Editor's Note

Professor Warren Strahle, who is a 1977 member and was the 1976 Chairman of the AIAA Technical Committee on Aeroacoustics, was asked to serve as Guest Editor of the *Journal of Aircraft* for this special issue on Aeroacoustics. In this August issue and in the following September issue you see the product of Dr. Strahle's and the authors' efforts.

The April 1975 issue of the *Journal of Aircraft* was exclusively on propulsion and turbomachinery. This August 1977 issue is mainly devoted to aeroacoustics. As a reader of the *Journal of Aircraft* (and reader of editorials) do you like or dislike theme issues? Do you prefer a homogeneous mixture of papers on topics comprising the many aircraft-related disciplines? The editorial staff of the *Journal of Aircraft* seeks to provide the articles best meeting the needs of our readers and subscribers. An expression of your thoughts on the *Journal of Aircraft* format and content would be welcome; call (408) 646-2586 or write the Editor, Professor A. E. Fuhs, 25932 Carmel Knolls Dr., Carmel, Calif. 93923.

Preface and Workshop Report for the 3rd AIAA Aeroacoustics Conference

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THIS issue of the *Journal of Aircraft* contains a collection of papers originally presented at the 3rd AIAA Aeroacoustics Conference. The choice of papers for this group was based not upon their relative merit, compared with other papers from the conference, but upon the fact that they were reviewed quickly. Additional papers from the Conference will be published later.

Interest in aeroacoustics is still high. There is much to be done to reach current goals of a commercial aircraft noise reduction of 10 EPNdB per decade. Fundamental understanding and technological tools are still lacking in many areas of aircraft noise abatement. The field of aeroacoustics is fascinating to the spectrum of technical people engaged in it. From the theoretical researcher who revels in a new approximation method to the noise suppression development engineer working with a new suppression device the people active in aeroacoustics have an exciting technical field before them.

Controversies in the various areas of aeroacoustics were amply aired on the last day of the 3rd Aeroacoustics Conference when a series of workshops were held. Workshops were conducted concerning several disciplines within aeroacoustics and provided for lively discussions on controversial items, the state-of-the-art, and future research directions. As a concept, the workshops were highly successful; they were well attended through the last hour of the last day of the Conference. The chairmen of these workshops prepared written summaries of their deliberations, and these have been edited for inclusion in this journal edition. Given below are the results of the workshops.

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Jet Noise Mechanisms and Suppression

Contributed by
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Jet noise levels are once again becoming a major factor in the reduction of engine noise for all of the airplanes of today. The advent of the bypass engine, and particularly the high-bypass engines (JT9D, CF6, RB211), has reduced jet exhaust noise significantly below other components such as turbomachinery noise. Recent developments in acoustical treatment, however, have reduced the noise from these other components to the point that jet noise is once again significant.

Noise Generation Mechanism

The physical mechanism that produces the quadrupole type acoustic sources in subsonic jets is still not understood. Even the spatial extent of the most intense sources is being strongly debated. Additional visual evidence is appearing in the literature indicating the presence of large-scale structures in turbulent jets. However, the participants all agreed that there is no direct experimental information, so far, as to the role of these structures, if any, in the noise generation process. A most relevant set of measurements were reported at this meeting and discussed in some detail at this session by researchers at ONERA. Their measurements strongly imply that the presence of large-scale acoustic sources could account for some of the results they had obtained. It was agreed that additional work on this question would be most productive, since the results are essential to the further development of analytical models.

Analytical Approaches

This topic generated the most lively and heated discussions. Since Lighthill's integral formulation, because of its generality and compactness, does not provide explicit details concerning the generation mechanism, new approaches have been suggested in the last few years. These approaches are forced, at an early stage, to introduce either the Reynolds decomposition of the fluctuating field or some type of linearization, or to formulate the problem in terms of modeling. Although the potential of some of these approaches seems to be better than that of others, there was by no means a unanimous agreement on this point. It is clear that additional experimental information is required to provide further guidance in the mathematical formulation of the problem.

Experimental Methods

A number of new experimental approaches were presented at the meeting. One of the most interesting ones, with possibly far-reaching consequences, consists of introducing certain periodic disturbances upstream of the nozzle exit and studying their effect on the jet flow and the far-field noise. The potential of this technique was discussed in some detail, and it was the general concensus that continuation of such an inquiry would be most useful and productive. Another promising method under discussion was the conditional sampling technique. Applying this to various optical or electronic devices, one may obtain more detailed information about the large-scale structures. The delibration of this approach inspired this observer, and most probably others, to put more effort into applying the technique to their experimental work.

Suppression

The degree of understanding of suppression mechanisms obviously can be no better than our understanding of generation and transmission mechanisms discussed previously. Empirical and semiempirical development of jet suppressors has been pursued for many years. The result of this work has been observed configurations and implied conceptual relationships that seem to correlate noise reductions. These correlations can be used for design guides and are aided by the application of analytical work with regard to fundamental source and transmission mechanism.

Suppression schemes fall into two categories: 1) mechanical and gasdynamics devices that are added to a basic engine, or 2) changes of the basic engine cycle to achieve desired exhaust flowfields. The reader should be aware that older attempts to generate a piece of hardware and try to correlate that geometry with far-field (community) noise radiation leaves out a very vital link – namely, the change in characteristics of the exhaust flowfield. Today nearly every research and development effort tries to establish two correlations: the change of flowfield with geometry and the change of noise with flowfield.

Work reported at the 3rd Aeroacoustics Conference included the controlling of the exhaust jet temperature and velocity profiles at the nozzle exit, gasdynamic shielding by a fluid layer external to the propulsive jet, and two papers giving apparently opposing views on the effect of swirl on exhaust noise.

Profile Control

In many representative turbofan engine installations, the fan and primary flow streams are allowed to mix to some extent before passing through the nozzle. The amount of internal mixing which occurs and the radial and circumferential distributions of velocity at the nozzle exit plane are functions of the length of the mixing region and the way in which the fan and primary streams are brought into contact.

Mixing of primary and secondary flows in a conventional turbofan engine provides a means of reducing jet noise. By shaping the nozzle exit velocity profile, noise reduction greater than that resulting from fully mixed flow has been achieved in AIAA Paper 76-511. In a static jet noise experiment, five primary flow nozzles were used with a common secondary nozzle to simulate exhaust flows of turbofan engines with bypass ratios from 1 to 5. Data were shown which relate jet noise to the location, extent, and magnitude of the peak velocity region. In general, minimum noise was obtained for inverted profiles where the peak velocity was 5 to 15% greater than the reference uniformly mixed velocity and the area of the peak velocity region is 40 to 50% of the total flow area. The inverted flow profiles produce noise characteristics similar to multielement jet suppressor nozzles, i.e. low frequencies are reduced and high frequencies are increased. Maximum noise reductions obtained for the flow systems in this test were about 3 dB in PWL, 4 dB in peak OASPL, 2 PNdb in peak PNL, and 2 PNdb in PNLW (1500-ft distance) relative to complete mixing.

Supersonically, coannular flow with profile shaping has been demonstrated as a method for reducing jet noise. The phenomenon involved here is related to the flow profile control scheme but includes more than that, especially for supersonic jets. Here the second flow has been shown in AIAA Paper 76-507 to significantly change the shock structure and hence the shock related noise. The strongest benefits seem to be when heat is added to the outer layer and an inverted flow profile obtained. Research is on-going to work with varying degrees of heating in a three-stream situation to determine the most effective situation.

Gasdynamic Shielding

Several papers have recently addressed the question of a lower-velocity hot gas flow surrounding the noise source and found that this gas shield can reduce the noise at the community. Questions of application of the concept are still not resolved or reported. However, paper 76-545 was presented and concluded the concept to be inapplicable for jet exhaust noise. This paper presented the results of a test with a two-dimensional cold (ambient temperature) shielding flow. Substantial reduction of noise was found at the peak jet noise angles, but some increase in noise observed in the forward quadrant (i.e., ahead of the exhaust nozzle) was noted. For many engines this increase would not be significant, as other (fan inlet) noise sources prevail.

Swirl

Studies have been conducted installing an annular set of swirling vanes located on the outside of the exhaust flow. The tests of AIAA Paper 76-508 conducted on a small turbojet engine (J85) were a parametric study to determine effects of swirling on jet noise production. Parameters included van geometry, blade angle, number of blades, and percentage of mass flow through the vanes. Noise reductions of the order of 3 dB were reported at sideline angles of 150° to the engine inlet.

A model scale test was also reported in AIAA Paper 76-510, testing swirl in a manner similar to that of AIAA Paper 76-508. These results showed reductions in the far aft angles, but noise increases in the other angles, resulting in a net increase of subjective noise parameters. Other configurations also were reported in AIAA Paper 76-510, including swirl in the presence of a centerbody. This also showed noise increases which were related to vortex flow and shock structure.

Results similar to the model scale results also were noted at the workshops, further indicating the lack of suppression with swirl vanes. However, the positive results of AIAA Paper 76-508 leave an open question and more work is needed in this area.

These papers do not include all of the work that is on-going in jet exhaust suppression research. Other studies include mechanical mixers that control the flowfield mixing with ambient (freestream) air to shift frequencies and source properties, analytical and semi-empirical modeling of suppression mechanisms, and ways of absorbing or shielding the radiated sound with hardware.

Applications of existing and new knowledge must continue. Particular emphasis, as noted by the number of papers at this Conference, must be placed on determining flight effects on the suppression system. Last, but most important, the suppression system must meet the constraints of the airplane system (weight, thrust performance, size for drag or airplane rotation, etc.). Suppression of reduction of bypass jet engine exhaust noise is required.

Turbomachinery Noise

Contributed by
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It is now recognized that static aircraft engine fan noise tests have been contaminated by the sound from inlet flow-distortion and/or inlet turbulence. On the basis of these tests, it once appeared that our ideas about "cut-off" of duct modes and about the effects of rotor-stator spacing were entirely wrong. However, forward flight tests have now revealed that the blade passing frequency tones observed in the static tests were almost entirely caused by inlet flow distortion and/or inlet turbulence. Since the inlet flow distortion/inlet turbulence tones disappear even at very small forward velocities, they probably are not too important in actual aircraft operations. However, multiple pure tones appear to be relatively (but not entirely) unaffected by inlet flow distortions and the sound emanating from the rear of an engine seems to be produced mainly by rotor-stator interactions (and not by inlet distortion). Consequently, the static test results would lead to erroneous conclusions about current high-bypass-ratio fan jet engines (which operate supersonically on takeoff) only during approach and then only for the sound emanating from the front of the engine. On the other hand, a number of the experimental quiet fan jet engines now being tested are designed to operate subsonically even on takeoff while the multiple pure tones generated by currently operational fan jets are easily suppressed. It is, therefore, important to develop test facilities that are relatively free of inlet flow distortions. Forward flight or moving frame facilities (vehicles) are expensive, inconvenient, and very difficult to control. We must, therefore, improve our static (i.e. fixed frame) test facilities to the point where they have good anechoic properties and are relatively free of inlet distortions.

Acoustic wind tunnels are relatively free of inlet distortions, but acoustic measurements in these facilities are contaminated by reflections from the walls and other nonanechoic behavior. These effects can be minimized by treating the walls acoustically and using small-scale models in large tunnels. Moreover, measurements taken within the engine duct are relatively uninfluenced by the acoustic properties of the tunnel. Such measurements have the additional advantage of being directly useful for the design of acoustic liners.

Recent tests have shown that there is a larger reduction in the blade passing frequency tone when an engine is inserted into a tunnel with the flow turned off than there is between the flow and no-flow tests in the same tunnel. This initial reduction is probably due to the flow induced in the tunnel by the operation of the engine – which supports the idea that only a small forward velocity is needed to bring about this effect. It may, therefore, be possible to develop facilities with no external flow source that are still relatively free of inlet flow distortions. Such facilities could have much better acoustic properties than existing wind tunnels.

The best and largest of the existing anechoic chambers are contaminated by inlet flow distortions that produce significant blade passing frequency tones. Moreover, these distortions tend to be strongly dependent on the conditions in the external atmosphere from which the flow entering the chamber is drawn. It may be possible to minimize inlet flow distortions in very small facilities by drawing the air into the chamber only through the wall that faces the engine. The variability of the residual flow distortions resulting from the external conditions can then be minimized by increasing the resistance offered to the external flow.

Outdoor test facilities are the most susceptible to inlet flow distortion/inlet turbulence. But even here, these effects can be significantly reduced by operating the engine behind a large blower. The problems involved in developing facilities for full-scale engines are greater than those for model tests and it may be necessary to conduct all full-scale tests out of doors.

In addition to the specific problems discussed above, there is one problem that affects all these frequencies – namely, there is as yet no precisely controlled moving frame (i.e. forward flight) test that can be used to "calibrate" the fixed-frame facilities. There is, therefore, a need to conduct such tests within the near future.

The question of which type of fixed-frame facility is best remains open. It may be necessary to use a combination of facilities to evaluate any given engine concept. Consequently, the simultaneous development of all existing facilities should be continued.

It has recently been found that the optimum design of acoustic liners depends on the modal content of the incident sound field. Although most existing fan noise models are capable of predicting this structure, it is not known whether they are sufficiently refined to give realistic results. The predictions of these models must, therefore, be compared with measurements. But in-duct modal structure is at best difficult to measure and nearly impossible when the signal is composed of many duct modes. The previously proposed "clean-up" of existing static test facilities will certainly help simplify this task (by greatly reducing the number of modes).

It appears that predicting the energy partition into radial modes will be more difficult than predicting its partition into circumferential modes. It may be necessary to account for the reflection by the stator of the rotor-stator interaction tones when calculating the sound emanating from the rear of an engine. (It appears that very little of the rotor-stator noise is transmitted upstream through the rotor at high subsonic tip speeds). Such reflections can cause tones of one harmonic of the blade passing frequency to be scattered into tones of another.

Duct Acoustics

Contributed by
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The trend toward the use of high-bypass turbojet engines has decreased jet noise but resulted in an increase of the fan noise. The overall noise level of such engines without acoustic treatment is greater than the noise level of low-bypass engines and consists of a broadband spectrum and high-pitched discrete frequency components; these frequencies are the blade passing frequency and its harmonics and multiple pure tones (the shaft frequency and its harmonics) in the case of supersonic rotor tip speeds. Part of the generated noise decays naturally while the other part can be reduced by acoustically treating the engine ducts. To achieve this without an economic penalty, one must optimize the acoustic treatment. To achieve the optimization, one must know the source characteristics, determine the transmission and reflection coefficients through the engine ducts, and predict the radiation conditions at the exhaust and inlet.

To calculate the transmission and reflection coefficients through the engine ducts, one needs to solve the acoustic equations subject to boundary conditions at the duct walls. Since there are no exact solutions available yet for the general problem, researchers have used simplifying assumptions. The viscous terms have been neglected for lined ducts because they produce a small effective admittance at the wall. The nonlinear acoustic terms can be neglected for sound pressure levels less than about 130 dB (re 0.002 dyne/cm^2); however, the sound pressure level in typical jet engines may be in excess of 160 dB.

The linear acoustics equations in a uniform duct are solved by using either Fourier and Laplace transforms or Green's function or normal mode approach, with most of the prediction programs being based on the last approach. A number of programs are available to compute the transmission and reflection coefficients in ducts with circular, annular, rectangular, and two-dimensional cross sections provided that axial variations in the liner properties and the boundary-layer thickness can be neglected. Programs also are available for the case of segmented liners. For other cross sections, programs are available only for the case of no mean flow.

Many of these programs idealize the mean flow by a simple profile, including uniform flow. It has been demonstrated that the attenuation rates are independent of the mean profiles provided that it has the same shape factor as the original profile and results are correlated with boundary-layer displacement thickness. Also, correlation of optimum liner properties for flow cases with and without a mean boundary layer has been accomplished and provides a useful design tool. When the mean flow Reynolds number is very large, one may be able to use a uniform-mean-flow model. However, there is still a controversy on whether the boundary condition at the wall should be based on the continuity of the particle displacement or the velocity. It has been demonstrated theoretically that the continuity of the particle displacement is the appropriate condition when the acoustic boundary-layer thickness is much less than the mean boundary-layer thickness. However, available experimental data indicate that either condition can be valid depending on the mean flow Mach number. One possible explanation is that the transition depends on the relative thickness of the acoustic and mean boundary layers.

Although the prediction of acoustic propagation in parallel ducts without axial gradients is well-developed, the modeling of the boundary conditions that are required to implement the results of such studies is less satisfactory. The various "optimization" procedures that have been developed for liners in straight ducts yield liner properties that depend strongly on the mode content of the sound and attenuation rates that are sensitive to small changes in liner properties. Thus, the critical areas for development are in modeling of the source characteristics, radiation impedance, and liner impedance.

Source characteristics are discussed elsewhere in this article; although considerable effort has been devoted to source modeling and to duct acoustics, very few investigations have examined both aspects of the problem. Ultimately, the determination of optimum duct designs will require the combination of accurate models from both fields. The prediction of radiation boundary conditions for actual engines is still rudimentary. The radiation conditions are known only for simple cases such as the case of no mean flow and simple duct terminations.

The desirable liner characteristics have been known for some time, and a variety of liner materials and configurations have been examined in light of these characteristics. For structural purposes, perforated plate liners are still the preferred design; unfortunately, the prediction of the impedance of such a liner in the presence of a mean flow remains a formidable problem. The feeling of researchers is that modeling of liners will follow understanding of the physics of the flow. Although the understanding of the physics of a grazing flow over a resonator has improved significantly in the past year, basic liner models are not improving as fast as the demand for application on engines. Generally, prediction of the reactance of a liner is less accurate than that of the resistance. Recent experiments show that the resistance of a liner in the presence of grazing flow is dependent on the frequency, though for some time it was believed that it is independent of frequency. Other experiments show that, if the sound pressure level is high, the resistance is independent of the frequency. Noise generated by liners (self-noise) is not well understood; hole size and liner reactance seem to be important parameters for determining conditions for singing.

The use of segmented liners for phased treatment seems to be a very effective mechanism for noise with small dimensionless frequencies. The mode content is critical for this mechanism because the suppression is achieved by reflections and by the redistribution of the energy. Phased treatment is considered by some researchers to be ineffective in large ducts or at high frequency, and others report interactive effects remain significant at the intermediate values of reduced frequency. A recent study suggests that each liner segment should be designed independently to be effective for a particular group of acoustic modes having similar mode cut-on ratios; such an approach circumvents the difficulty of not knowing the detailed mode composition.

Unlike the case of straight ducts, techniques of analysis of wave-propagation in ducts with a variable area of a continuously varying wall impedance are still under development. These techniques include quasi-one-dimensional approximations, solutions for slowly varying cross sections, solutions for weak wall undulations, approximation of the duct by a series of stepped uniform sections, variational methods, a variation-of-parameters or wave-envelope technique, and direct numerical methods of the finite-difference and finite-element type. Each approach has unique characteristics and advantages as well as obvious limitations, either of a numerical or a physical nature. Results of studies now underway will clarify which of the methods is most advantageous and efficient for realistic flow situations. It should be noted that there is a lack of experimental data for validation of these models.

The use of choked inlets has long been recognized as an effective means of reducing upstream noise propagation, although such inlets require careful design to prevent excessive loss in compressor performance. Most of the experimental investigations have noted significant reductions of the noise level when the inlet is choked. Further, most of the potential noise reduction is achieved by operation in the partially choked state. Some investigators reported the possibility of substantial leakage through the wall boundary layers, whereas others reported that such leakage is minor. Although the experimental studies have demonstrated that the choked inlet is a viable technique, they have not provided insight into the physical mechanisms that are responsible for the noise reductions or that explain some differences among the several experimental results. To provide such insight, one needs to solve the nonlinear acoustic equations in a duct with large axial gradients. Efforts in this direction are under way using the wave envelope technique.

When the sound intensity is above 130 dB, the nonlinear terms must be included. Most of the existing nonlinear work is devoted to the case of no mean flow or quasi-one-dimensional flow. The results of the nonlinear work with a uniform mean flow indicate that the creation of the multiple pure tones is due to the strong interaction among the blade passing frequency and its subharmonics in the case of hard-walled ducts because they travel with the same phase speed (resonance). Thus, the generation of multiple pure tones can be inhibited by a proper treatment of the duct walls that will make these subharmonics travel with phase speeds which are different from that of the blade passing frequency.

Aircraft Engine Core Noise

Contributed by
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Scope of Core Noise

The term "core noise" is used to designate the contribution to the overall exhaust noise emanating from sources within an aircraft engine. Candidate noise sources generally considered in this category include combustion noise, strut noise, turbine noise, and noise generated at the nozzle exit plane due to unsteady flow interacting with the nozzle exit.

While noise generated by the turbine dominates the high-frequency portion of the core noise spectra, research over just the last two years has led to general agreement that core noise at low frequencies (i.e. 0 to 2000 Hz) is controlled by combustion related sources. Discussion at the workshop and in the core noise session were restricted primarily to noise in this low-frequency regime.

Combustion noise has been categorized in terms of direct and indirect contributions. Direct combustion noise is used to designate the pressure fluctuations generated directly by the unsteady heat release rate in the turbulent combustion region. Indirect combustion noise results from combustion-induced temperature inhomogeneities interacting with the pressure gradient through the turbine. Research is currently underway, both in industry and university laboratories, to assess the relative importance of direct vs indirect combustion noise in typical aircraft engines. Data gathered and models formulated to date resulted in a concensus of those present at the workshop that direct combustion noise contributions are more dominant than indirect combustion noise. More definitive data are needed, however, to establish the regimes of dominance of each of these sources of combustion noise.

Understanding of Direct Combustion Noise Sources

It is known that the time derivative of the heat release rate (i.e. the unsteadiness) in a turbulent burning region is the source of density fluctuations which behave as aerodynamic noise sources. There is current controversy, however, concerning whether the total time derivative of the heat release rate following the fluid particle is needed to describe the combustion noise source region or if the local Eulerian time derivative is sufficient. Research is currently underway to evaluate the relative importance of the various terms in the total derivative formulation. All of the terms arise due to turbulence in the flow which causes the fluctuation in heat release. Since turbulent combustion is an essential feature of aircraft engine combustors to ensure efficient burning within a compact region, there will always be noise. The challenge of reducing combustion noise in an engine is, therefore, reduced to the problem of developing a combustor which provides adequate turbulent mixing to allow efficient combustion in a compact region, with stable flameholding over a broad range of operating conditions, while not generating any more unsteadiness than is needed, in order to minimize noise generation.

Advances Accomplished and Research Needed

In the area of direct combustion noise prediction, recent methods have been developed which quite adequately relate the noise spectra and levels from various types of burners (e.g., annular, can-type) to relevant burner performance and geometry parameters. By necessity, these methods are semiempirical, and in some cases completely empirical in nature, and there is still no proven theory to allow extrapolations to be made from conventional to new type configurations. This problem usually arises in data correlation methods because such correlations assume the existence of a universal relationship between nonsteady fluctuations and time-averaged values of temperature, pressure, heat release rate, etc. Consequently, correlations which may be very impressive for one class of combustors designed by a given manufacturer may prove unacceptable when used to predict the noise emission from another.

What is needed, therefore, is a better understanding of the relationships between fluctuating quantities which are the direct cause of noise and the relevant performance and geometry parameters which are more easily measureable. There is some work of this type being conducted on open flame (using sophisticated optical technques) but additional work on enclosed combustors is needed. A better understanding is needed of how changes in the flow pattern on a macroscopic level affect the flow and flame pattern on a more localized level and, consequently, affect noise emission. The effects of fuel type and droplet size have been examined to some extent, but no clear trend has been noted to suggest that the influence of these changes can be explained or used to advantage. The relationship between turbulence and the macroscopic flame properties can be explored through use of laser velocimetry and flame radiative emission studies. Such explorations were recommended at the workshop.

Another area where future work is needed deals with the magnitude of the acoustic transmission loss (or attenuation) which occurs across single or multistage turbines between the combustor and the exhaust nozzle. While some estimates of this loss are in excess of 50 dB, a more realistic value, based on recent comparisons of combustor rig and engine noise data, appears to be about 8 to 12 dB. Although a realistic model was presented at the meeting for predicting this loss, future experimental and theoretical studies should consider in more detail the modal distribution of the noise at the combustor/turbine interface, realizing that for typical engine sizes, the plane wave and first circumferential mode are the only ones propagating in the frequency range of interest. All higher order modes are below cutoff and therefore do not carry acoustic energy to the far-field.

Regarding the potential for future reduction of core noise, recent analytical and experimental studies have shown that, within certain operating regimes, geometrical changes in the combustor will effect changes in the level of combustion generated noise. For example, increasing the number of fuel injectors within a given cross-sectional area appears to have the effect of reducing the size of the coherent region, thereby reducing the noise. Proper mixing of primary air with the fuel spray, with or without swirl vanes, appears to promote stable combustion with less macroscopic unsteadiness and, fortunately, less noise generation. Some configurations developed to reduce chemical pollutant emissions have resulted in small reductions of noise emission as well, whereas others have not.

Conclusion

Some basic progress has been made over the past few years toward a better understanding of the role of combustion as a source of core noise in aircraft engines. Many basic questions remain unanswered, however. A better understanding is needed regarding the relationship between mean flow quantities, which are controlled by the engine design, and their fluctuating components which are the cause of noise. Without such understanding, combustor design changes to reduce core engine noise will be conducted on empirical or, at best, semiempirical bases, with no guaranteed improvement. Additional effort is, therefore, warranted in seeking such relationships.

V/STOL Noise Technology

Contributed by
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Introduction

The V/STOL area actually includes a number of possible propulsion and/or propulsive lift systems. For example, there is the rotary airfoil class which includes various forms of helicopter rotors, tilt-wing propellers, shrouded propellers, lift fans, conventional fans, etc. There is also the fixed airfoil/jet exhaust class which include under-the-wing blown flaps, over-the-wing blown flaps, augmentor wing, various types of internally blown jet flaps, vectored jets, etc. An aircraft using any one of these propulsive-lift systems also has some sources in common, such as the various turbine engine internal noise sources (compressor, combustion, etc.) and nonpropulsive airframe noise sources (wing turbulence, landing gear turbulence, etc.), both families of which are discussed elsewhere.

The rotary airfoil and the fixed airfoil/jet exhaust classes each have several unique noise sources. Some sources are similar between the two classes, and others are somewhat different or at least there are differences as to which sources are more dominant. Since these differences do exist, it is useful to discuss each class separately.

Rotary Airfoil Class

While there are several types of rotary lifting airfoil systems, most noise reduction work currently in progress is related to helicopters which will be discussed here as typical of this class. Helicopter rotor noise sources basically consists of: 1) blade rotational pressure fields resulting in harmonically related pure tone noise; 2) inflow turbulence interactions with the rotating blades that causes broadened harmonic peaks, more high frequency harmonics, and some broadband noise; and 3) turbulent wakes generated behind the blades that result in broadband random type noise. Source 1 also may have a severe impulsive form called blade slap or band which occurs due to blade interaction with a strong tip trailing vortex shed from a previous blade passage and/or abrupt shock formations on advancing blades in forward flight. Source 2 also may have several forms depending on whether the inflow turbulence is small, moderate, or is more severe due to previous blade wake turbulence. In addition, source 3 also can be made more severe by increased upstream turbulence from any unsteady phenomena flowing into the trailing edge wake area.

Much work in the past has been devoted to reduction of the impulsive blade slap type noise, as it is usually the most severe problem in current helicopters. The problem can be improved greatly by utilizing new design rotor airfoils and tips to minimize tip vortex strength, better clearance between blades and previously shed top vortices, and reduction in blade loading and rotational speed. These same techniques also help reduce ordinary rotational noise, inflow turbulence noise, and broadband wake turbulence noise. Much of the current activity in rotor noise reduction is related to the more broadband sources, since these appear to be the next barrier to overall helicopter noise reduction. This point was emphasized in the workshop session and further illustrated in several of the papers presented at one of the main technical sessions (e.g. see papers 76-560 and 76-561).

Fixed Airfoil/Jet Exhaust Class

In this area there also are several types of propulsive-lift systems as previously mentioned; however, the two types receiving the most current attention will be discussed here as typical of this class. These types are under-the-wing blown flaps and the over-the-wing blown flaps. These systems also are sometimes known as a lower-surface blown and upper-surface blown flaps. Both systems have many noise sources in common. For example, both have turbulent jets flowing over wing and flap surfaces, and trailing edges, and turbulent flow mixing zones and wakes. Under-the-wing installations also have direct turbulent jet impingement at large angles to the flaps, which is another noise source. Some over-the-wing installations also can have this impingement source when the exhaust nozzle is located above the wing surface and is vectored downward rather than blended into the wing as is usually done. In addition, there are aeroacoustics resonances or feedback loops in many installations such as those resulting from flap impingement instability energy or trailing edge instability energy feeding back to the nozzle exit plane instability region. These types of resonances cause discrete frequency or pure tone noise, whereas the previously mentioned turbulence sources produce basically broadband random noise.

Considerable amounts of work have been devoted in the past few years to better theoretical understanding of noise source mechanisms, better prediction techniques, and noise reduction concepts. This class of V/STOL systems is still rather new compared to the rotary class, and consequently work is very active in all aspects of the problem as discussed in the workshop and in two of the main technical sessions (e.g., see AIAA Papers 76-500, 76-501, 76-503, and 76-521).

Noise reduction efforts have concentrated on four areas. The first is reduction of jet velocity by the use of low turbofan exhaust pressure ratios. This is a powerful step since blown flap noise typically is reduced in proportion to jet velocity reductions to the sixth power. The basic design of flap airfoils with low turbulence characteristics is another noise reduction step, since turbulence reduction results in noise reduction. Related to this are passive devices (e.g. trailing edge porosity or comb-like extensions) and active devices (e.g. trailing edge slot blowing) that modify and reduce turbulence formation at the trailing edge and/or modify the acoustic impedance at the trailing edge.

Concluding Remarks

There are many obvious similarities between some of the noise sources in the rotary airfoil and fixed airfoil classes. Much of the theoretical and noise reduction work in both areas is related. For example, slowing down the rotor speed is comparable to using a lower fan pressure ratio for an over-the-wing blowing installation. Both actions result in broadband noise reduction approximately proportional to airfoil or flow velocity the sixth power, which suggests that dipole type acoustic sources are predominant in both cases.

The most pressing problem currently is to attain a better theoretical understanding of the exact nature of broadband noise sources for both classes of propulsive lift systems. In the blown flap class, trailing edge and leading edge flow surface interaction noise appears to be dominant and needs renewed attention in order to achieve efficient noise reductions. In addition, the broadband V/STOL noise phenomena are closely related to the wing noise area of the nonpropulsive or airframe noise problem discussed elsewhere. Thus, technology advancements made in any of these areas will be very useful in the other related areas as the quest for quiet aircraft proceeds.

Airframe and Interior Noise

Contributed by
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Airframe Noise

Much of the airframe-noise segment of the workshop was concerned with the still controversial issues of airframe noise mechanisms and airframe noise prediction. As pointed out in AIAA Paper 76-525, all of the prediction methods for airframe noise that are now available are semiempirical and can be placed into one of three categories. Methods in the first category predict overall sound pressure level for a complete aircraft. Methods in the second category predict overall sound pressure level or spectra for components as well as complete aircraft from gross aircraft and component parameters such as drag, aircraft speed, wing area, etc. Methods in the third category predict spectra for aircraft and components using local flow properties and models of noise of individual components.

Two of the papers presented at the Conference and discussed at length in the workshop fell into the third category but the results were used to devise a method for the first category. AIAA Papers 76-526 and 76-527 both started with the result of Ffowcs Williams and Hall as a basis for calculating noise generated by flow over a wing. However, due to different assumptions made in their further analyses, Fink and Hersh arrived at different final expressions for noise from the wing. Although the expressions are different in their formulation, each seems capable of correlating the overall sound pressure levels from a number of airplanes. It was suggested at the workshop that additional comparisons with flight data are needed along with new data, both from flight tests and acoustic wind-tunnel tests, to determine the merits of various prediction methods – methods such as those presented at this Conference and other methods such as outlined in AIAA Paper 75-539, a method which received a great deal of discussion at the workshop. Work is needed to develop generalized methods for predicting both directivity and spectral variations as a function of aircraft configuration and time during a flyover.

Since there is similarity between a wing on a CTOL airplane and a helicopter rotor blade, it seems reasonable to use methods developed for predicting airframe noise from wings to predict noise produced by helicopter rotor blades. There were differences of opinion, however, as to the chances of success of doing so. Some participants in the workshop maintained that helicopter rotor noise was predicted to be much higher than measured, while other participants claimed that helicopter noise could be predicted accurately.

Although most of the discussion on airframe noise prediction was concerned with noise from wings and flaps, noise produced by airflow over landing gears and wheel wells also was discussed. Three papers at the Conference addressed the problem of cavity noise – 76-524, 76-528, and 76-529. AIAA Paper 76-552 was concerned with wheel well/landing gear combinations. The workshop discussions led to the conclusion that while work on cavity noise was important because cavity noise was a major source of uncertainty, wheel-well noise is probably not a major source of airframe noise, although landing-gear noise may be imporatnt for some airplanes. However, cavities other than wheel wells on an airplane may be important noise sources.

Progress is being made in the use of wind tunnels for airframe noise studies as shown by AIAA Papers 76-550 and 76-553. Wind tunnels have the potential for allowing accurate noise and flowfield measurements to be made, along with control over freestream turbulence and velocity, and model configuration. Additional work is needed, however, to ensure that the problems have been adequately solved for separating the airframe noise from the wind-tunnel noises, accounting for multiple reflections from closed-section wind tunnels, accounting for shear-layer refraction effects for open-jet wind tunnels, and accounting for Reynolds number effects.

The workshop ended with a discussion of ideas on how to reduce airframe noise on future aircraft. Since airframe noise is strongly velocity-dependent, varying as the fifth or sixth power of aircraft speed; one way to reduce airframe noise is to modify the aerodynamic charateristics of the airplane as well as onboard avionics and the ground-located air traffic control system in order to enable future aircraft to land slower. However, the required design changes to accomplish that, such as larger wings or flaps or less wing sweep, may themselves increase noise. A study to determine the total effect on aircraft noise and performance of varying the important parameters affecting airframe noise would be useful in guiding future noise reduction efforts.

Interior Noise

Interior noise is an important design consideration in commercial, business/executive, general aviation, and military airplanes. High levels of noise may interfere with speech communications and even cause auditory fatigue. On the other hand, the noise level should not be so low that there is inadequate acoustical privacy for the passengers. The acoustical comfort of an aircraft, therefore, is important for both passengers and crew.

The major sources of interior noise external to the aircraft are the engines and the turbulent boundary layer. Various internal equipment items also can produce high noise levels during various phases of flight. The papers presented at this Conference and the discussion during the workshop were directed at minimizing interior noise levels due to external noise sources.

For some types of advanced aircraft, low-frequency noise levels from the propulsion engines may be substantially higher than from current low- and high-bypass-ratio turbofans or from current subsonic-tip-speed propellers. STOL airplanes with externally blown flaps (either lower or upper surface blown) could be exposed to high levels of low-frequency noise during takeoff and landing. Airplanes with upper-surface-blown flaps might even experience high external noise levels during cruise because of the close proximity of the engines to the fuselage. Future airplane designs with advanced turboprop engines having supersonic tip speeds also might be exposed to high levels of low-frequency noise during takeoff and cruise.

Consequently, it was felt that future aircraft designs would have to consider methods of incorporating acoustical design features that yielded substantially more low-frequency noise reduction than achieved by current aircraft design practices. Close cooperation would be required among various engineering disciplines to obtain the required noise reduction for minimum penalty in weight and costs. As potential designs, it was suggested that advanced fuselages might be made from nonmetallic bonded materials or with metallic honeycomb-sandwich designs. Such designs would increase the stiffness of the structure with little increase in mass per unit area. Another possibility would be to use interior trim panels having relatively thick gauges as part of a double-wall design all the way around the perimeter of the airplane, above and below the floor.

Better methods for predicting the noise reduction of a fuselage structure also are needed. There is a need both for approximate methods and more exact but complex methods. For example, a statistical energy analysis (SEA) such as described in AIAA Paper 76-548 is useful because it may be able to predict noise in fuselages of complex structure. Moreover, when the excitation is such that there is a high density of vibration modes in the structure, the SEA method can provide useful results. On the other hand, a more "exact" method such as that proposed in AIAA Paper 76-549, which is difficult to apply to complex structures, may nevertheless be a useful technique to apply when the fuselage modal density is low.

More important requirements than improving the acoustical design of the fuselage, however, were felt to be 1) establishment of rational acoustical design criteria, and 2) establishing methods of accurately predicting the strength and coupling efficiences of the external noise sources. To establish reasonable design criteria for passenger aircraft may require a series of subjective tests to study factors such as speech communication, auditory fatigue, and acoustical comfort. Aircraft designed for cargo or military missions would require special considerations. Reliable methods of estimating near-field noise levels from engine noise sources during takeoff and cruise conditions should be developed. The unique problems associated with externally blown flap STOL transports require special attention. Also, the special problems of propeller-powered general-aviation and business/executive airplanes are worthy of additional study, as pointed out in AIAA Paper 76-551. The consensus was that additional analytical and experimental studies were both needed to develop improved design tools.

Forward Flight Effects

Contributed by
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The workshop addressed the general question of the effect of forward flight on aircraft noise. While jet exhaust noise had long been recognized as an engine noise source that would be affected by flight speed, research conducted over the past five years has shown that forward flight can have major effect on other aircraft noise sources such as a fan or propeller. In addition, a number of important problems have been raised regarding the interpretation of flight test noise measurements and simulated flight measurements in wind tunnels. By the nature of the subject, this area of aeroacoustics research is strongly dependent upon experimental measurements.

Relative to jet exhaust noise it was the consensus of the workshop that the effect of forward flight on such noise can be simulated accurately in wind-tunnel experimentation when suitable corrections are applied to the data. In the case of open-jet wind tunnels, the need for additional theoretical research and supporting experimentation relative to wind-tunnel shear-layer refraction and turbulence-interaction corrections to measured noise data is clearly evident. Questions do remain as to whether the exhaust nozzle external boundary layer has a significant effect on jet noise and whether this potential effect has been modeled in an appropriate manner in wind-tunnel investigations conducted to date.

Despite significant effort over the past several years to obtain flight measurements of jet noise, it was concluded that the need exists for additional reference in-flight data. A wider range of jet operating conditions is needed, as well as assurance that the data are not contaminated by other aircraft noise sources such as core engine noise. Comparison between flight and wind-tunnel results also have been adversely affected by the failure to achieve the true far field in some measurements. In these cases, additional corrections are required (and assumptions introduced) to account for the axial distribution of jet noise sources. The effect of flight on exhaust jet shock noise is also a problem requiring additional investigation.

The effect of forward flight on the propagation of core engine noise is a current area of research. Changes in low-frequency core engine noise directivity with flight speed may influence noise spectra in the frequency range nominally attributed to jet exhaust noise, thereby influencing conclusions with regard to the jet exhaust noise forward flight effect.

Forward flight has been shown to cause significant reduction in fan and propeller noise relative to measurements obtained on static test stands. It is now apparent that the ingestion of atmospheric turbulence during static testing is a major cause of noise. The large contraction of inflow streamlines which occurs during static tests but not in forward flight causes an intensification and distortion of the ambient turbulence field and the production of extraneous narrowband random (quasi-tonal) and broadband noise by the spectra and thereby interfere with measurements of the effect of design changes on other fan or propeller noise mechanisms. A clear need therefore exists to develop inflow turbulence suppression devices that permit meaningful static test stand noise measurements.

Due in part to the lack of a suitable test facility, the question remains as to the effect of forward flight on fan noise when the inflow turbulence and distortion noise mechanism has been suppressed. With this question unanswered, it is unclear whether a static test stand equipped with inflow turbulence suppression devices and the necessary bellmouth inlet will produce fan noise signatures representative of fans in forward flight. In the latter case, the inlet is different and the fan is operating in the presence of the aircraft structure. Another uncertain forward flight effect is the potential alteration of aft radiated fan noise spectra and directivity by refraction and turbulence scattering in the shear layer between the fan exit flow and the ambient air.

The question of atmospheric turbulence ingestion effects also applies to helicopter rotors. Differences can be expected between the turbulence ingestion noise in hover and that obtained in vertical ascent or forward flight. Main rotor-tail rotor interaction noise would be affected by flight as would impulsive noise associated with tip vortex-blade interaction and high tip speed. Research recently has been initiated in some of these areas using controlled flight experiments, an acoustically treated closed-jet wind tunnel, and, at smaller scale, open-jet acoustic wind tunnels designed for forward flight effects noise research.

In summary, the effect of forward flight on turbofan engine, propeller, and helicopter rotor noise is complex having a demonstrated or potential influence on the majority of individual aircraft noise sources and mechanisms. A number of priority research problems have been identified. The rate of progress in these areas will be hindered to some extent by the high cost of full-scale flight experimentation and the limitations of existing wind-tunnel test facilities with regard to background noise, an acoustic freefield test environment, attainment of the acoustic far field, and model size test capability. Existing tunnels are deficient in one or more respects for the full range of potentially desirable experimental investigations. Carefully designed experiments will therefore be required to combine essential test characteristics in a given forward flight effects investigation.