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INTERIM PREDICTION METHOD FOR LOW FREQUENCY CORE ENGINE NOISE

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ABSTRACT

A literature survey on low-frequency core engine noise is presented. Possible sources of low frequency internally generated noise in core engines are discussed with emphasis on combustion and component scrubbing noise. Core noise generated by the turbine is high frequency, and is not included. An interim method, taken from the literature, is recommended for predicting low frequency core engine noise that is dominant when jet velocities are low. This prediction procedure is developed in support of the NASA Aircraft Noise Prediction Program. Recommendations are made for future research on low frequency core engine noise that will aid in improving the prediction method and help define possible additional internal noise sources.

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SUMMARY

A literature survey on low-frequency core engine noise is presented. Possible sources of low frequency internally generated noise in core engines are discussed with emphasis on combustion and component scrubbing noise. Core noise generated by the turbine is high frequency, and is not included. An interim method, taken from the literature, is recommended for predicting low frequency core engine noise that is dominant when jet velocities are low. This prediction procedure is developed in support of the NASA Aircraft Noise Prediction Program. Recommendations are made for future research on low frequency core engine noise that will aid in improving the prediction method and help define possible additional internal noise sources.

INTRODUCTION

The noise reduction potential of engine cycles and various noise suppression techniques may be limited by the presence of internal noise sources in the core engine. Further engine noise suppression, in such cases, will require reducing core noise generation or the use of core noise suppression. For evaluation of the noise reduction benefits of new engines or modifications to existing engines, a prediction technique for core engine noise is required.

Measurements of the acoustic power generated by low velocity jets often show a deviation from the eighth-power velocity relation found at higher velocities. This discrepancy has been shown to be at least partially caused by additional noise sources upstream of the nozzle. In the case of noise from an engine, the internal noise from the core engine adds to the jet exhaust noise.

At the present stage of definition of core engine noise sources, it is not possible to identify all the sources with certainty. Some of the probable sources are:

(1) The combustion process

(2) Flow around internal obstructions

(3) Scrubbing of the duct walls

(4) Local temperature fluctuations or hot spots flowing through the turbine and nozzle

(5) Flow through the turbine

(6) Turbine blade and stator interactions

Of these, the noises associated with the turbine appear at relatively high frequencies and therefore are not considered in this report. Combustion noise and internal flow noises appear in the low- to mid-frequency range and are difficult to separate from jet noise. In a current study (DOT-FAA Contract No. DOT-FA72WA-3023), an attempt is being made to isolate and study these effects separately, but the results are not yet available.

Core engine noise data are sparse and of questionable accuracy. Fan noise and jet noise from the engine must be adequately suppressed so that the core noise remains as the major noise contribution in the low- and mid-frequency range. In most cases jet noise is deducted from the data for the total engine noise by means of existing jet noise prediction techniques. Unfortunately, much of the resulting core noise data is considered proprietary by the engine manufacturers and cannot be shown in this report.

Prediction of core noise levels has followed two main lines of approach. The first approach was based on treatment of the core noise as a deviation from pure jet noise (refs. 1 and 2), and hence related the core noise levels to jet exhaust velocity. The second approach used engine operating parameters to predict the low frequency core noise. The prediction method chosen herein is based on engine operating parameters, that is, engine mass flow rate, compressor pressure and temperature ratio, and the combustor temperature rise.

This prediction method is presented in response to the need for predicting low-frequency core noise as a component of total aircraft noise for the NASA Aircraft Noise Prediction Program (ANOPP). The responsibility of this program is assigned to the Langley Research Center; however, it is being developed jointly by various NASA centers with help from industry representatives. In the Program, the various contributors to and modifiers of aircraft noise are summed at various ground locations in order to predict a noise footprint for single- or multiple-event aircraft flights. The need for the ANOPP requires that this prediction method be based on the present state-of-the-art. Refined techniques and better data may be available in the near future to permit up-dating this prediction method.

This report selects an interim prediction method for estimation of the low-frequency component of core engine noise. Combustion noise, internal flow noise, and perhaps entropy fluctuations contribute to the low-frequency core noise. A review of recent published work in this area is included. Various recommendations are made for further work in the area of low-frequency core noise, which might contribute to better understanding of the controlling mechanisms and lead to firmer prediction techniques.

All symbols used in this report are defined in the appendix. U.S. Customary Units were found to be used in the literature, hence the equations given in the literature survey section retain these units. The equations given for the recommended prediction method are also given in U.S. Customary Units but factors for converting to S. I. Units are given. In the list of symbols, U.S. Customary Units are given in parentheses following the S. I. Units.

LITERATURE SURVEY

For convenience of presentation, the literature dealing with low-frequency core engine noise is divided into applied and fundamental research.

Applied research is considered that work which makes use of engine data, and fundamental research is considered that which uses component testing for its primary source of data. In general, the fundamental research work has been performed by the universities; however, several aircraft engine companies are conducting basic acoustic tests with individual combustion chambers. The applied research is generally being done by the aircraft engine companies.

This literature survey is not comprehensive. However, it should be sufficient to give the reader an appreciation of the state of the art of low frequency core engine noise prediction techniques. Table I lists most of the references and identifies the type of information contained in each reference for power level, sound pressure level, spectra, and directivity. The equations given herein were modified from those found in the references in order to use the standard symbols list given in the appendix. Reference power and reference sound pressure used in this report are 10^{-13} watts and 20 $\mu N/m^2$, respectively.

Applied Research

Bushell (ref. 1) and Marshall (ref. 2) are among the many investigators to note that typical jet noise measurements at low jet velocities from both jet noise rigs and engines show a deviation from the classical eighth power dependence on jet velocity derived by Lighthill (ref. 3). Bushell cites internal noise sources associated with turbulence, struts, and flow through combustors as possible reasons for the deviation. He gives curves of overall sound pressure level as a function of jet velocity that can be used to calculate the noise at low jet velocities. Marshall (ref. 2) makes use of the curves presented by Bushell and also directs attention to the general directivity of the various sound sources in engines, i.e., compressor, fan, jet, turbine, and tailpipe (internal noise). In general both Bushell and Marshall agree that the source of noise causing the deviation from the jet noise is or can be internally generated.

Ho and Tedrick (ref. 4) investigated combustion noise in small gas turbine engines. They state that "one of the most significant sources of noise from small turboshaft engines and auxiliary power units is the combustion process." The power spectra of individual combustors and of turbine engines using the same combustor were obtained experimentally. These measurements showed that the combustion noise peaked at low frequencies, on the order of 125 hertz. Several types of combustors and engines were tested. Empirical methods and dimensional analysis were used to obtain equations for the acoustic power generated for both the component combustor tests and the engine tests. No directivity and only one spectrum was reported in reference 4. The equations given for the acoustic power due to the combustion process are:

$$\mathrm{OAPWL} = 81 + 10\ \log_{10}\left[\frac{(T_4 - T_3)^2}{T_4} P_4 V_4 (1 + F)^2\ D_e\right] \tag{1}$$

based on data taken in the combustion test rig; and

$$\mathrm{OAPWL} = 23 + 10\ \log_{10}\left[\frac{(T_4 - T_3)^4}{T_4^2} P_4^2 V_4^2 (1 + F)^4\ D_e^2\right] \tag{2}$$

based on data derived from engine tests.

Motsinger (ref. 5) used the work of Knott (ref. 6) in conjunction with TF39 combustor pressure fluctuation data to predict the noise of the T64 turboshaft engine. Knott's data for nonpremixed (diffusion) flames at atmospheric pressure showed that the "acoustic combustion efficiency is a simple function of the fuel mass flow rate." Motsinger added corrections for pressure and temperature effects based on TF39 engine combustor data and found good correlation with the noise data from a T-64 turboshaft engine. The final prediction equation given by Motsinger for acoustic power due to combustion noise is:

$$\mathrm{OAPWL} = 56.5 + 10\ \log_{10}\left[\frac{(T_4 - T_3)^2}{T_3^2} T_0^2 \left(\frac{P_3}{P_0}\right)^2 \dot{m}_a\right] \tag{3}$$

The power spectrum for the T-64 engine is given in tabular form in reference 5. The peak frequency and spectrum for the T-64 engine may not be the same as for other engines, as pointed out by Motsinger. Directivity data for the T-64 engine shows a maximum sound pressure level at 120 degrees from the inlet axis.

In a contractor report for NASA, Neitzel et al. (ref. 7) reported that the maximum overall sound pressure level at a 200-foot sideline due to combustion noise is:

$$\text{OASPL} = -2.5 + 10 \log_{10}\left[(T_4 - T_3)^2 \left(\frac{P_3}{P_0}\right)^{1.3} \dot{m}_a\right] \tag{4}$$

No spectral or directivity data are given other than a statement that the peak OASPL occurred at an angle of 110 degrees from the inlet axis.

Grande (ref. 8) concludes that the primary contribution to core engine noise is combustion. He presents an equation for combustion generated noise based on Arnold's analysis of open flames (ref. 9). The equation is modified for the transmission of this noise through the turbine and jet exhaust nozzle. The equations are:

$$\text{OAPWL} = 205.5 + 10 \log_{10}[B_N B_T W_C] \tag{5}$$

where the nozzle transmission coefficient B_N is

$$B_N = \frac{T_0}{T_N} \tag{5.1}$$

the turbine transmission coefficient B_T is

$$B_T = \left(\frac{T_0}{T_4}\right)^{N/2} \left(\frac{P_4}{P_5}\right)^{0.072(N-1)} \tag{5.2}$$

the combustion noise W_C is

$$W_C = \left(\frac{T_4 - T_3}{T_0}\right)^2 \frac{1}{T_3^3} \frac{P_4}{P_0} V_b^2 V_3 \left(\frac{\dot{m}_a \sqrt{\frac{T_4}{t_0}}}{\delta_4}\right)(1 + F) \left(\frac{DL}{D_4^2}\right) \tag{5.3}$$

where:

$$\frac{DL}{D_4^2} = \frac{L}{\Delta D_{ann}} \quad \text{for annular combustors} \tag{5.3.1}$$

$$\Delta D_{ann} \equiv 2 \text{ times the annulus height}$$

and

$$\frac{DL}{D_4^2} = \frac{L}{D_{can}} \quad \text{for can type combustors} \tag{5.3.2}$$

Grande states "Ho and Tedrick's empirical correlation," for engines, "agrees fully with" the above equation for W_C, "except for a factor of $\sqrt{T_4}$." He compares data from low and high bypass ratio engines and finds agreement with his correlation to within ±1 dB. However, he points out: ". . . similar comparisons involving other engines are desirable to permit an assessment of the prediction scheme accuracy." No spectra or directivity predictions are given by Grande.

Gerend et al. (ref. 10) investigated core engine noise using both model and engine tests. The model test consisted of an internal noise source in a pipe supplying air to the inner nozzle of a coaxial nozzle in a configuration approximating bypass type engines. These tests show that internal noise can trigger system resonance so as to increase the resonant peak SPL over that of the internal noise generator alone.

Full scale engine tests of a JT9D high bypass turbofan engine (ref. 10) showed that there was internally generated low-frequency noise, and that it could be attenuated by acoustic treatment of the plug used in the core engine. The design frequency of the acoustic absorber was 500 Hz.

The core engine noise prediction parameters used by Gerend (ref. 10) assume that "combustor monopole noise is significant" and "engine gas generator size will influence the magnitude of the core noise." From monopole source theory and the fact that the turbine nozzle is choked in most engines, the combustion noise is found to be proportional to the square of the combustor outlet temperature. The corrected engine mass flow rate is assumed to provide a size correction. The frequency range considered is 50 to 1000 hertz. Gerend's equation for the overall sound pressure level at a 200 foot sideline and 110 degrees from the inlet axis is:

$$\mathrm{OASPL} = C + 10 \log_{10}\left[T_4^2 \left(\frac{P_4}{P_5}\right)^3 \left(\frac{\dot{m}_a\sqrt{\frac{T_4}{t_0}}}{\delta_3}\right)\right] \tag{6}$$

The recommended constant, C, was -15 dB for annular combustors and -6 dB for can or can-annular combustors. For high bypass engines the accuracy of the prediction was quoted as ±5 dB on OASPL.

The recommended spectral shape used by Gerend (ref. 10) was the SAE flight Strouhal jet spectrum given in reference 11 with the peak frequency dependent on the corrected mass flow rate. The equation for the peak frequency is:

$$f_p = \frac{740}{\sqrt{\frac{\dot{m}_a\sqrt{T_4/t_0}}{\delta_3}}} \tag{6.1}$$

A curve is given for directivity that shows a peak at 110 degrees from the engine inlet axis.

In a contractor report for NASA an equation similar to that of Gerend is given by Dunn and Peart of Boeing Commercial Airplane Company (ref. 12). The equation is for the overall sound pressure level (free field) at a one meter radius due to low frequency core engine noise:

$$\mathrm{OASPL} = 76 + a + K + \mathcal{F}(\theta) + 10 \log_{10}\left[\left(\frac{T_4}{T_R}\right)^2\left(\frac{P_4}{P_5}\right)^3\left(\frac{\dot{m}_a\sqrt{\frac{T_4}{t_0}}}{\dot{m}_R\delta_4}\right)(1 - M_o \cos \xi)^{-2}\right] \tag{7}$$

where

$\mathcal{F}(\theta)$ = directivity factor

$(1 - M_o \cos \xi)^{-2}$ = source convection factor

M_o = aircraft Mach number

This equation is based primarily on acoustic tests of full-scale high bypass ratio turbofans.

The spectrum was assumed to follow the Strouhal flight spectrum for jet noise given by SAE (ref. 11). The 1/3 octave sound pressure level spectrum is defined as:

$$\mathrm{SPL}(f) = \mathrm{OASPL} + \mathcal{F}(f/f_R) \tag{7.1}$$

where $\mathcal{F}(f/f_R)$ = flight spectrum shape for jet noise given in reference 11 and

$$f_R = \frac{1850}{(1 + M_o \cos \xi)\sqrt{\frac{\dot{m}_a\sqrt{T_4/t_0}}{\delta_4}}} \tag{7.1.1}$$

is the frequency corresponding to a Strouhal number of 1.0. The directivity curve, $\mathcal{F}(\theta)$ given in reference 12, shows a nearly constant sound pressure level for directivity angles, measured from the inlet axis, greater than 110 degrees. For angles less than 110 degrees the sound pressure level decreases.

Fundamental and Component Research

Strahle, et al. (refs. 13 to 19) has experimentally and analytically investigated open premixed turbulent flames to determine their acoustic properties. The analytical work followed Lighthill's approach (ref. 3). The conclusions drawn are that combustion noise in open flames peaks at low frequencies (250 to 700 Hz) and that its radiated acoustic power is primarily monopole type (the directionality is weak).

The specific equation for acoustic power given by Strahle (ref. 17) for open turbulent premixed hydrocarbon-fueled flames is:

$$\mathrm{OAPWL} = 86.9 + 10\ \log_{10}\left[V_3^{2.68} D_c^{2.84} V_{bL}^{1.35}\left(\frac{F}{1+F}\right)^{0.41}\right] \tag{8}$$

The peak frequency is given by:

$$f_p = 11.83\ V_3^{0.19} D_c^{-0.082} V_{bL}^{0.53}\left(\frac{F}{1+F}\right)^{-0.69} \tag{8.1}$$

Directionality curves are given in reference 17.

Diffusion flames were also investigated by Strahle (ref. 19). The following qualitative conclusions were drawn for both diffusion and premixed flames: "Sound refraction by temperature and velocity discontinuities in a jet-flame configuration are insufficient to explain observed directionality characteristics of turbulent flame noise." "A pronounced effect of temperature discontinuity refraction is the lowering of sound output at higher frequencies for a given behavior of the combustion-noise source." He developed an analytical formula for the acoustic power correlation of turbulent diffusion flame noise that agrees with a given body of experimental data.

Arnold (ref. 9) presented a discussion of premixed steady laminar flames. From the momentum change across the flame front he derived an equation for the steady state pressure change at the flame front. This pressure change is proportional to the rate of heat evolution in the system, and flame speed. A time-dependent upstream velocity was assumed and an argument is made for the amplification of the original upstream disturbance due to the changing pressure during combustion. General discussions of flameholders sonic effects, turbulence, diffusion flames, gaseous and liquid fuel combustion and turbojet engine combustion noise are presented.

Swan and Simcox (ref. 20) present sound pressure level spectra for large and small component combustors with and without the combustion process. The cold flow results show higher peak frequencies (approximately 4000 Hz) than the combustion spectra (500 Hz). The fact that the combustion noise was found to dominate at low frequency is a significant result. The increase in the low frequency combustion noise was accompanied by a decrease in the 4000 Hz sound pressure level. This decrease in the high frequency noise was probably due to the decrease in mass flow rate with increase in temperature from combustion. This effect has also been observed in unpublished data from a hot-flow jet noise rig at the NASA Lewis Research Center.

Abdelhamid et al. (ref. 21) showed experimentally that the far field sound pressure level for combustion augmented jets was substantially greater than that for clean cold jets at either the same velocity or Mach number. The pressure fluctuations in a duct were related to the velocity fluctuations at the exit nozzle of a small scale combustor-nozzle rig. Monopole radiation of sound due to the velocity fluctuations was assumed. The sound pressure level spectrum in the far field was then calculated. Agreement with the measured far field SPL spectrum was reasonably good. The combustion noise was found to be greater in overall sound power and lower in frequency than the jet noise. Cross correlations verified that a large part of the noise observed in the far field originated inside the combustor. The combustion noise level was found to depend upon the fuel/air ratio, the combustor geometry, and the overall mass flow rate through the combustor. The experimental data for spectrum and directivity were given. No prediction techniques were given.

In a two part investigation Plett et al. (ref. 22) first analyzed the noise generated by unconfined turbulent combustion. Based on a one-dimensional approximate solution of the convected wave equation of the reacting gas, he concludes that the "sound pressure level of the radiated wave is proportional to the intensity of the turbulence with the proportionality factor depending on the rate of total heat production in the reaction zone, the Mach number and the frequency of the turbulent fluctuation." He adds that "the most important nondimensional parameter is the ratio of the rate of chemical energy release to the typical convective energy." In the second part of the investigation the effect of noise sources in a confined duct is shown to be important. Tests with struts placed in the duct of a jet noise rig indicate that for low jet velocities the internally generated noise dominates.

Chiu et al. (ref. 23) performed an extensive theoretical analysis of open flames. An equation is derived for the acoustic intensity as a product of a scaling factor and the flame structural correlation function. The structural correlation function is then developed for the wrinkled flame and the distributed reaction models. Strahle compares this theory with his in reference 18.

Noise generation by spray combustion was also investigated in reference 23. An equation for the maximum acoustic intensity is given assuming that "all of the droplets burn simultaneously in the period of the droplet life time." It was pointed out that the excitation of a specific sound mode is largely determined by the interaction of the burning zone and its environment, i.e., liquid spray combustion in a duct may give acoustic instabilities increasing the heat release and hence result in greater acoustic intensity.

Chiu, et al. (ref. 24) investigated analytically and experimentally the effect of combustion in a duct and analyzed the effect of a compressor and turbine on combustion generated noise. Duct resonance was shown to influence the combustion process and the resulting far field sound pressure level spectrum.

Several empirical relations found in the literature have been derived from noise data obtained in different component and engine tests. A summary of the parameters used in equations (1) through (8) is given in table II. No attempt has been made to simplify the parameters or to eliminate their interdependence. It appears that no general agreement has been reached on the important governing parameters.

RECOMMENDED INTERIM PREDICTION PROCEDURE

The interim prediction method given herein is for low-frequency core engine noise. Contributions due to combustion and internal flow are included as core noise. Turbine noise occurs at higher frequencies and is not treated in this report. Low-frequency core noise is predicted by an equation for overall noise power, and by curves giving the directionality and spectrum of the noise.

Evidence indicates that low-frequency core noise is dependent on combustor type and design and on system interaction effects which are unique to the specific engine. However, these effects are difficult to extract from far field noise data taken during engine tests so that special tests are required. As shown by the literature search, only a limited amount of data is available. No definitive choice of a sound power or sound pressure level prediction equation can be made at present due to the general lack of substantiating data. Therefore, the choice of the sound power level prediction equation given here was based on the simplicity of the equation and the fact that it required information that should be readily available.

All symbols are defined in the symbols list given in the appendix of this report.

Sound Power Level Prediction

It is recommended that the equation given by Motsinger (ref. 5, eq. (3) in this report) for the calculation of the overall sound power level be used. The equation in rewritten form is given here:

$$\mathrm{OAPWL} = 56.5 + 10 \log_{10} \dot{m}_a \left[(T_4 - T_3) \frac{P_3}{P_0} \frac{T_0}{T_3} \right]^2 \qquad (9)$$

where $\dot{m}_a$ is in lbm/s (if $\dot{m}_a$ is in units of kg/s divide by 0.4536 to convert to lbm/s) and the pressure and temperatures ratios are in consistent units and the temperature difference is in degrees R.

In reference 5, Motsinger shows that equation (9) fits the data for turboshaft engines, but he states that it overpredicts the noise for turbofan engines. The magnitude of the overprediction is uncertain, so caution is advised in applying this prediction to turbofan engines at this time.

OASPL and Directionality

The recommended directivity for low frequency engine-core noise was taken from reference 12. Figure 51 of that report gives the sound pressure level correction as a function of angular location referenced to the engine inlet axis. That curve has herein been normalized by the overall sound power level obtained by calculating the intensity at each angular location and then integrating over the spherical surface area. The recommended directivity curve normalized to the overall sound power level is given in figure 1 of this report. The direction of maximum low frequency engine-core noise radiation is between 110° and 120° from the engine inlet axis. While the drop off is large for lesser angles, the sound pressure levels at greater angles remains nearly constant.

The overall sound pressure level at any selected angular location (θ) measured from the engine inlet axis can be found as follows:

First the OAPWL is calculated using equation (9). Then the ($OASPL_{\theta}$-OAPWL) parameter is determined for the desired angular location from figure 1. The following equation is then used to calculate the free field overall sound pressure level, OASPL, in the direction θ at any radius r in feet (neglecting atmospheric attenuation):

$$OASPL_{\theta,r} = \underbrace{OAPWL}_{\text{from eq. (9)}} + \underbrace{(OASPL_{\theta} - OAPWL)}_{\text{from fig. 1}} - 20 \log_{10}\left(\frac{r}{3.28}\right) \qquad (10)$$

The recommended directivity curve of figure 1 was determined from data from several types of engines. However, data for the T64 turboshaft engine (ref. 5) shows a definite peak at 120 degrees with a definite decrease at angles greater than 120 degrees. On the other hand, Strahle (ref. 17) points out that the low-frequency noise should have only weak directionality. Until more data are available, some uncertainty will exist in this directivity curve.

Spectrum

Since jet noise and low-frequency core noise have been difficult to separate, reference 12 recommended that the in-flight SAE spectrum for jet noise be used for low-frequency core noise. Lacking more definitive data, the same spectrum is recommended here and, with some modification, is shown as figure 2. The abscissa in figure 2 has been modified from that given in reference 12 by dividing the reference 12 values by 0.4, where 0.4 is the value of the Strouhal number given in reference 12 for the peak sound pressure level. Third-octave SPL spectra can then be found by

$$SPL_{\theta,f,r} = \underbrace{OASPL_{\theta,r}}_{\text{eq. (10)}} + \underbrace{(SPL - OASPL)_{\theta}}_{\text{fig. 2}} \tag{11}$$

As in reference 12, the frequency, neglecting the Doppler shift factor, corresponding to the peak of the spectrum is taken as

$$f_p = 740\sqrt{\frac{1}{\dot{m}_a}\frac{P_3}{P_R}\sqrt{\frac{T_R}{T_4}}} \tag{12}$$

where

$\dot{m}_a$ in lbm/s (if $\dot{m}_a$ is in units of kg/s divided $\dot{m}$ by 0.4536 to convert to lbm/s)

P_R consistent with P_4, 2116 lb/ft^2 (101.3×10^3 N/m^2)

T_R consistent with T_4, 518.7° R (288 K)

The difference between equation (12) and (7.1.1) is a result of changing the SAE flight spectrum to a reference frequency corresponding to the frequency at the flight spectrum peak.

Although the recommended spectrum shape of figure 2 is felt to be reasonable, the validity of equation (12) for the peak frequency is open to question at this time. In studies of open premixed and diffusion flames, Strahle (ref. 17) found a relatively constant peak frequency of 400 hertz. Motsinger's T64 data (ref. 5) also show a 400 hertz peak frequency. It is suggested, at least for the combustion of hydrocarbon fuels, that a peak frequency of 400 hertz be substituted if the peak frequency calculated by equation (12) falls outside the range of 300 to 1000 hertz.

Research in Progress

Extensive work is currently in progress at the General Electric Company on core engine noise under contract from the FAA (Contract No. DOT-FA72WA-3023). Information from this work, when available, should provide insight into the core engine noise problem.

NASA Lewis Research Center is currently investigating relative noise levels of advanced-type combustors. This preliminary work will provide acoustic information that can be used to choose combustor configurations that exhibit the lowest combustion noise levels. This activity includes: (1) in-house tests of advanced combustors in which measurements are taken of pressure fluctuations upstream and downstream of the combustor; and (2) concurrent similar work in the Experimental Clean Combustor Program (NASA Contract NAS3-16830 with General Electric and NASA Contract NAS3-16829 with United Aircraft Corporation, Pratt & Whitney Aircraft Division). The measured sound pressure levels from each of the combustor configurations will be compared in an attempt to determine relative combustion noise levels of advanced-type combustors. This information should aid in selecting future combustor configurations when it has been determined that combustion noise is a dominant problem.

In-house combustion noise work is currently underway at the Lewis Research Center on the TF-34 engine and in the NASA Quiet Engine Test Program. Acoustic measurements during tests of Lewis Research Center's Hot-Flow Jet Noise Facility show evidence of combustion noise; further tests are in progress.

NASA is supporting fundamental combustion noise research through a contract (NAS3-17861) with Georgia Institute of Technology with Dr. Strahle as the principal investigator. This work will extend the open flame work carried out by Strahle et al. (refs. 13 to 19) to ducted burners. NASA is also supporting work at Princeton University through a grant (NGR 31-001-307); with Dr. Summerfield as principal investigator. The three year grant is for fundamental and applied research on core engine noise of aircraft engines. The interrelations among core engine-combustion and jet-noise, and the various attendant flow fluctuations will be studied.

During NASA's Refan Project (contract NAS3-17840) acoustic measurements will be made on the refanned JT8D turbofan engine. Internal pressure fluctuation measurements will be made in the combustor and downstream of the turbine in the core engine duct. Far field noise measurements will be made concurrently.

Under contract to NASA (contract NAS3-17863) the United Aircraft Research Laboratory is studying the internal noise generated by nonmoving surfaces exposed to the flow such as struts and flow splitters.

Recommended Additional Research

The literature search has revealed a lack of information in certain problem areas required to improve the low frequency core engine noise prediction techniques. Generally, the recognized contributors to the low-frequency core engine noise are: the combustion process, scrubbing of nonmoving internal surfaces and the interaction of engine-core components resulting in higher noise levels than each of the engine components would exhibit if tested independently.

The purpose of this section is to recommend more specific research in areas where the state of knowledge allows such recommendations. Emphasis has been placed on research related to combustion generated noise; however, certain recommendations apply equally well to other noise sources. The recommendations of the authors are listed in order of priority.

(1) The first recommendation concerns the transmission of low-frequency combustion noise through the turbine stages of an engine. Impedance, or transfer functions are needed for both single- and multiple-staged turbines. Some work has been done in this area (see ref. 8), but further work is necessary. A similar situation exists for the core engine and fan exhaust nozzle and ducting. Transfer functions are required for various types of nozzles and ducts.

(2) The effect of combustor pressure level on the combustion noise should be determined. Exploratory work is now under way at NASA's Lewis Research Center (LeRC), but more effort is required.

(3) Various current and advanced combustor geometries such as can-annular and annular combustors should be investigated to determine the effect of combustor geometry on combustion noise.

(4) The effect of fuel injection methods and the mixing processes on combustion noise should be determined.

(5) Extensive tests should be made to determine if acoustic measurements made in component rigs, designed for combustion tests, can be applied to the prediction of the combustion noise of similar combustors installed in engines.

(6) The propagation of low frequency noise from a hot core engine jet through a surrounding cold bypass flow needs to be evaluated.

(7) High-bypass duct-burning configurations should be investigated to determine the contribution of duct burning to the engine noise.

(8) Sources of low-frequency noise other than combustion noise should be defined. Scrubbing noise over duct walls, struts, and splitter plates should be investigated further and their relative importance as noise contributors in real core engines determined. Effective means for minimizing their noise generation should be investigated.

(9) Methods for reducing combustion noise generation should be explored, such as stabilization of the flame front.

(10) Efforts should be expanded on determining the interaction effects of combustion, compressor-turbine, and ducting on combustion associated noise.

(11) The contribution to noise produced by entropy or temperature fluctuations passing through the turbine, flowing through the nozzle, and entering the jet free mixing layer, requires further examination.

(12) The effect of nozzle contour and contraction ratio on both the nozzle scrubbing noise and the transmission of internal noise to the far field should be determined.

(13) The effect of jet noise suppressors such as multitubes or lobed configurations on the transmission of internally generated noise should be determined.

(14) Internal noise generated by flow splitting designs of the various jet noise suppressor configurations should be evaluated.

CONCLUDING REMARKS

An interim method for predicting low frequency core engine noise has been recommended. At best the recommended prediction method should be considered as an estimate. It uses empirical curve fits to data from a limited number of engines. The data have been restricted to the lower frequencies, i.e., less than 2000 hertz. The contribution of the internal scrubbing noise at this time cannot be separated from combustion noise. Independent experiments are needed to improve prediction methods.

Use of analytical solutions promises to aid in determining scaling laws and the interaction effects of compressor-turbine, duct, and nozzle on the combustion process. However, at this time analytical methods are not advanced enough to be of great help in developing a general solution to the combustion noise problem. Work in progress by a number of companies and universities promises better insight into the low-frequency core engine noise problem in the near future. It is expected that updating of the recommended prediction method will be a continuing process for some time to come.

It has been shown that jet noise decreases with forward velocity and that if the jet noise is reduced by forward velocity the internally generated noise floor may be reached (ref. 25). However, the question that at this time cannot be answered with any degree of certainty is: How significant a problem does combustion noise present in current or near future aircraft engines if jet-generated noise is minimized?

There can be no doubt that combustion noise can be loud enough to create a noise problem. Open flames in commercial furnaces having high heat release rates create significant combustion noise. The sizable heat release rate of current aircraft engines are large enough to expect significant combustion noise. However, when combustion is enclosed in a chamber, as in an aircraft engine, the prediction of the external far field noise becomes far more difficult. The effect of the combustor walls on the combustion process itself as yet has not been determined. Furthermore, in many of today's aircraft engines the turbine stator blades (nozzles) operate close to or at a choked condition. It is uncertain how much of the low-frequency sound can pass through the turbine assembly and how the reflected sound effects the combustion process itself. Resonance also occurs in combustion chambers, and this could drive the noise level still higher, thus increasing the sound in the far field.

Another source of sound that has received little attention in the literature is entropy noise, i.e., that noise generated when a hot spot or time varying temperature wave travels through a velocity gradient. Dr. Strahle (ref. 17) discussed entropy noise, but an evaluation of its contribution has yet to be made. The possibility of combustion-associated disturbances creating a secondary sound source in the jet external to the exhaust nozzle cannot be overlooked. The literature seems to lean heavily on the jet noise spectrum for an approximation for the combustion or core noise spectrum. This might suggest that the entropy noise and jet noise are, at least partially, interdependent.

From this report it is apparent that the state of the art for predicting core engine combustion noise in the far field is in its infancy.

APPENDIX - SYMBOLS

[U.S. Customary Units are listed first with S. I. Units in parentheses.]

A	area, ft^2 (m^2)
a	constant, correction for type of combustor, ref. 12
B	acoustic transmission coefficient, dimensionless
C	constant
D	diameter, ft (m)
F	ratio of fuel to airflow rates
f	frequency, Hz
$\mathcal{F}(\ )$	functional notation
K	constant, depending on engine, ref. 12
L	length, ft (m)
M	Mach number
$\dot{m}$	mass flow rate, lbm/s (kg/s)
N	number of turbine stages
OAPWL	overall sound power level re 10^{-13} watts
OASPL	overall sound pressure level, re 20 $\mu N/m^2$
P	total pressure, lb/ft^3 (N/m^2)
p	static pressure, lb/ft^2 (N/m^2)
r	radial distance, ft (m)
SPL	sound pressure level for 1/3 octave band center frequency re 20 $\mu N/m^2$
T	total temperature, ^oR (K)
t	static temperature, ^oR (K)
V	velocity, ft/s (m/s)
W	acoustic power, watt

δ ratio of total pressure to atmospheric or reference pressure, P/p_0

θ directivity angle referenced to engine inlet axis, deg

ξ angle between direction of aircraft motion and sound propagation path, deg

Subscripts:

a	air
ann	combustor, annular type
b	flame speed
c	combustor
can	combustor, can type
d	directivity factor
e	equivalent
f	fuel or frequency
L	laminar
N	nozzle
p	peak
R	reference
r	radial distance
S	spectrum shape
T	turbine
0	atmospheric or free stream
3	combustor inlet station
4	combustor exit station
5	turbine exit station
θ	angular location

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TABLE I. - LITERATURE SEARCH SURVEY

Reference		Acoustic power level	Sound pressure level	Spectrum	Directivity
Bushell	1		D	D	
Marshall	2		D	D	D
Ho & Tedrick	4	D		D	
Motsinger	5	D		D	D
Neitzel	7		D		
Grande	8	T			
Arnold	9	T			
Gerend	10		D	D	D
Dunn	12		D		
Strahle	13	T			
Strahle	14	T			
Strahle	15	T,D		D	D
Shivashankara	16	T,D		D	D
Strahle	17	T		D	D
Strahle	18	T,D		D	D
Strahle	19	T			
Swan	20			D	
Abdelhamid	21		T	D	D
Plett	22		T	D	D
Chiu	23	T			
Chiu	24		T,D	D	

T - Theoretical analysis
D - Empirical data

TABLE II. - COMPILATION OF PARAMETERS FOUND IN THE LITERATURE AND USED TO COMPUTE LOW-FREQUENCY CORE NOISE

Equation number	Reference number	Compute	Temperature	Pressure	Mass flow rate	Fuel mixture	Velocity	Dimension
(1)	4	OAPWL	$\frac{(T_4 - T_3)^2}{T_4}$	P_4		$(1 + F)^2$	V_4	D_e
(2)	4	OAPWL	$\frac{(T_4 - T_3)^4}{T_4^2}$	P_4^2		$(1 + F)^4$	V_4^2	D_e^2
(3)	5	OAPWL	$\left[\frac{(T_4 - T_3)T_o}{T_3}\right]^2$	$\left(\frac{P_3}{P_0}\right)^2$	$\dot{m}_a$			
(4)	7	OASPL	$(T_4 - T_3)^2$	$\left(\frac{P_3}{P_0}\right)^{1.3}$	$\dot{m}_a$			
(5.3)	8	OAPWL	$\left(\frac{T_4 - T_3}{T_0}\right)^2 \frac{1}{T_3^3}$	$\frac{P_4}{P_0}$	$\frac{m_a\sqrt{T_4/t_0}}{\delta_4}$	$(1 + F)$	$V_b^2V_3$	$\frac{DL}{D_4^2}$
(6)	10	OASPL	T_4^2	$\left(\frac{P_4}{P_5}\right)^3$	$\frac{\dot{m}_a\sqrt{T_4/t_0}}{\delta_3}$			
(7)	12	OASPL	$\left(\frac{T_4}{T_R}\right)^2$	$\left(\frac{P_4}{P_5}\right)^3$	$\frac{m_a\sqrt{T_4/t_0}}{\delta_3}$			
(8)	17	OAPWL				$\left(\frac{F}{1 + F}\right)^{0.41}$	$V_3^{2.68}V_{bL}^{1.35}$	$D_c^{2.84}$

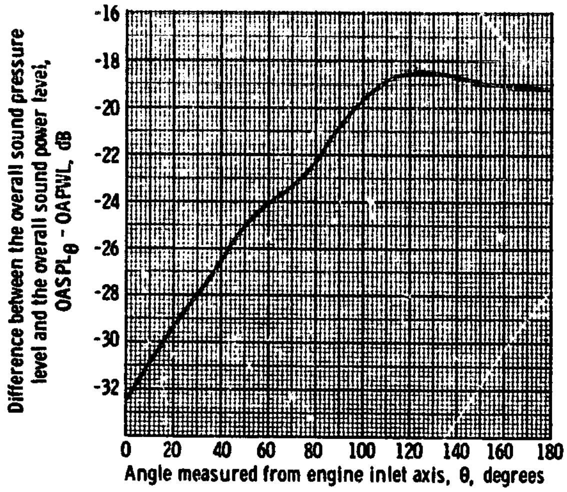

Figure 1. - Directivity of low-frequency core noise in terms of free field OASPL at one meter radius as a function of angular location, θ. OAPWL, dB reference 10^{-13} watt; OASPL, dB reference 0.00002 N/m^2.

E-8154

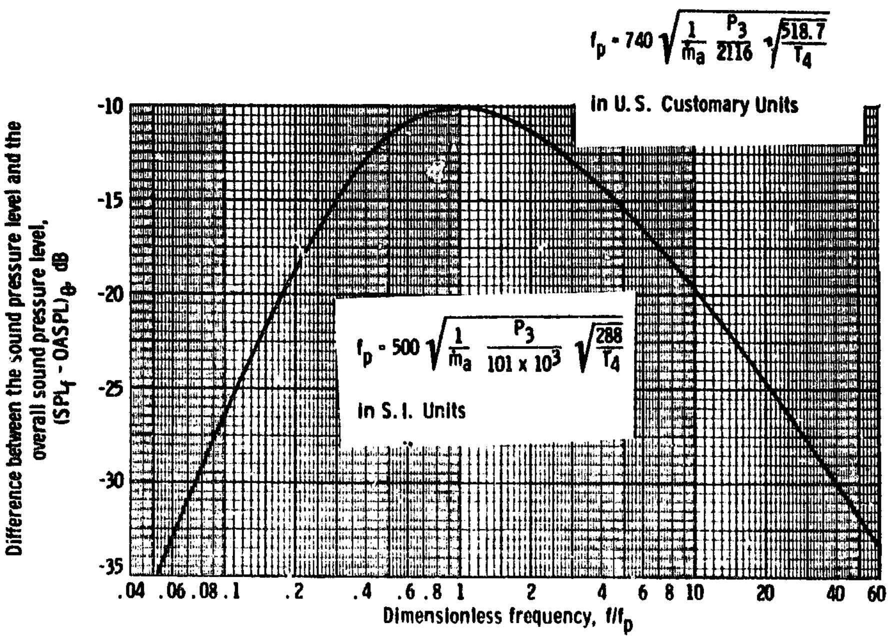

Figure 2. - Low-frequency core noise spectrum shape interms of one-third octave sound pressure level as a function of dimensionless frequency.