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Semi-Empirical Modeling and Prediction of Direct Combustor Noise

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Semi-Empirical Modeling and Prediction of Direct Combustor Noise

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Abstract

Due to turbofan design trends, advances in fan-noise-mitigation techniques, and expected aircraft configuration changes, the impact on overall airport community noise from certain aircraft-propulsion-noise sources, such as fan and jet noise, will be reduced at all certification points in the future. The situation with regard to turbofan-core noise is less clear however. Combustor noise in particular—which presently is an important core-noise component, but not dominant from an overall noise perspective—could become more prominent in upcoming high-power-density core designs. Its detailed source structure in the combustor, including the indirect combustor-noise mechanism, and the effects of the propagation path through the engine and exhaust nozzle need to be better understood. This report reviews the current status of modeling and prediction of direct combustor noise. This work is carried out under the NASA Advanced Air Vehicles Program, Advanced Air Transport Technology Project, Aircraft Noise Reduction Subproject.

1 Introduction

Commercial air traffic is expected to significantly increase in the future and subsonic transport-aircraft community noise needs to be further reduced in order to minimize the associated negative environmental and economic impacts. For current-generation engines, noise generated in the core by components such as the combustor, the turbine, and (to a much lesser extent) the compressor can be significant contributors to the overall noise signature at low-power conditions, typical of approach flight. Of these core-noise sources, combustor noise is the one potentially most negatively affected, i.e. increased in strength, by the current turbofan design trend toward ultra-high bypass-ratio engines with large fans and small cores. Furthermore, the relative importance of the propulsion-noise sources (fan, jet, and core) is likely to change as aircraft and propulsion-system designs evolve. System-level noise studies for concept subsonic transport aircraft [1–4] have shown that jet noise will no longer be a significant noise source due to the ultra-high bypass ratios that are envisioned. The dominating noise sources will originate (in alphabetical order) from the airframe, the combustor, and the fan, with airframe noise being an issue mainly at approach. The proposed lower fan-pressure-ratio turbofans, with reduced fan-tip speeds, and advanced fan-noise-reduction strategies will lessen the overall impact of fan noise. Consequently, the relative importance of combustor noise will be increased at all engine-power levels. [1,2]

The present report is concerned with combustor noise, which is a low-frequency broadband contributor to the noise generated in the turbofan engine core. The terminology 'combustor noise' purposely is used here, rather than the more traditional 'combustion noise,' to indicate the rich structure of this engine-internal noise source. Even though this propulsion-noise component has many aspects in common with open-flame combustion noise, it is generated in a confined geometry at a higher pressure, it is modified by resonances and transmission effects, and it also has an indirectly produced element. Direct measurement of turbofan-engine combustor noise is difficult because of the presence of jet noise in the frequency range of interest. Since flight effects reduce jet noise more than combustor noise, [5] combustor noise can be a significant contributor to aircraft in-flight noise but may be masked by jet noise under the corresponding static-engine test conditions. Summaries of the current status of combustor-noise source modeling, as well as historical perspectives, are given in the review chapters by Mahan and Karchmer, [5] Candel et al., [6] Hultgren et al. [7] (see also Hultgren [8]), Duran et al., [9] Dowling and Mahmoudi, [10] and Ihme. [11] Progress must be made in the modeling and understanding of combustor noise, ultimately incorporating effects of various lean-burn concepts for reduced emissions, in order to develop improved core-noise prediction tools that can be used to evaluate the acoustic

implications of new advanced-core designs. The current report provides a further discussion of the basis for, and a brief summary of, existing semi-empirical methods for the prediction of direct combustor noise.

2 Combustor Noise

Combustor noise consists of both direct and indirect components. The frequency range for either type is set by the unsteady combustion process and the peak value is generally observed to fall in the range of 400–500 Hz.[7] The unsteady combustion process is the source of pressure, entropy, and vorticity fluctuations. Only a fraction of the pressure disturbances caused by the unsteady heat release in the combustor are acoustic pressure fluctuations, with the balance being hydrodynamic unsteadiness. The former is what is referred to as direct combustor noise. Its spectrum can be modified by the combustor geometry as well as pressure feedback on the unsteady combustion process itself. The direct combustor noise is reduced due to transmission effects during its propagation through the turbine stages. The combustor entropy (temperature) fluctuations are convected downstream with the local mean velocity and are converted to acoustic pressure fluctuations in the turbine and other regions where flow properties change rapidly. This is the indirect process of turbomachinery combustor-noise generation. This mechanism occurs at all turbine stages and potentially is very effective. The indirect noise occurs in the same basic frequency range as the direct noise, but their spectral-distribution shapes could be quite different and both are affected by the propagation through the engine core. Figure 1 illustrates the dual paths of combustor noise. Note that the direct and indirect noise contributions are correlated at the source because both are caused by the unsteady heat addition. The relative importance of the two combustor-noise components is still an unresolved issue.[12–17]

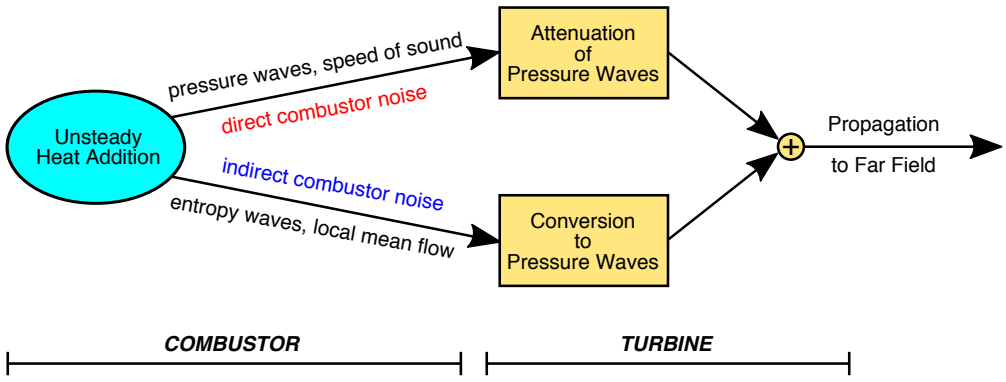

Figure 1. Dual paths for turbofan combustor noise

The essential ingredients in predicting combustor noise are:[8,18,19] first, the understanding of the fluctuating pressure and entropy fields, i.e., the source characteristics, inside the combustor and, second, their further propagation and interaction with turbine stages through the turbofan core. In particular, the combustor unsteady entropy field and its propagation and interaction with the turbine are still areas of emerging understanding and active research. The fluctuating pressure field in the combustor is comparatively better understood, but this situation might change with the emergence of premixed lean combustor designs.

3 Modeling and Prediction of Direct Combustor Noise

Efficient low-order noise modeling and prediction techniques are essential for system-level community-noise projections and engineering trades at the preliminary/conceptual design stages of aircraft-propulsion systems. In general, the semi-empirical methods for turbofan core/combustion-noise prediction in use today have their roots in developments that mainly took place during the 1970s. These early advances in core/combustion-noise modeling are discussed in the review chapter by Mahan and Karchmer[5], and references therein. The approaches used can broadly be divided into fundamental and applied research avenues.

From a fundamental-research perspective, it was commonly postulated that the noise generated in an aircraft combustor is closely related to that of an open flame. Theories and models for open-flame noise were developed and validated by correlating observations with variations in physical parameters. Successively more complex situations were then considered such as the effects of ducting on flame noise and finally combustor-rig experiments. References and a further discussion can be found in the comprehensive review article by Strahle[20] and in Hultgren et al.[7] It was found that the radiated sound from an open turbulent flame has a relatively universal spectrum. On an 1/3-octave basis, it gradually rises to a peak somewhere in the 300 to 600 Hz frequency range and monotonically falls off thereafter.

In principle, to model the direct combustion noise emanating from an aircraft engine, an understanding is needed of the acoustic pressure field inside a combustor, how it is affected by changes in engine-operational parameters, and finally its further propagation and interaction with turbine stages through the engine-internal flow path. Inside actual combustors, operating either in rigs or engines, the confined geometry leads to the existence of a multitude of acoustic modes, (m,n), where m and n denote the azimuthal and radial mode numbers, respectively. These modes are driven by the unsteady heat release of the combustion and their amplitudes are generally statistically independent. However, for the common situation where there is no significant global swirl present in the combustor, then modes with opposite azimuthal mode numbers, but identical radial mode numbers, can be taken to be of the same random amplitude. The plane wave mode $(0,0)$ can always propagate, but the other modes can only propagate if the frequency is higher than a mode-dependent cut-off/cut-on value. If the frequency is less than this value, the mode is evanescent.

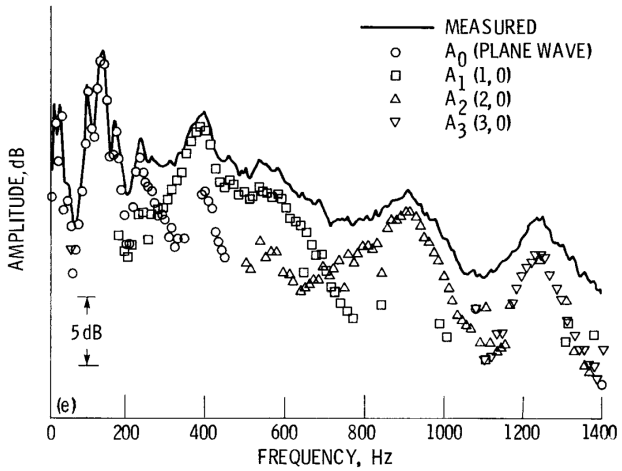

Figure 2. Modal decomposition of YF102 combustor pressure at conditions corresponding to 60% speed; from Karchmer[18] Fig. 7(e)

Karchmer[18] and, more recently, Royalty and Schuster[21] have documented the modal structure of the unsteady pressure field in aircraft-engine non-premixed combustors. The former[18] utilized a ducted full-scale YF102 annular-combustor in a rig experiment, whereas the latter[21] analyzed measurements obtained for a particular EVNERT[23] configuration of the TECH977 research turbofan engine in which the fan was replaced by a water brake in order to remove fan sources from the total noise signature. Karchmer[18] measured unsteady pressures using six probes arranged circumferentially in the outer annular wall of the combustor liner at a single axial location for several operating conditions corresponding to engine-power settings in the 30 through 60 percent range. Karchmer's[18] modal-decomposition result at an operating condition roughly corresponding to 60 percent YF102-engine power is reproduced here as Fig. 2. In the EVNERT[21,23] no-fan configuration, the combustor internal instrumentation consisted of a circumferential array of 16 equally-spaced pressure probes near the combustor exit. Figure 3 here reproduces their results for the approach and flight-idle conditions of 60 and 48 percent corrected fan speed, respectively.

These investigations both showed that the acoustic pressure spectrum at the exit of a real combustor has a multi-peak nature/structure and that individual modes could be uniquely identified within separate frequency bands. The plane-wave $(0,0)$ mode dominates for the lowest frequencies up to the cut-on frequency of the $(\pm 1,0)$ mode pair. For higher frequencies, the most recently cut-on mode, or mode pair, dominates the unsteady pressure field; that is,

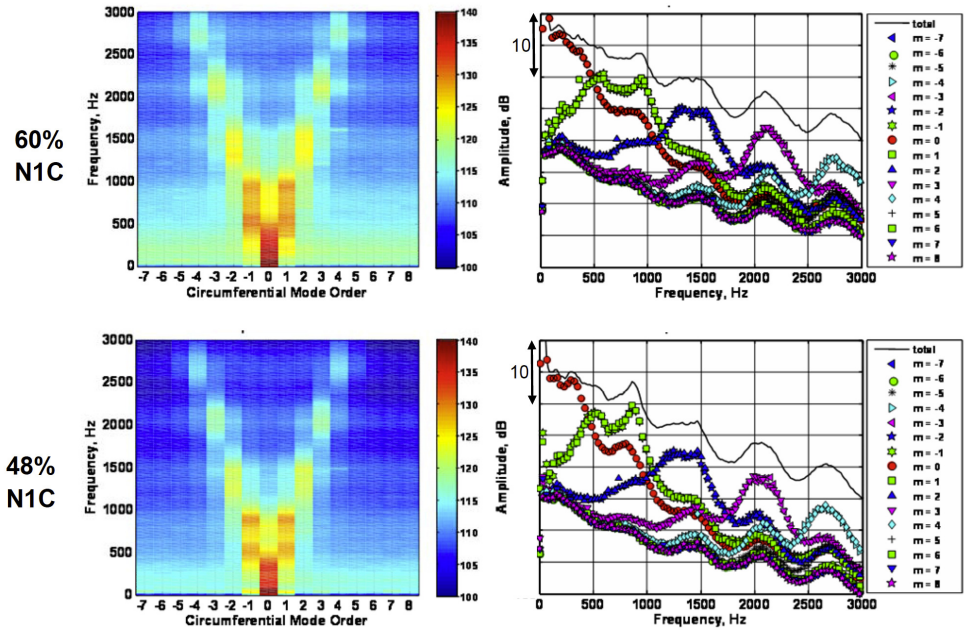

Figure 3. Modal decomposition of Honeywell TECH977 combustor pressure; from Royalty and Schuster[21] Fig. 19

successively higher azimuthal modes dominate with increasing frequency. Radial modes, $n \neq 0$, in general, do not appear to play a role due to their cut-off/on frequency values being higher than the direct-combustion-noise frequency range. Similar results were obtained by Krejsa and Karchmer[22] for the core-nozzle unsteady pressure field of an AiResearch QCGAT turbojet engine. They found that the plane-wave $(0,0)$ mode was dominant up to about 800–900 Hz at the tail-pipe exit. Their tailpipe-exit results, at the highest power setting of the test, are partially reproduced here in Fig. 4.

Karchmer[18] concluded that the basic source generating mechanism itself has a relatively smooth and featureless spectral shape, but the geometry of the combustor is extremely effective in promoting resonant modes and thus modifying the unsteady pressure spectrum in the combustor. This conclusion was echoed by Schuster and Lieber,[19] who also suggested that the far-field spectrum can be thought of as the product of a single-peak broadband combustion noise spectrum, that is related to the spectrum of an open turbulent flame, and a spectral transfer function that represents the resonance and propagation effects in the engine core and exhaust. They[19] observed that "it is unre-

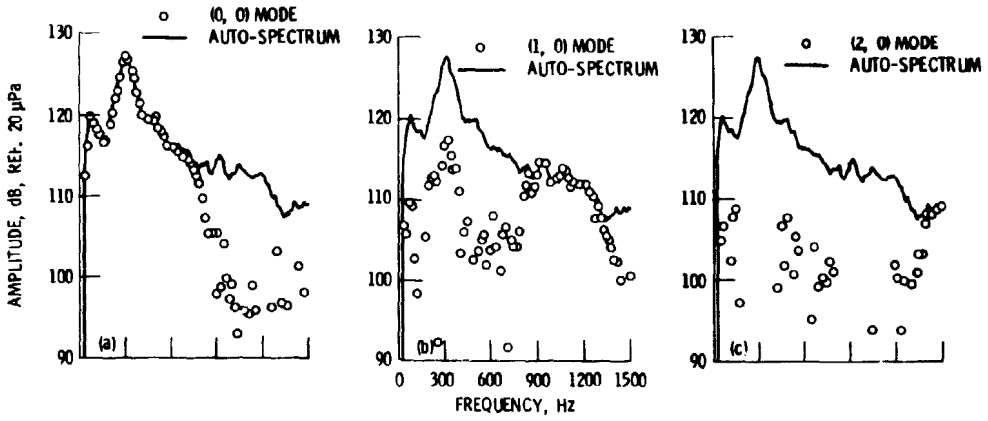

Figure 4. Modal decomposition of QCGAT core-nozzle-exit pressure; from Krejsa and Karchmer[22] Fig. 9(a–c)

alistic to expect that a single transfer relation will be generally applicable to the wide variety of combustor, turbine and exhaust geometries." However, as pointed out by Mahan and Karchmer,[5] the higher modes are often cut-off in the smaller diameter turbine and core nozzle and are thus unable to propagate efficiently through the engine to the surroundings. As a consequence, it is generally accepted that the direct combustion noise emanating from turbofan engines is dominated by the plane-wave mode and therefore effectively has a single-peak spectrum. That is, spectral peaks associated with the non-plane-wave modes are in practice reduced to such an extent that their amplitudes are well below the dominant plane-wave peak as well as the levels of other propulsion-noise components. For current generation engines, jet noise in particular dominates even the peak value of the direct combustion noise except at low engine-power settings. Figure 5 conceptually depicts the expected change in the direct-combustor-noise spectrum as the acoustic waves propagate through the engine-internal flow path to the exterior for a turbofan engine equipped with a singular annular combustor. The situation can be different for auxiliary power units (APUs) due to their low exit velocities and often long tailpipes, however. The low exit velocities significantly reduce the importance of jet noise and make combustion noise the dominant low-frequency exhaust noise source for APUs. Schuster and Lieber[19] also found that APU far-field combustor-noise peak frequencies correlated strongly with the exhaust duct length and mean exhaust duct sound speed according to plane-wave radiation from an unflanged circular pipe.

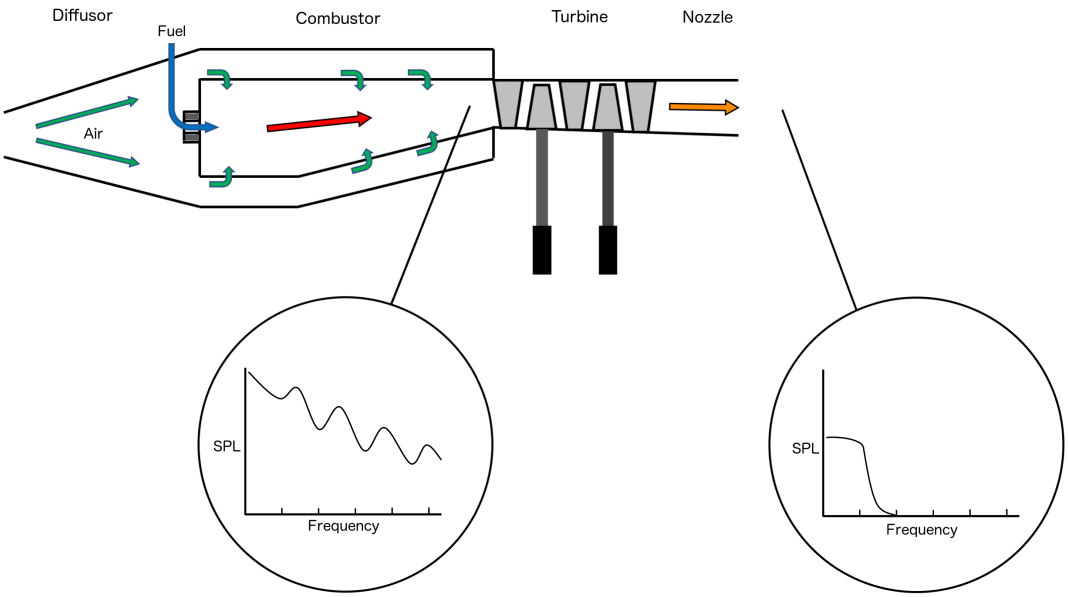

Figure 5. Conceptual narrowband-spectrum change as the direct-combustor noise propagates from the combustor to the exterior

A substantial amount of applied research, relating measured real-engine noise levels to operating parameters, was published in the open literature during the 1970s. This work, eg. Ref. 15,24–27, was mainly carried out by aircraft-engine company researchers in the United States, often with support from the Department of Transportation/Federal Aviation Administration (DOT/FAA) or the National Aeronautics and Space Administration (NASA). Largely informed by the physical understanding obtained from the early fundamental studies briefly described above, the General Electric Company[a] (GE)[27] and Pratt & Whitney (PW)[26] determined semi-empirical, engine-manufacturer-specific formulas for the total radiated acoustic power, with model coefficients/constants determined using rig testing of isolated components and full-engine static-test data. These models[26,27] also included simple frequency-independent formulas to account for the turbine attenuation of the broadband noise originating in the combustor. The decoupled far-field directivity and spectral distribution were obtained empirically from full-engine static tests.

[a]Now simply named GE

In general, each of these acoustic-power prediction tools[26,27] showed good agreement with data from the engine manufacturer that developed the method, but not necessarily with data from other companies.[5,28] Zuckermann[28] suggested that the need for distinct models may be caused by differences in burner design philosophy. A common difficulty encountered during the development of these methods was that the measured total far-field acoustic signature in static-engine tests normally had to be adjusted by subtracting the low-frequency jet noise using an appropriate model to reveal the core noise. This is because, in the absence of forward-flight effects, combustor noise is not a dominant noise source even at low engine-power settings. This makes the quality of the results somewhat dependent on the accuracy, particularly at low frequencies, of the jet-noise model used.

In 1980, The Society of Automotive Engineers International (SAE) adopted the method developed by GE[27] as the SAE ARP876[29] technical standard for the prediction of noise from conventional combustors installed in gas-turbine engines. This semi-empirical direct-combustion-noise model[27,29] still forms the kernel of the core-noise module in the NASA Aircraft Noise Prediction Program (ANOPP)[30,31] and it is referred to therein as the SAE method. The NASA-ANOPP core-noise module also contains several extensions to the GE/SAE formulation. The GE/SAE, the PW, and the NASA-ANOPP methods are further discussed in Sections 4 and 5 below. Tam[32] provides a further discussion of the spectral distributions used in the methods as well as a suggestion for an improved universal far-field spectrum for direct combustion noise.

4 A Common Form of the Semi-Empirical Models

A common feature of most of the semi-empirical models for direct combustor noise is that the far-field directivity and spectral distribution are decoupled. In this case, the (dimensional) combustor-noise mean-square pressure in each 1/3-octave band (b), in the absence of atmospheric attenuation, is given by

$$< p'^2 >^{(b)} = \frac{\rho_o c_o \Pi D(\theta) S(f_b)}{4\pi r_o^2} \tag{1}$$

for a static-engine test, where r_o is the distance between the source and the observer and ρ_o and c_o are the ambient density and speed of sound at the observer location. Π is the total radiated acoustic power by the source. $D(\theta)$ is a directivity function that depends only on the polar angle θ and satisfies the normalization condition

$$\int_0^\pi D(\theta)\sin\theta \mathrm{d}\theta = 2\,. \tag{2}$$

$S(f_b)$ is a spectrum function satisfying

$$\sum_b S(f_b) = 1 \tag{3}$$

and f_b is the 1/3-octave-band center frequency. Note that the total radiated acoustic power at the distance r_o from the source

$$\int_A \frac{\sum_b < p'^2 >^{(b)}}{\rho c} \mathrm{d}A = \Pi\,, \tag{4}$$

where $\mathrm{d}A = r_o^2 \sin\theta \mathrm{d}\theta \mathrm{d}\phi$, with ϕ denoting the azimuthal angle. That is, in the absence of atmospheric attenuation, the total radiated acoustic power Π is preserved as the acoustic waves propagate towards the observer.

The sound pressure level $SPL^{(b)}$ in a 1/3-octave frequency band, the overall sound pressure level *OASPL*, and the overall power level *OAPWL* are given by

$$SPL^{(b)} = 10\log(< p'^2 >^{(b)} / p_{ref}^2)\,, \tag{5}$$

$$OASPL = 10\log(\textstyle\sum_b < p'^2 >^{(b)} / p_{ref}^2) = 10\log[\rho_o c_o \Pi D(\theta)/4\pi r_o^2 p_{ref}^2]\,, \tag{6}$$

$$OAPWL = 10\log(\Pi/\Pi_{ref})\,, \tag{7}$$

where $p_{ref} = 2\times10^{-5}$ Pa and $\Pi_{ref} = 1\times10^{-12}$ W if SI units are used. Note that some authors use *PWL* to denote the overall power level and also simply refer to it as the power level. Guided by Ref. 29, here

$$PWL^{(b)} = OAPWL + 10\log S(f_b) \tag{8}$$

denotes the acoustic power radiated in all directions associated with a given 1/3-octave frequency band (b), however, and is referred to as the power-level spectrum.

4.1 *Atmospheric Attenuation*

Acoustic waves are attenuated due to atmospheric absorption as they propagate from their source to the observer. A detailed discussion of the physics of atmospheric attenuation is beyond the scope of this report, but see Zorumski [30] and the technical standards SAE ARP866A [33] and ANSI S1.26-1995 [34] for more details. The sound attenuation depends on the frequency as well as the mean temperature, pressure, and humidity the wave encounters during its propagation, and is commonly expressed as an absorption coefficient (dB/m). Noise prediction codes normally determine and tabulate the atmospheric properties as functions of altitude, which allows the absorption coefficient to be described as a function of frequency and altitude. It turns out [30] that the attenuation can be expressed in terms of an average absorption coefficient, i.e.

$$SPL^{(b)}_{actual} = SPL^{(b)} - \bar{\alpha}^{(b)} r_o \,, \tag{9}$$

where $\bar{\alpha}^{(b)}$ is the average absorption coefficient for the 1/3-octave frequency band (b). The subscript 'actual' indicates that the actual conditions at the source, along the propagation path, and at the observer are accounted for. The actual overall sound pressure level at the observer location can then be computed as

$$OASPL_{actual} = 10\log\left[\sum_b 10^{(SPL^{(b)}_{actual}/10)}\right] . \tag{10}$$

4.2 *Meteorological Correction*

Sometimes, but not always, it is desirable to convert measured or predicted acoustic data at actual conditions to those that would have been obtained at particular reference conditions. Two commonly used reference atmospheric conditions are the sea-level standard (SLS) conditions and the SLS+10 conditions. The first is the international standard day conditions at sea level ($P_{SLS} = 101.325$ kPa, $T_{SLS} = 288.15$ K, $\rho_{SLS} = 1.225$ kg/m^3, $c_{SLS} = 340.294$ m/s, in SI units). [35] The second is broadly used for aircraft noise certifications (Ref. 36, Appendix B, Section B36.7) and airport community noise levels. In this latter case, $P_{SLS+10} = 101.325$ kPa and $T_{SLS+10} = 298.15$ K, i.e. the temperature is 10 K higher. The relative humidity is also specified to be 70 percent for both conditions.

The sound pressure level $SPL^{(b)}$ in an 1/3-octave frequency band (b) can be converted from actual to, say, SLS conditions as follows:

$$SPL^{(b)}_{SLS} = SPL^{(b)}_{actual} + C_1 + C_2 + C_3 \,, \tag{11}$$

where C_1, C_2, and C_3 are corrections accounting for three distinct physical effects. The first,

$$C_1 = 10\log\frac{(\rho c)_{SLS}}{\rho_o c_o} = 10\log\left(\frac{P_{SLS}}{P_o}\sqrt{\frac{T_o}{T_{SLS}}}\right) , \tag{12}$$

corrects for the observer-location impedance difference between actual and SLS conditions. The second,

$$C_2 = 10\log\frac{\Pi_{SLS'}}{\Pi_{actual}} = OAPWL_{SLS'} - OAPWL_{actual} \,, \tag{13}$$

accounts for changes in the radiated acoustic power by the source due to changes in the source-location conditions. SLS' denotes the conditions at the source corresponding to SLS conditions at the observer location. For a monopole source, of fixed strength, this correction would read

$$C_{2,monopole} = 10\log\left[\left(\frac{\rho}{c}\right)_{SLS'}\left(\frac{c_s}{\rho_s}\right)\right] = 10\log\left[\frac{P_{SLS'}}{P_s}\left(\frac{T_s}{T_{SLS'}}\right)^{3/2}\right] , \tag{14}$$

where the subscript 's' denotes actual ambient conditions at the source location. However, the situation is more complicated for a real-engine noise source. In that case the change in radiated acoustic power needs to be determined using a noise-source model as well as taking into account any changes in the engine-operational parameters due to the change in ambient conditions. The third,

$$C_3 = \left(\bar{\alpha}^{(b)}_{actual} - \bar{\alpha}^{(b)}_{SLS}\right) r_o \,, \tag{15}$$

corrects for the different atmospheric attenuation occuring at SLS and actual conditions, respectively. The overall sound pressure level, $OASPL_{SLS}$, is then computed using a formula analogous to Eq. (10).

4.3 *Forward-Flight Effects*

For aircraft noise-certification purposes, or airport community-noise assessment, forward-flight effects must be included in the noise-prediction models. Only a rudimentary description is given here of the two modifications needed to accomplish this since the primary focus of the current report is the prediction of direct-combustor noise under static-engine conditions. The first correction is to account for the convective amplification of the emitted sound due to the movement of the aircraft. Since direct-combustor noise is of relatively low frequency, the simplifying assumption to treat the moving source as a monopole source traveling at a quasi-steady speed is commonly made, but see Dowling [37] for a discussion of the intricacies and difficulties involved in modeling flight effects on real aircraft-noise sources. With this assumption, the effective in-flight sound pressure level $SPL^{(b)}_{flight}$ emitted by the source in each 1/3-octave frequency band (b) is given by

$$SPL^{(b)}_{flight} = SPL^{(b)}_{static} - 40\log(1 - M_s\cos\theta)\,, \tag{16}$$

where $SPL^{(b)}_{static}$ is the corresponding static sound pressure level and M_s is the Mach number of the source, i.e. the aircraft, with both either for actual or standard conditions.

Secondly, the observed frequencies are related to the frequencies emitted in the source frame of reference through,

$$f^{(b)}_o = \frac{f^{(b)}_s}{1 - M_s\cos\theta}\,, \tag{17}$$

where $f^{(b)}_o$ is the Doppler-shifted frequency registered by the stationary observer and $f^{(b)}_s$ is the center frequency corresponding to the 1/3-octave frequency band (b) in the source frame of reference.

5 Existing Semi-Empirical Models

5.1 *The GE/SAE Model*

In 1980, The Society of Automotive Engineers International (SAE) adopted the method developed by GE [27] as the SAE ARP876 technical standard [29] for the prediction of noise from conventional combustors installed in gas-turbine engines. This standard was the culmination of a roughly ten-year effort with contributions from major American and European companies. The standard (Ref. 29, Appendix D) also contains a background history of its development as well as an extensive list of relevant references.

In the GE/SAE direct-combustor-noise model,[27,29] the total radiated acoustic power is given by

$$\Pi = 10^{K/10} c_r^2 \dot{m}_c \left(\frac{T_{t,ce} - T_{t,ci}}{T_{t,ci}}\right)^2 \left(\frac{P_{t,ci}}{P_r}\right)^2 F_{TA}\,, \tag{18}$$

where F_{TA} is a turbine attenuation, or loss, factor and is given by [25,29]

$$F_{TA} = F_{TA,GE} = \left(\frac{\Delta T_{des}}{T_r}\right)^{-4}. \tag{19}$$

The constant $K = K_{SAE} = -60.53\ldots$, Ref. 29. $\dot{m}_c$ is the mass flow rate into the combustor, $T_{t,ci}$ and $T_{t,ce}$ are the total temperature at the combustor inlet and exit, $P_{t,ci}$ is the total combustor-inlet pressure, and P_r and T_r are the reference (static) pressure and temperature. The reference state, denoted by the subscript 'r', is the sea-level standard conditions, i.e. the SLS conditions described above. ΔT_{des} is the design-point temperature drop across the turbine. If this is not known, the temperature drop at takeoff can be used. Note that the acoustic transmission loss is independent of both the frequency and the engine operating condition. The spectrum and directivity functions are defined in SAE ARP876. [29] In particular, the spectrum is the SAE single-peak in-flight jet-noise spectrum with the peak frequency fixed at 400 Hz. Equation (18), with $K = K_{SAE}$, combined with Eq. (19) for the turbine-transmission loss, will be referred to as the SAE formulation herein.

5.2 *The Pratt & Whitney Model*

Also during the latter half of the 1970's, researchers at Pratt & Whitney [15,26] developed a semi-empirical prediction method for direct combustor noise. They derived models for the total acoustic power level, turbine coupling/

transmission losses, and peak frequency; and they empirically determined model constants, the directivity pattern, and a universal normalized spectral distribution using a range of burner-rig and full-scale static engine tests.

In this model, the total radiated acoustic power is given by[5,26]

$$OAPWL = 10\log_{10}\left[\frac{1}{N_f}A_c^2 P_{t,ci}^2\left(\frac{\dot{m}_c\sqrt{T_{t,ci}}}{P_{t,ci}A_c}\right)^4\left(1+\frac{h_{PR}F_{st}}{c_p T_{t,ci}}\right)^2 F_c^2\right] + 132 + 10\log_{10}(F_{TA}), \tag{20}$$

where N_f is the number of fuel nozzles in the combustor, A_c is the combustor cross-sectional area, h_{PR} is the constant-pressure fuel heating value, c_p is the specific heat at constant pressure, F_c and F_{st} are the combustor fuel-air ratio and the stoichiometric fuel-air ratio; and as earlier $\dot{m}_c$, $P_{t,ci}$, and $T_{t,ci}$ are the mass flow rate and total pressure and temperature at the combustor inlet. The frequency-independent, turbine-attenuation factor is given by

$$F_{TA} = F_{TA,PW} = \frac{4\zeta(\ell/\pi D)}{(1+\zeta)^2} = \frac{0.8\zeta}{(1+\zeta)^2}, \tag{21}$$

where $\zeta = \rho_{te}c_{te}/\rho_{ti}c_{ti} \approx (P_{t,te}/P_{t,ti})\sqrt{T_{t,ti}/T_{t,te}}$, with the subscripts '$te$' and '$ti$' indicating turbine exit and inlet, is the ratio of the characteristic impedances across the turbine. ℓ is the circumferential correlation length of the direct-combustor noise at the combustor-turbine interface, D is the outer diameter of this interface. Mathews and Rekos[26] found that combustor-rig and transmission-loss-corrected engine data agreed when $\ell\pi/D = 0.2$, which led to the final, and simplified, result in Eq. (21). Note that the acoustic transmission loss depends on the engine operating condition through ζ in the PW formulation.

Unfortunately, the argument of the base-ten logarithm, i.e., the quantity inside the square brackets, in Eq. (20) is not dimensionally correct. It should be nondimensional, but it is not! This means that the constant (= 132, here) depends on the choice of units for the independent variables. Consequently, to use this formula (20), customary US engineering units must be used in the input, see[26] for unit details.

The peak frequency involves burner design and geometry parameters and is given by

$$f_p = K_f\frac{Rh_{PR}}{c_p}\left(\frac{\dot{m}_f}{P_{t,ci}}\right)_{des}\frac{1}{A_c L_c}, \tag{22}$$

where R is the gas constant, $\dot{m}_f$ is the fuel mass flow rate, L_c is the combustor length, and the subscript 'des' indicates evaluation at the design point (which can be taken as takeoff conditions); K_f is a nondimensional parameter which depends only on burner type. The PW researchers[15,26] (see also Ref. 5) found that engine data was well described by Eq. (22), with $K_f = 3$ for annular combustors and $K_f = 8$ for can-type combustors.

5.3 *The NASA-ANOPP Combustor-Noise Models*

The purpose of the NASA-developed modular computer program ANOPP is "to predict aircraft noise with the best currently available methods."[38] In order to maintain and enhance the program, NASA has continued to contract with industry[39–42] to evaluate ANOPP against fly-over and real-engine data and to suggest improvements to its modules. These investments have over the years led to significant improvements in the capability of ANOPP.

The GE/SAE direct-combustor-noise model[27,29] was the first method implemented in the ANOPP[30,31] core-noise module GECOR and is referred to as the SAE option therein. However, in contrast to the original SAE formulation, the reference state, denoted by the subscript 'r' in Eqs. (18) and (19), is in ANOPP taken to be the actual ambient conditions at the source (denoted by 's' above), which generally are different from standard sea-level values. Equations (18) and (19), with $K = K_{SAE}$ and relaxed reference state, will be referred to as the ANOPP-SAE-GE formulation herein.

The ANOPP prediction capability was extended to a larger class of engines during the mid 1990s by updating the propulsion-noise modules in ANOPP to also cover small turbofan engines such as typically used by smaller regional-transport and business aircraft. For the GECOR module, this led to the introduction of a new small-engine (SmE) option. The SmE-option formulas are identical to those of the SAE option, except that the acoustic power level is reduced by 4 dB, i.e., the constant $K = K_{SmE} = -64.53\ldots$ in Eq. (18). Equation (18), with $K = K_{SmE}$, combined with Eq. (19) for the turbine-transmission loss, will be referred to as the ANOPP-SmE-GE formulation herein.

Hultgren[43] used time-series data, obtained during the NASA/Honeywell Engine Validation of Noise and Emission Reduction Technology program (EVNERT),[23] to assess the turbine transfer of direct combustor-noise and to develop an update to the turbine-attenuation formula used in ANOPP. The program used the Honeywell TECH977 research turbofan engine, which is typical for a business-jet application in the 31–36 kN (7,000–8,000 lbf) thrust class. The true combustor-noise turbine-transfer function was educed from the EVNERT data by applying a three-signal technique utilizing one sensor in the combustor and two at the turbine exit. Note that the true turbine gain factor (< 1) is always underpredicted (i.e., attenuation is overestimated) by a direct measurement using only two sensors because of a positive bias error caused by the presence of pressure fluctuations in the combustor that are uncorrelated with the propagated direct-combustor noise.[43] The gain factors, determined from the three-sensor technique, were compared with the corresponding constant values obtained from the GE and the simplified PW acoustic-turbine-loss formulas, Eqs. (19) and (21). Hultgren[43,b] found that the gain factor obtained from the simplified PW formula agreed better with the experimental results for frequencies of practical importance. He also found that replacing the GE combustor-noise turbine-attenuation function used in Hultgren and Miles[44] with the simplified PW formula, Eqs. (19) and (21) above, clearly improved the total-noise predictions and also improved the combustor-noise predictions. The latter comparison was not as conclusive as the former due to the inherent difficulty in extracting the combustor-noise component from the total noise signature over its whole frequency range. However, the former would not be true if the combustor-noise component predictions had not been improved by the attenuation-formula change.

The ANOPP core-noise module was subsequently updated to allow the user a choice of using either the GE or PW turbine transmission formulas for both the SAE and SmE options, i.e., the two additional configurations ANOPP-SAE-PW and ANOPP-SmE-PW were added (ANOPP L30v3 and later). The ANOPP module also contains a separate intermediate-narrow-band method[19] to account for tail-pipe resonances. Figure 6 shows the SAE ARP876[29] directivity and 1/3-octave spectrum functions used by the 1/3-octave based methods in the NASA ANOPP GECOR core-noise source prediction module; $f_p = 400$ Hz.

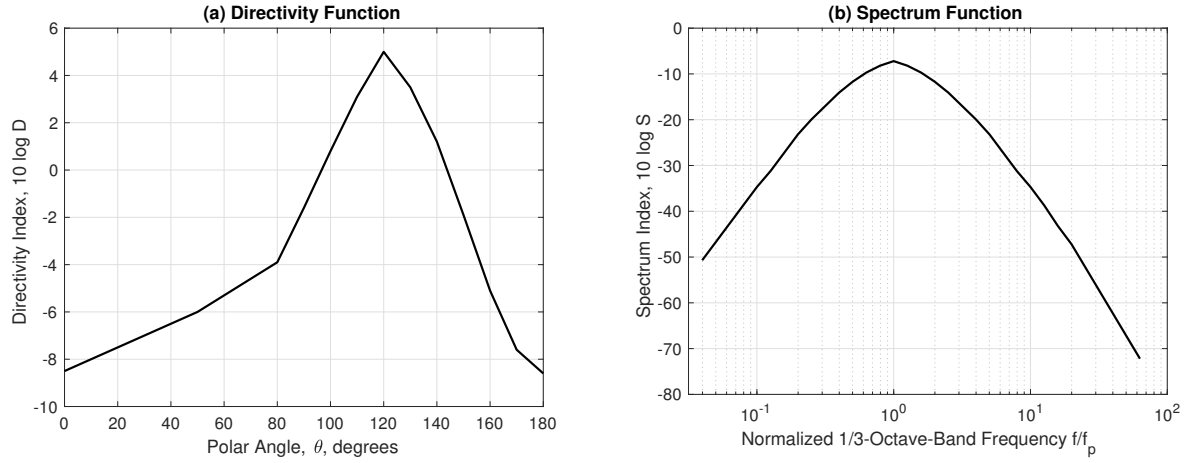

Figure 6. The SAE ARP876[29] directivity (a) and 1/3-octave spectrum (b) functions used in the NASA ANOPP GECOR module

5.4 *European Semi-Empirical Models for Aircraft-Noise Prediction*

Since the early 2000s (in particular the last ten years), there has been an upswing in European aircraft-noise research and prediction-tool development. Historically, most of the development of non-proprietary models and semi-empirical tools for the prediction of aircraft noise took place in the US, but this is now changing. Several efforts are underway (or at a mature stage), some of which are of the database type, using flyover data from existing aircraft, and some of which are for physics-based semi-empirical models. Some of the latter efforts are briefly discussed

[b] Due to a typographical error, the formula in[43] corresponding to Eq. (21) is inverted, but the computations therein are correct.

below. Even though these efforts are very impressive and overall they advance the state-of-the-art, it appears that any advancement of semi-empirical models for direct-combustor noise has yet to take place.

ANOTEC Consulting SOPRANO Tool. Based on the description found in Ref. 45, the SOPRANO tool for aircraft-noise calculations, developed by ANOTEC Consulting during the European SILENCE(R) research program (2001–2007), contains several airframe- and propulsion-noise (including core) components implemented from models available in the open literature at that time. The core noise is predicted using the SAE ARP876 method.[c] Since then SOPRANO has been extended with additional modules mainly within various European research and development projects, but no other core-noise module has been included.[c]

DLR PANAM Prediction Tool. The German Aerospace Center (DLR) developed the Parametric Aircraft Noise Analysis Module (PANAM) overall-aircraft-noise prediction tool[45–47] to enable comparative design studies with respect to airport-community noise and to identify promising low-noise technologies at early aircraft-design stages. Each included airframe and propulsion noise-source is simulated using a semi-empirical model. The engine-noise models are based on existing models in the literature. However, it appears[46,47] that only the two dominant propulsion-noise sources for current generation aircraft, namely jet and fan sources, are currently implemented in the engine-noise module.

ONERA IESTA Project. The French Aerospace Lab ONERA (Office National d'Etudes et de Recherches Aérospatiales) developed a generic simulation platform, IESTA (Infrastructure for Evaluating Air Transport Systems), for the purpose of assessing future air-transport concepts[48]. The prediction of aircraft noise is a significant part of determining the environmental impact (noise and emissions) of these concepts. This capability has been implemented in an acoustic model labeled CARMEN,[49] which consists of three modules: CEASAR-S containing acoustic-source models, CEASAR-I modeling installation effects (reflections and scattering by aircraft surfaces, etc.), and SIMOUN propagating the sound field to observers on the ground. The CARMEN methodology is similar to the ones used by NASA ANOPP[30,31] and DLR PANAM[49]. It is not clear from the open literature, if a core/combustor-noise model has been implemented in CEASAR-S, at least it appears not normally used in predictions. It is often stated that CEASAR-S "computes noise source levels coming from main noise components of current jet aircraft: jet, fan, high-lift devices and landing gear,"[50] see also Ref. 49.

5.5 *Other Codes*

All major engine and airframe companies have proprietary in-house noise-prediction codes with capabilities similar to those of ANOPP. Their confidential, semi-empirical, direct-combustor-noise prediction methods are most likely based on the models described herein. Because each company has a large database of test results (including noise-certification tests), their models can be tailored for the engine type (for an open-literature example of this see Ref. 51), and maybe even specific aircraft, under consideration.

The companies more than likely also have multiblade-row actuator-disk-type codes (eg. Refs. 10,51,52) to determine the transfer of direct noise and the generation of indirect combustor noise by the turbine. In general, this type of code needs somewhat detailed mean-line data for each turbine stage in order to solve a matrix problem for the transmission/generation of noise. Consequently, this type of codes might not be used directly in first-cut exploratory studies, but rather later when noise estimates are refined or to tune parameters in simpler semi-empirical models.

6 Summary

Combustor noise, which is a low-frequency broadband contributor to the noise generated in the turbofan engine core, has two components, namely direct and indirect contributions. The direct contribution is currently the best understood component and it is commonly assumed to be the dominating source of noise originating in the combustor for current turbofan engines. It is at most a significant contributor to the overall noise signature only at low-power conditions, typical of approach flight, at present. However, the relative importance of combustor noise is expected to increase at all engine-power levels in the future due to turbofan design trends and advances in mitigation techniques for other propulsion-noise sources.

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[c]N. van Oosten, private communication, April 2017

The present report reviews the current status of direct-combustor noise modeling and prediction methods and provides a brief discussion of the underlying physics. The existing prediction capability for direct-combustor noise, suitable for engineering-design and system studies, is essentially based on the state of the art of the 1970s, even though method refinements have countinued to be implemented over the years. From the open litterature, most prediction-method implementations are based on the SAE ARP876[29] approach, some with various variations of model coefficient values, to cover a larger class of aircraft engines, as well as alternate turbine attenuation formulas.

This combustor-noise-prediction capability has been deemed adequate up till now, but its applicability to developing aircraft-engine-combustor designs is unknown, particularly because of lean-combustion requirements with higher pressure ratios and shrinking core size. This trend towards lean-burn, high-efficiency, low-emission combustor designs could have profound implications for combustor noise. It could change the balance between the direct and indirect components of the noise as well as increase its overall level. In view of the projected increase in subsonic commercial air traffic, coupled with the expected changes in both propulsion-system and aircraft designs, it is essential that a better understanding and modeling capability of combustor noise is achieved. These models must be able to predict the effects of various lean-burn concepts for reduced emissions and high efficiency, in order to evaluate the acoustic implications of emerging advanced-core designs.

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