peculiar characteristics of the multiple-tone noise, which belongs to this category, are presumably explained by the propagation of the sound in the vicinity of the rotor. The noise emanating from blade lift fluctuations can be either discrete in frequency, if the lift varies periodically, or broadband if the lift fluctuations occur randomly in time.

Principles of Noise Reduction

The basic principle in noise control is the reduction of sound generation at the source. However, as demands for noise reduction have increased faster than advances in noise generation control have been made, exterior means of noise reduction have been sought. Two approaches are apparent: attenuation of the sound in its propagation path and redirection of the radiated sound. The first approach has been successful with the development of absorptive linings for both inlet and fan duct, whereas the second approach has been given little attention, despite some potential, because of the directionality of compressor noise. Devices for blocking the propagation path through the inlet, such as the sonic throat, could be grouped as redirecting devices, since the forward radiated noise is reflected so that it partly escapes through the fan duct. We should, however, notice that the reflected sound with these devices influences the sound pressure distribution over the compressor face, and hence, also the noise generation.

In the following section, we will discuss engineering applications of the three noise reduction principles mentioned above: reduction of generation at the source, absorption with linings, and blocking devices in the propagation path.

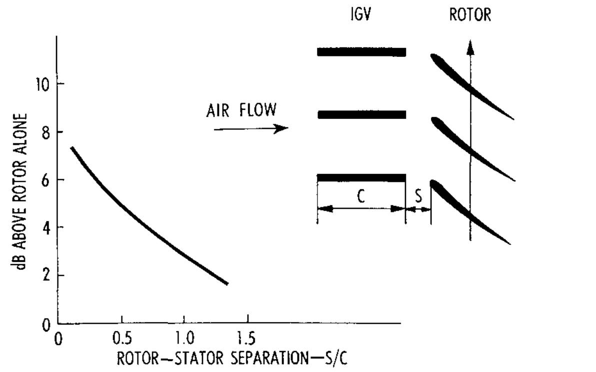

Fig. 9 Influence of rotor-stator separation on compressor noise generation.

Development of Engineering Practices in Compressor Noise Reduction

Reduction of compressor noise generation

Though the theory of compressor noise has been studied since the 1930's, engineering practices in compressor noise reduction, with one exception, have not evolved from theory, but rather from speculation and qualitative descriptions of the generating mechanisms. This is understandable, since no unified compressor noise theory exists, and existing pieces of theory generally grossly underestimate the noise generation.

To date, the most important blade lift fluctuation noise has been the so-called interaction noise that originates from the interaction between rotor and inlet guide vanes (IGV) or stator. Lift fluctuations on a rotor blade occur as a result of changes in angle of incidence at an encounter between rotor blade and stator blade. The change is due either to variations in the flow direction in the potential flowfield around the blades or to velocity variations across the viscous wake of the blade. The effect of rotor-stator separation on discrete frequency interaction noise has been studied experimentally by many investigators, and typical results are shown in Fig. 9. The observed noise reduction with increased separation has been exploited in "hush-kits," essentially spacers, for existing engines. The benefit has, however, been limited. A more drastic solution, which has been used by Pratt & Whitney and Rolls Royce on their high bypass ratio engines, is the complete removal of IGV's in addition to a large rotor-stator spacing.

Broadband noise is generated as vortices are randomly shed at the trailing edge of a blade or as a blade is working in oncoming turbulence from the inlet or from a previous blade row. By having only one fan stage, the previously mentioned high bypass ratio engines can benefit from low noise generation due to this mechanism.

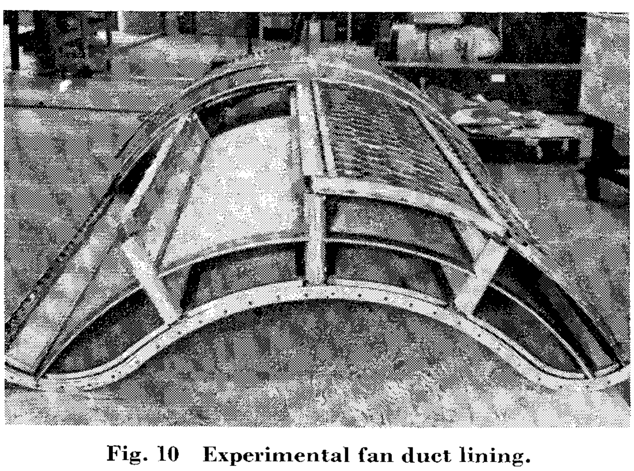

Fig. 10 Experimental fan duct lining.

At an encounter between a rotor blade and a radial IGV, the lift fluctuation occurs simultaneously at all radial positions. By having a nonradial IGV, the lift fluctuations would be more gradual along the radius and we could expect a weaker interaction noise generation. This has been borne out by model experiment.[2] The Rolls Royce Spey engine has nonradial IGV's, but the influence of the IGV tilt on noise generation is not known to the author.

The propagation of compressor noise in ducts is a more tractable theoretical problem than compressor noise generation and has consequently been extensively studied. Even though simplifying assumptions regarding the airflow have been made, one important result with engineering application has been reached. Pressure fluctuations at the compressor face can form acoustic waves only if they move at a speed slightly above or greater than sonic speed. For a single rotor, this occurs with supersonic tip speeds, and for a rotor-stator combination, it occurs when the point of encounter between rotor and stator blade moves supersonically. It can be shown that the ratio between the Mach number for the point of encounter M_E and the rotor Mach number M_R is

$$M_E/M_R = R/(R - kS)$$

where R is the number of rotor blades and S is the number of stator blades. The parameter k can take all integer values between $-\infty$ and $+\infty$. As can be seen from the formula, the absolute value of M_E will not exceed M_R for any value of k, if S is at least twice as large as R. This fact has been exploited in the previously mentioned advanced technology turbofans.

Absorption of compressor noise with linings

Even if absorptive linings have substantially reduced noise through inlet and fan duct in experimental installations, they should be regarded as a temporary means of noise reduction. Many nonacoustical engineering problems remain to be solved before application of linings to commercially operated aircraft can be made; freezing of the large lining surfaces required is one such problem.

Fan duct linings are being developed by The Boeing Company under NASA contract. An early experimental lined fan duct extension for the Pratt & Whitney JT3D engine is shown in Fig. 10. In this particular installation a circumferential splitter lining has been added to the wall linings. Also radial splitters are lined. The lining is constructed of a porous layer, in this case a metal felt, on top of a honeycomb layer, as can be seen in the portion where the fan duct wall has been removed. More recent linings use a smaller size honeycomb, and can be constructed with one or two porous layers. The attenuation as a function of frequency for a typical single layer lining is shown in Fig. 11.

The performance of linings can be predicted theoretically with good accuracy only in the idealized case of no airflow over the lining surface and low-amplitude sound. The

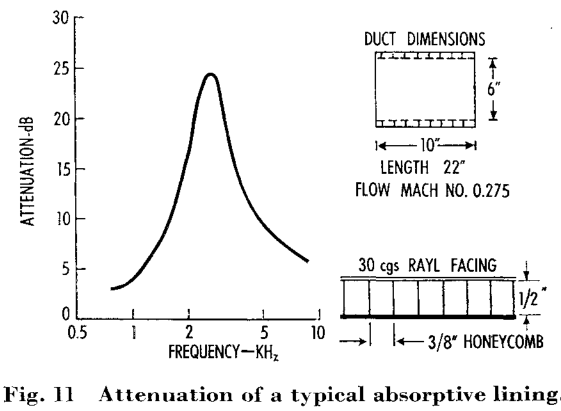

Fig. 11 Attenuation of a typical absorptive lining.

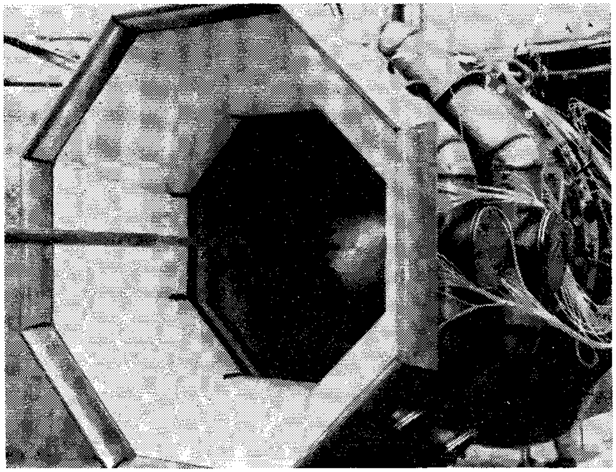

Fig. 12 Sonic throat inlet with boundary-layer control.

development of linings for compressor noise absorption has therefore been mainly experimental, using theoretical guidelines.

The aforementioned multiple-tone noise is believed to originate in shock waves from the tips of supersonic rotors. Close to the tips, the sound is periodic with blade passage frequency; not until it has propagated a short distance in the inlet duct do multiple-tone noise characteristics develop. Control of multiple-tone noise by absorption would thus most efficiently be performed with linings at the rotor tips, designed for shock wave absorption. These linings would be different from the aforementioned inlet and fan duct linings since they would have to be designed for high-intensity pressure fluctuations. They are expected to provide larger attenuations per unit area than linings for low-intensity sound and also to have a wider frequency coverage.

Blockage of compressor noise propagation

The sonic inlet and the inlet rotary silencer are next discussed as examples of devices for blockage of inlet noise propagation. Development of sonic inlets has been based on the obvious notion that sound cannot propagate against a flow of sonic or higher velocity. Numerous experiments have, however, borne out that substantial noise reduction occurs even at flow speeds less than sonic. It appears that the mechanism is sound reflection at density and velocity gradients. Steep gradients are obtained in an inlet with a large diffusion angle behind the throat. Designing inlets as short as possible for reasons of weight and aerodynamic load thus coincides with an acoustic requirement. The main problems with sonic inlets are of aerodynamic nature, and are not elaborated on here. An example of a sonic inlet is shown in Fig. 12. This inlet, developed by The Boeing Company under NASA contract, has eight movable lips and boundary-layer control.

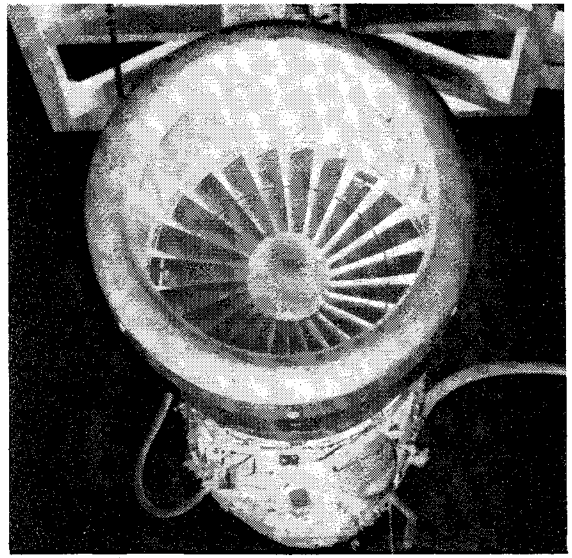

Fig. 13 Experimental rotary inlet silencer.

An inlet rotary silencer is shown in Fig. 13. This device has been tested in model scale and has given promising reduction of discrete frequency compressor noise. It consists of a flat blade free-wheeling rotor with minimal resistance to the airflow, but it is supposed to provide complete blockage to sound in the ray acoustics sense. A complete acoustic analysis of the device is complicated by the fact that the relevant acoustic wavelengths are of the same order as the blade chord of the rotor; thus diffraction phenomena occur. A full scale test of the device is under way.

References

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