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A study of the integration of an inlet noise radiation code with the Aircraft Noise Prediction Program

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A STUDY OF THE INTEGRATION OF AN INLET NOISE RADIATION CODE WITH THE AIRCRAFT NOISE PREDICTION PROGRAM

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ABSTRACT

A numerical method has been developed in order to study the effect of turbofan inlet acoustic treatment on the resulting cumulative noise heard by observers on the ground. The approach to creating the tool was to combine the capabilities of the NASA-developed Aircraft Noise Prediction Program (ANOPP) with the fan noise propagation and radiation code developed at Missouri University of Science and Technology. ANOPP can be used to predict the noise metrics resulting from a typical commercial aircraft with turbofan engines on several different flight profiles, including takeoff, approach/landing and a steady (constant altitude/airspeed) flyover. These capabilities are valuable for studying the effects of varying the parameters of turbofan acoustic liners on the overall noise footprint of the aircraft during a steady flyover event. The fan noise code includes a model of the two-degree-of-freedom acoustic treatment typical in many turbofan engine inlets and is, thus, appropriate for including the effects of the liner itself as well as the variation of liner parameters in the study. The combination of the two computational schemes results in a tool for predicting not only the effects of including the fan inlet acoustic treatment during a flyover, but also the variation of the geometric parameters describing the acoustic treatment and their associated realistically achievable manufacturing tolerances. This research is also intended to develop the tool through which acoustic liner manufacturers can study the effects of their designs and tolerances on the realized attenuation of cumulative noise that reaches the observer on the ground and is subject to federal aircraft noise regulations.

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NOMENCLATURE

Symbol	Description
ρ_∞	Free Stream Air Density [kg/m^3]
c_∞	Free Stream Speed of Sound [m/s]
M_∞	Free Stream Mach Number (non-dimensional)
SPL	Sound Pressure Level [dB]
P_{rms}	Target Acoustic Pressure [Pa]
P_{ref}	Reference Acoustic Pressure [0.00002 Pa]
SIL	Sound Intensity Level [dB]
I_1	Target Acoustic Intensity [W/m^2]
I_0	Reference Acoustic Intensity [10^{-12} W/m^2]
Phon	Loudness Level [dB]
Sone	Perceived Loudness
i	Frequency Band (based on the 1/3-octave-band spectrum)
k	Time Step (sec)
n	Instanteous Perceived Noisiness Level
N	Instantaneous Total Perceived Noisiness Level
PNL	Perceived Noise Level [PNdB]
PNLT	Tone-Corrected Perceived Noise Level [TPNLdB]
PNLTM	Maximum Tone-Corrected Perceived Noise Level [TPNLdB]
C	Tone Correction Factor [dB]
D	Duration Correction Factor [dB]
L_{eq}	Equivalent Continuous Sound Pressure Level [dB]
T	Normalizing Time Constant [s]
EPNL	Effective Perceived Noise Level [EPNdB]
f	Frequency [Hz]
θ	Polar Directivity Angle [radians]
ϕ	Azimuthal Angle [radians]
Z	Liner Characteristic Acoustic Impedance [N*s/m^3]
Z_1	Face Sheet Acoustic Impedance [N*s/m^3]

NOMENCLATURE - Continued

Z_S	Septum Acoustic Impedance [N*s/m^3]
k	Wave Number (2π*f*/c) [1/m]
h_1	Cavity Length between Face Sheet and Septum [m]
h_2	Cavity Length between Septum and Hard Wall [m]
h	Total Cavity Length ($h_1 + h_2$) [m]
BPF	Blade Passage Frequency [Hz]
N_1	Fan Shaft Speed [rpm]
n	Number of Fan Rotor Blades [blades (per revolution)]

LIST OF ACRONYMS

ANOPP	Aircraft Noise Prediction Program
ATM	Atmospheric Module
BPF	Blade Passage Frequency
FAR	Federal Aviation Regulations
CNT	Contour Module
dB	deciBel
EFF	Effective Perceived Noise Level Module
EPNL	Effective Perceived Noise Level
FAA	Federal Aviation Administration
GEO	Geometry Module
HDNFAN	Heidmann Fan Noise Source Module
Hz	Frequency, Hertz or Cycles Per Second
ICAO	International Civil Aviation Organization
LEV	Noise Levels Module
NASA	National Aeronautics and Space Administration
PNLT	Tone-Corrected Perceived Noise Level
PRO	Propagation Module
SFO	Steady Flyover Module
SPL	Sound Pressure Level
TBIEM3D	Thin-duct Boundary Integral Equation Method 3-Dimensional

1. INTRODUCTION

1.1. BACKGROUND

Aircraft noise is of increasing interest, particularly in the commercial aviation community, where the Federal Aviation Administration (FAA) in the United States and the International Civil Aviation Organization (ICAO) have implemented increasingly strict rules with the Federal Aviation Regulations (FAR), which regulate permissible aircraft noise around airports. Figure 1.1 shows the impact of technologies implemented in commercial aircraft engine and airframe design that, since the 1960's, have resulted from greater stringency of noise regulations.

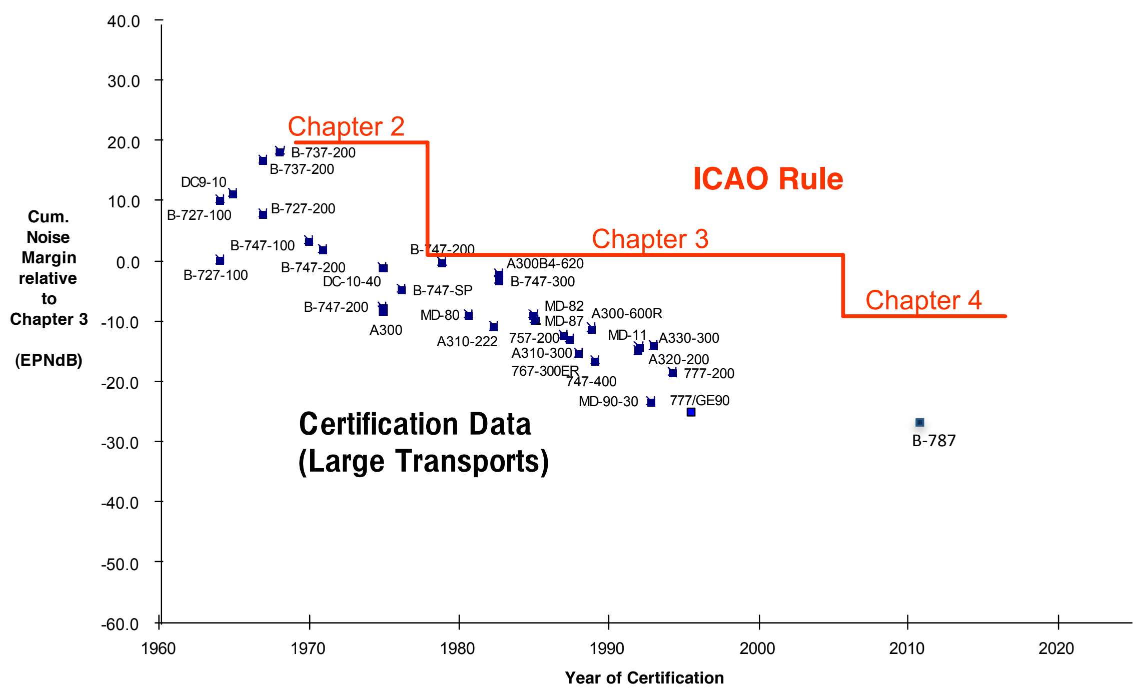

Figure 1.1. Noise certification stages and current commercial aircraft falling in each level.

The figure represents the past, present and future noise certification stages for commercial turbofan-equipped aircraft. The technologies have emerged from the regulations demanding reduced noise impact on airport communities. These technologies resulted in better propulsive efficiency as well as lower noise levels from new aircraft and engines that were subject to the more strict noise requirements. The figure shows each stage of noise certification requirements relative to ICAO Annex 16 Chapter 3 - equivalent to FAR Part 36 Noise Certification Stages and hereafter referred to as Stage in lieu of Chapter - which was in effect for aircraft certified between 1977 and 2006. The noise certification limits are described in terms of Effective Perceived Noise Level (EPNL), a noise metric that accounts for psychoacoustic effects of particular frequencies and tones that annoy airports' neighboring communities more than broadband noise. The EPNL is used to describe a single aircraft flyover event cumulatively. Stage 2 represents the beginning of noise regulation for commercial aviation. Each stage contains a specific EPNL for each measurement point based on aircraft mass that must not be exceeded. While Stage 4 regulations took effect in the beginning of 2006, Stage 3 is the reference point because most of the current commercial fleet has been certified under this regulation. Stage 4 characterizes the advancement of noise control for the future. The rule identifies a significant reduction, at least 10 EPNdB, from Stage 3. Unlike in Stage 2 and 3 certification standards, Stage 4 does not allow the noise metric at any of the points to exceed the minimum value nor any tradeoffs for excesses.

1.1.1. Noise Metrics. Perceived sound results from fluctuations of pressure in a compressible medium such as air. The pressure fluctuations span a very large range. Noise is measured using a logarithmic scale in deciBels (dB). Humans can only perceive sounds between frequencies of about 20 Hertz (Hz) and 20,000 Hz. Some of the frequencies are perceived to be more annoying than others. The range of human hearing has an accepted lower pressure threshold of P_{ref} = 20 μPa or 0.00002 Pascals in air. Acoustic pressure is taken as the root mean square of the fluctuation, denoted by P_{rms}. The reference pressure, P_{ref}, is used as a reference to calculate the sound pressure level according to the definition

$$SPL = 20 \log (P_{rms}/P_{ref}) \text{ dB}. \quad (1)$$

The logarithmic nature of sound pressure level is due to the wide range of possible pressure values, spanning several orders of magnitude. This concept extends to sound intensity level as well, where

$$SIL = 10 \log (I_1/I_0) \text{ dB}. \quad (2)$$

I_1 is the measured intensity, $I_1 = P_{rms}^2 / \rho_0 c^2$, and the reference intensity is $I_0 = 10^{-12}$ W/m^2, ρ_0 is the ambient density and c is the ambient speed of sound. Equations (1) and (2) yield nearly equivalent results for SPL and SIL at standard atmospheric conditions.

The human ear perceives loudness differently at different frequencies [1]. Loudness is defined by the subjective response of humans to sound intensities at various frequencies. The Loudness Level L_N in phons is a metric that describes pure tones at varying frequencies judged to be equally as loud as a reference tone at 1000 Hz at Sound Pressure Level L_N dB. For example, a tone at Sound Pressure Level 70 dB at 2000 Hz would be judged to be approximately as loud as a tone at Sound Pressure Level 80 dB at 1000 Hz. Both tones would have Loudness Level 80 phons. The Loudness S of tonal noise is a metric defined by

$$S = (10^{(L_N - 40)/10})^{0.3}, \quad (3)$$

where S is the Loudness in sones and L_N is the Loudness Level in phons. A sone is related to a phon by Equation (3) in such a way that a 10 dB increase in Loudness Level (phon) is very nearly a doubling of the Loudness (sones). An important result is that for tones not within a critical bandwidth of one another the net Loudness is the sum of the individual Loudnesses. The relation between Loudness Level L_N and Loudness S is obtained from Equation (4) as

$$L_N = 40 + \frac{10}{0.3} \log(S) \approx 40 + \frac{10}{\log(2)} \log(S). \quad (4)$$

The perception of loudness is not necessarily related to the perception of annoyance, which may be defined as the positive or negative response of humans to sounds, particularly pure tones. Annoyance is also a frequency and intensity dependent relationship only quantified subjectively. A relationship between annoyance in noys and Perceived Noise Level PNL in dB similar to that of Loudness and Loudness Level has been the result of research by Kryter [2,3]. Tones at varying frequencies and Sound Pressure Levels judged to be equally annoying have the same Perceived Noise Level (analogous to Loudness Level). As might be expected, curves of equal Perceived Noise Level as a function of frequency and Sound Pressure Level have an appearance similar to their counterparts representing curves of equal Loudness Level. Analogous to Loudness in sones, noisiness (annoyance) index N in noys and PNL are related by

$$PNL = 40 + 10\log_2(N) = 40 + \frac{10}{\log(2)}\log(N)\,. \tag{5}$$

The superposition of Noisiness Index N, though additive, is quite different in detail than the superposition of Loudness. Noisiness Index N for a 24 1/3-octave-band spectrum superposes according to

$$N = 0.85 n_{max} + 0.15 \sum_{i=1}^{i=24} n_i\,. \tag{6}$$

The Noisiness Index of the dominant 1/3-octave-band n_{max} plays an important role in the Noisiness Index N for the spectrum. The Noisiness Index for the spectrum is the Noisiness Index of the dominant 1/3-octave-band plus only 15 percent of the superposed noisiness indices of the remaining bands.

Effective Perceived Noise Level, EPNL, is a single number metric used to describe the effect of a single flyover event on the community surrounding the airport. It is similar in concept to Equivalent Continuous Sound Pressure Level, L_{eq}, frequently used in rating community noise. A procedure for calculating EPNL for an aircraft flyover using measured sound pressures is detailed in Section A36.4, Appendix A2, Part 36 of the Federal Aviation Regulations [4]. The calculation of EPNL begins with the formulation of Perceived Noise Level. First, the instantaneous perceived noisiness is calculated by considering the instantaneous sound pressure levels at each 1/3-octave-band center frequency from 50 Hz to 10,000 Hz using a time increment of 0.5 seconds. A procedure for calculating the relationship between Sound Pressure Level and Noisiness Index is described in FAR Part 36. The total instantaneous perceived noisiness at each time step k, N(k), is described using equation (7) by

$$N(k) = 0.85 n_{max}(k) + 0.15 \sum_{i=1}^{i=24} n(i,k), \tag{7}$$

where $n_{max}(k)$ is the noy value in the dominant 1/3-octave-band for the time step, *i* is the index representing the frequency band (i.e. *i*=1 represents the 50 Hz 1/3-octave-band), *k* is the time increment and $n(i,k)$ are the band noy values for the time step and the entire 1/3-octave-band spectrum from 50-10,000 Hz. Once the total instantaneous perceived noisiness is obtained, the corresponding instantaneous Perceived Noise Level can be calculated using Equation (8) for time step k

$$PNL(k) = 40 + 10\log_2(N(k)) = 40 + \frac{10}{\log(2)}\log(N(k)), \tag{8}$$

where PNL(*k*) is the instantaneous perceived noise level and N(*k*) is the total perceived noisiness at time increment, *k*.

The next step in the process of calculating EPNL from physical noise data is to apply a tone correction to the instantaneous PNL values defined by Equation (8). This tone correction is added to calculated PNL to represent the additional psychoacoustic response effect of discrete tonal content in the spectrum. The procedure amounts to scanning the spectrum at the time increment k to find 1/3-octave-bands that have significantly higher Sound Pressure Level than adjacent bands. FAR Part 36 provides a step by step procedure to identify such tones and a tabular procedure to generate a tone correction C(k) for the spectrum that is added to the previously calculated PNL. Tone Corrected Perceived Noise Level, at time increment k is then given by

$$\mathrm{PNLT}(k) = \mathrm{PNL}(k) + C(k). \tag{9}$$

Also made available by this procedure is the Maximum Tone Corrected Perceived Noise Level, PNLTM, defined over the period of observation at a specified observer location by

$$\mathrm{PNLTM} = \max\left[\mathrm{PNLT}(k)\right]. \tag{10}$$

The information now available at an observer location is the time variation of Tone Corrected Perceived Noise Level at discrete times, PNLT(k). In order to reduce this to a single number metric, the concept used in defining Equivalent Continuous Sound Pressure Level, L_{eq}, is introduced [1]. L_{eq} is defined as the steady state sound that has the same Sound Intensity Level as that of a time varying sound averaged on the basis of energy over a specified time interval,

$$L_{eq} = 10\log\left[\frac{1}{T}\int_0^T \frac{I(t)}{I_0}\,dt\right] = 10\log\left[\frac{1}{T}\int_0^T 10^{(\mathrm{SIL}(t)/10)}\,dt\right]. \tag{11}$$

It is proposed that a similar concept be used to define an equivalent PNLT, defined as Effective Perceived Noise Level, EPNL, by

$$\mathrm{EPNL} = 10\log\left[\frac{1}{T}\int_{t_1}^{t_2} 10^{(\mathrm{PNLT}(t)/10)}\,dt\right], \tag{12}$$

with the additional provision that the averaging only be carried out over the period of time $(t_1 \le t \le t_2)$ when PNLT(k) is within 10 dB of PNLTM. EPNL is then written in terms of PNLTM as

$$\text{EPNL} = \text{PNLTM} + 10\log\left[\frac{1}{T}\int_{t_1}^{t_2} 10^{(\text{PNLT}(t)/10)}dt\right] - \text{PNLTM} = \text{PNLTM} + D \quad , \tag{13}$$

where D is defined as the duration correction (correcting the use of PNLTM as EPNL),

$$D = 10\log\left[\frac{1}{T}\int_{t_1}^{t_2} 10^{(\text{PNLT}(t)/10)}dt\right] - \text{PNLTM}. \tag{14}$$

Since PNLT(t) is known only in terms of discrete values of time, the integration is replaced by summation

$$D = 10\log\left\{\frac{1}{T}\sum_{k=1}^{k=K} \Delta t\left[10^{(\text{PNLT}(k)/10)}\right]\right\} - \text{PNLTM}. \tag{15}$$

FAR Part 36 specifies that the reference time for averaging is 10 seconds and the time increment $\Delta t = 500\ \text{ms} = 0.5\ \text{sec}.$ so that

$$D = 10\log\left\{\sum_{k=1}^{k=K}\left[10^{(\text{PNLT}(k)/10)}\right]\right\} - \text{PNLTM} - 13. \tag{16}$$

The limits of summation, $0 \le k \le K$, correspond to the time span over which PNLT(k) remains greater or equal to PNLTM-10. Effective Perceived Noise Level is then defined by

$$\text{EPNL} = \text{PNLTM} + \text{D}. \tag{17}$$

The duration correction tends to be negative when PNLT(t) is within 10 dB of PNLTM for a short period of time.

Having calculated EPNL at several observer locations around the airport approach and departure paths of aircraft, shown in Figure 1.2, the noise footprint (a contour plot of EPNL) of the airplane can be constructed. The later generations of high bypass ratio turbofan engines used on typical airliners have become quieter with advanced technologies within the core of the engine and with improved noise suppression. These advances have reduced the noise contribution from the turbojet exhaust, thus making the fan noise more evident in turbofan engines where bypass ratios and fan tip speeds continue to increase as engines become larger.

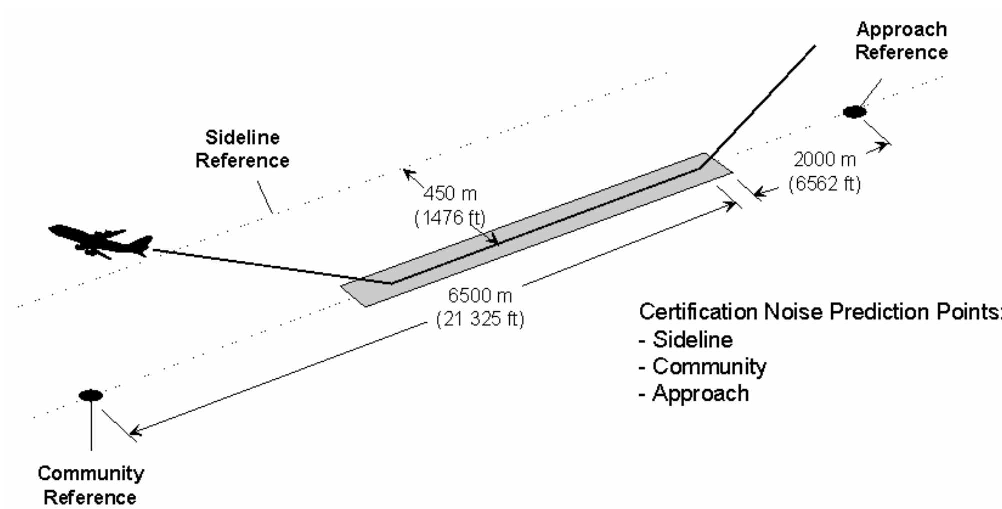

Figure 1.2. Effective Perceived Noise Level reference measurement locations.

1.1.2 Noise Sources on Commercial Aircraft. The sources of noise on modern aircraft originate from the engine and airframe. The main sources of noise due to the airframe include the turbulent flow created by the flaps, slats, wings and landing gear. Airframe noise is particularly important during the landing phase of flight when the engines are at low power. Engine noise can come from the fan (rotor/stator interactions, supersonic fan tip speeds, broadband noise), the compressor, the combustor and from jet mixing in the exhaust. The engines contribute in a significant way to the noise footprint of the aircraft. Engine noise consists of broadband and tonal noise content. The source of engine related broadband noise typically is difficult to determine and is difficult to attenuate with tuned acoustic treatment because it has no significant tonal content. Several noise sources on the engine are primarily attributed to tones arising from the blade passage frequency of the rotor blades of the fan, compressor and turbine. Attenuation of the dominant tones can be achieved through a properly designed and optimized passive acoustic liner. The liner, structurally integrated into the inlet, is capable of attenuation of several dB when properly designed. It can also be designed to attenuate multiple tone frequencies through the use of layers. Figure 1.3 shows the common noise contributions within a typical high bypass ratio turbofan engine and the location of the inlet and bypass flow acoustic lining (blue).

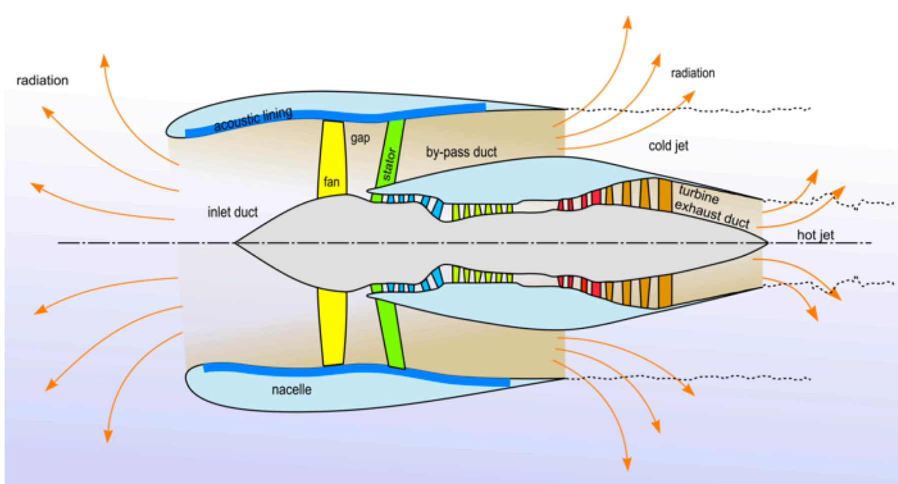

Figure 1.3. Noise sources in a turbofan engine.

1.2. CODES USED FOR NOISE PREDICTION

The Aircraft Noise Prediction Program (ANOPP) [5] is a FORTRAN-based code that includes modules for noise prediction from several sources such as fan noise, jet noise and airframe noise. The modules cover every aspect of noise propagation and radiation from sources on a moving aircraft to a fixed observer location. The module of interest for this study is the HDNFAN module that uses the method developed by Heidmann [6] for predicting fan noise propagation. The Heidmann method calculates fan noise, but does not include the effects of acoustic treatment in the fan duct. ANOPP enables the prediction of cumulative noise metrics such as Effective Perceived Noise Level (EPNL) at one or multiple observer locations. The calculation of EPNL at several prescribed observer locations enables the prediction of an aircraft's noise "footprint", its effect on the surrounding community as a result of the noise radiating from the airframe, engines and other sources on the aircraft. ANOPP can be used in conjunction with the code developed by Eversman [7], which is used to numerically predict the attenuation of tonal noise propagating through a duct to the far field resulting from the use of an acoustic liner in the duct walls. By combining the capabilities of the Eversman Code and those of ANOPP, a research tool emerges that can predict the direct impact of an acoustically lined turbofan nacelle inlet on the noise footprint produced by a commercial aircraft flyover or takeoff/landing. The effect of the variation of lining parameters either for liner optimization or studies of the effects of variation of attenuation resulting from manufacturing process tolerances can be investigated.

1.3. PREVIOUS WORK IN LINER NOISE ATTENUATION PREDICTIONS

Work has been done to predict the noise attenuation in the near field through ducts with locally reacting acoustic liners. Since ANOPP presently does not include the effects of acoustic treatment in the prediction of fan noise, other codes must be considered. Eversman's code is capable of predicting the attenuation of noise propagating through an acoustically treated duct from a fan using finite element methods. Related work has been conducted using other codes, including the Thin-duct Boundary Integral Equation Method 3-Dimensional (TBIEM3D) code developed by Dunn [8] for prediction and optimization studies of passive acoustic liners found in most modern high bypass turbofan inlets. Burd and Eversman [9] studied the effects of acoustic liner manufacturing tolerances on the realized attenuation in turbofan ducts. The implications of the present research are such that an understanding of the effect of manufacturing tolerances on liner performance under flight conditions can enable better optimization and installed performance than could be achieved without the tool.

1.4. RESEARCH OBJECTIVES

The objectives of this research have included studying ANOPP to understand how it could be combined with the Eversman code and determining which modules within ANOPP needed to be replaced by the output from the Eversman code in order to include acoustic liner attenuation in the fan noise propagation model. The purpose of this combination of ANOPP and the Eversman code is to provide a tool to study the effect of inlet acoustic treatment on the attenuation of fan noise and, more generally, the noise footprint of the aircraft. The prediction tool developed will also be useful to study the effect of manufacturing tolerances on the liner's noise attenuation performance on an aircraft in flight. Ultimately, the goal is a user-friendly code capable of providing the capability for predictions of aircraft flyover cumulative noise levels that included imbedded acoustic liner models with the tolerances appropriate to typical manufacturing processes.

2. COMPOSITION OF AIRCRAFT NOISE PREDICTION PROGRAM

2.1. ANOPP TEMPLATES

The Aircraft Noise Prediction Program uses a series of modules, many of which depend on the output of the preceding module. In all, there are ten templates that may be run independently or consecutively. The code is executed by selecting a template, which effectively acts as an input file. Each template is identified based on the primary noise source considered within the template. The templates follow the same basic format that first calculates the atmospheric parameters, followed by the flight path of the aircraft and the specification of the observer locations and ending with the calculation of the noise propagation from the source to the observer and the noise metrics specified by the user. The templates are as follows:

1. Free field jet mixing noise prediction – the prediction of single stream circular nozzle shock-free jet exhaust mixing noise.
2. Free field jet mixing noise prediction including suppression – the prediction of single stream circular nozzle shock-free jet exhaust mixing noise including suppression effects.
3. Free field jet mixing and broadband shock noise prediction – the prediction of single stream circular nozzle jet exhaust mixing noise with shock-turbulence interaction noise.
4. Free field jet mixing and broadband shock noise for a co-annular jet – the prediction of dual stream co-annular circular nozzle jet exhaust mixing noise with shock-turbulence interaction noise.
5. Standard atmosphere and atmospheric absorption – verification of standard atmosphere and atmospheric absorption at various altitudes for a standard day.
6. Atmosphere and atmospheric absorption for a non-standard day – verification of standard atmosphere and atmospheric absorption at various altitudes for a non-standard day.

7. Steady flyover using a single noise source – single aircraft constant-altitude flyover event considering one noise source (default is single stream circular jet mixing noise).
8. Steady flyover using a single noise source applying atmospheric absorption and ground effects – single aircraft constant-altitude flyover event considering one noise source (default is single stream circular jet mixing noise) considering the effects of atmospheric absorption and ground interaction.
9. Takeoff maneuver using two noise sources – single aircraft approach and landing event considering two noise sources (default is single stream circular jet mixing noise and nozzle shock noise).
10. Landing maneuver using two noise sources – single aircraft takeoff event considering two noise sources (default is single stream circular jet mixing noise and nozzle shock noise).

These templates provide a complete set of modules such that when the templates are independently executed, they predict the noise from the source for which the template is intended. Many of the templates within ANOPP consider several factors that influence the propagation of noise from an aircraft, such as atmospheric effects, aircraft configuration, flight path and operating conditions. The template of interest for this study is Template 7, the steady flyover using a single noise source. This template is a simple constant altitude, constant speed aircraft flyover that includes only one noise source (the default is the jet noise source). The single noise source flyover includes other effects such as atmospheric effects (ATM module) and flight effects (Steady Flyover Module, SFO). The ATM module builds a table of standard atmospheric conditions (pressure, temperature, density, speed of sound, average speed of sound, humidity, viscosity coefficient, thermal conductivity coefficient and characteristic impedance) using the temperature and relative humidity as a function of altitude for inputs. The resulting atmospheric property table is used by the Steady Flyover (SFO), Geometry (GEO) and Propagation (PRO) modules to account for atmospheric attenuation. The Steady Flyover Module is used to calculate the following flight path of the aircraft for each time step:

three-dimensional position relative to the reference start point, Euler angles from vehicle to body axis and Euler angles from body to wind axis.

The SFO also produces flight data, including Mach number, power setting, pressure, density, temperature, viscosity, sound speed, humidity and landing gear and flap position. Following the SFO module, the GEO module produces the source-to-observer geometry for the given aircraft flight path (flyover, landing, takeoff) and for a single observer or multiple observers, each defined by a three-dimensional location. The GEO module is the means by which multiple observer locations are defined and later used as the points from which a contour plot of cumulative flyover noise can be made. The observer locations can be determined by referring to the applicable noise regulations defined in the Federal Aviation Regulations. For the purpose of the present study, the observer locations used are such that a proper aircraft noise footprint contour plot can be developed with the EPNL values at the defined locations.

Following the GEO module, the Heidmann Fan (HDNFAN) noise source module, documented by Rawls and Berton, predicts the anticipated noise from a fan or axial flow compressor based on the method developed by Heidmann at NASA Glenn Research Center [6]. The HDNFAN module is used to predict the broadband and tonal noise that originates in the fan of a typical turbofan engine. The six contributions considered and summed in the HDNFAN module are inlet broadband noise, inlet rotor-stator interaction tonal noise, inlet flow distortion tone noise, combination tone noise, bypass flow exhaust turbulent noise and bypass exhaust rotor-stator interaction tonal noise. The components are combined into a single spectrum of 1/3-octave-band frequencies for all combinations of polar directivity angle azimuthal angles, although only the zero-degree azimuth angle is considered due to the assumed independence of fan noise on azimuth angle. The HDNFAN module inputs are both geometric and performance parameters. The independent input variables include the frequency represented as a 1/3-octave-band spectrum, f, the polar directivity angle, θ, and the azimuth directivity angle, ϕ. The fan geometry includes the dimensionless fan face annular flow area relative to the engine reference area (A_e), A^*, the number of rotor blades, B, the dimensionless fan rotor diameter relative to the square root of A_e, d^*, the inlet guide vane index, i, the fan rotor tip relative Mach number on design, M_d, the inlet flow distortion index (=1 if inlet flow distortion effects from broadband and aft tone noise sources are not included and =2 if they are included), *l*, the dimensionless rotor-stator spacing relative to the length of the rotor in the axial direction, s*, and the number of stator vanes, V. The performance parameters include the ambient density, ρ_∞, the ambient speed of sound, c_∞, the dimensionless mass flow rate relative to ambient air density, speed of sound and A_e, $\dot{m}*$, the fan rotational speed relative to ambient speed of sound and fan rotor diameter, N*, total temperature increase across the fan relative to ambient static temperature, $\Delta T*$, and aircraft Mach number, M_∞.

The HDNFAN module outputs a table of dimensionless mean-square acoustic pressure relative to $\rho_\infty^2 c_\infty^4$, $\langle p^2(f,\theta,\phi)\rangle *$, as a function of the 1/3-octave-band spectrum, polar directivity angle and the azimuthal directivity angle, although the fan noise is assumed not to vary with azimuth angle. An example of the table produced by the module is shown in Appendix B.

While the HDNFAN module is capable of predicting the far field noise propagating from an axial flow fan on a moving aircraft and of calculating the cumulative noise metric at each observer location, more robustness is necessary in order to study the effects of inlet acoustic treatment. A model of the two-degree-of-freedom acoustic liner is essential for studying the liner's effects on aircraft noise metrics. Thus, a suitable alternative was required in order to study the attenuation achieved by inlet acoustic liners. The first step was to replace the HDNFAN module with a table representative of what the module would have produced if executed. This was done by executing the steady flyover template using the HDNFAN module. Once the template was executed, the output table of dimensionless mean-square acoustic pressures for the 1/3-octave-band spectrum and various polar directivity angles could be extracted to replace the module's operation. ANOPP modules are designed such that any one can be substituted for the table it would have produced. The new template, called temp7_hdnfan_tables.inp, is shown in its entirety in Appendix A. The content of the template will be discussed, but the details of ANOPP syntax is sufficiently described in the ANOPP user manual.

2.2. RESEARCH TEMPLATE

For the purpose of the present research objective of creating a tool for investigating the effect of acoustic two-degree-of-freedom liner physical parameters and manufacturing tolerances on aircraft noise metrics, template 7 has merit for use in studying the effects of acoustic treatment on total cumulative noise resulting from an aircraft flyover. With some modifications, temp7_hdnfan_tables is composed of several key elements, detailed herein and annotated in the sample template. The first (1) component is the beginning of the input file and the selection of the variable JECHO to be TRUE. This ensures that a record of the input is echoed in the output file, which is the only way to maintain the HDNFAN table when it used in lieu of the HDNFAN module. The command STARTCS is also the beginning of the execution of the template.

The second component, 2 within Appendix A, is the table of frequencies to be used in subsequent calculations requiring spectral content. Additionally, the polar directivity and azimuthal angles are defined at this point. This is also representative of the structure of other tables defined by the user.

Third, section 3 identifies the units to be used with the variable IUNITS, SI is default, and the output file print options using IPRINT (a selection of 3 is appropriate to display both the input and output in the file created upon execution of the template).

The fourth element, the atmospheric or ATM module, begins with its description at 4 of Appendix A. Commented code begins with a '$' and command lines are terminated with the use of a '$' as well. The ATM module, as described above, is simply used to build a table of the atmospheric parameters as a function of altitude for later use by the steady flyover module, the geometry module and the propagation module.

The steady flyover module, SFO, begins at element 5. The purpose of the SFO module is to calculate the flight trajectory data (aircraft position and angles with respect to time) as well as the aircraft performance (Mach number, sound speed, density, etc.) and pertinent aircraft configuration data (power setting, flap position, landing gear position, etc.). This module calculates the parameters for a flyover at a constant altitude defined by the user (default is 2500 meters) along a datum line, an analog to runway centerline.

Following the SFO module, the geometry or GEO module begins with element 6 of the example input template. The GEO module is the point at which the user can define the appropriate observer locations that will be used to calculate cumulative noise metrics and ultimately a contour map of such metrics.

After the aircraft and observer geometries are calculated with respect to each other, the noise source module is executed. In this example, the module is replace with the table it would otherwise have produced, as seen in 7 of the sample input file. In this case, the HDNFAN module is replaced with the tables of dimensionless mean-square acoustic pressure as a function of frequency, polar directivity angle and azimuthal angle for each time step due to the change in source-to-observer geometry and, thus, sound intensity.

The propagation (PRO) module (8) uses the noise source data from the HDNFAN module in the source reference frame and translates the data into the observer location frames of reference. The propagation module sums the noise from each of the sources and translates that noise from the source to the observer.

From the PRO module, the noise levels module (LEV, 9) calculates the noise metrics chosen by the user, including overall sound pressure level, A-weighted sound pressure level, D-weighted sound pressure level, perceived noise level and tone-corrected perceived noise level.

The tone-corrected perceived noise levels calculated by the LEV module are further refined to calculate an effective perceived noise level (EPNL) that is similarly tone-corrected in the effective noise module, EFF, beginning at element 10.

Finally, the contour or CNT module at element 11 is used to organize the EPNL values at each observer location into a format suitable for contour plotting using an external routine such as MATLAB. The plotting script used is shown in Appendix C.

The description of template 7 shows that ANOPP contains many of the methods employed to calculate the perceived noise reaching the observer from a moving aircraft with atmospheric effects. It also shows, however, that no provisions exist within the standard ANOPP modules to account for the effects of acoustic liner parameters or tolerances.

3. THE INLET NOISE SOURCE CODE

The modules of the template temp7_hdnfan_tables comprise an essentially complete process of noise generation and propagation through the atmosphere to user-defined observer locations. However, the research objective of studying the effect of the acoustic liner parameters and manufacturing tolerances on aircraft noise metrics requires the introduction of a code with such effects included. The non-linear two-degree-of-freedom liner model used is built into Eversman's code [10]. The two-degree-of-freedom liner is capable of optimized attenuation at two different frequencies and, thus, two different conditions of flight (i.e. takeoff and landing) or it can also attenuate noise containing prominent multiple pure tones at a single operating conditon. The liner configuration is shown in Figure 3.1.

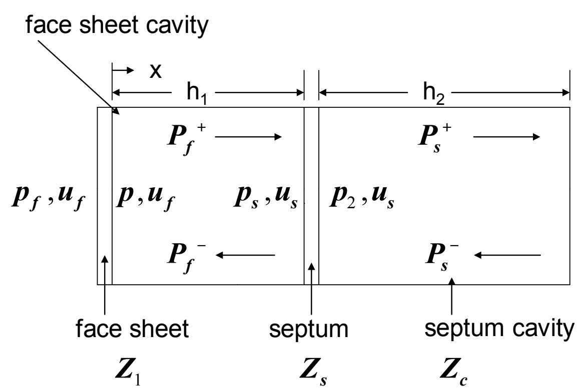

Figure 3.1 Two-degree-of-freedom lining showing essential elements of the lining model in the Eversman Code.

The essential features of the lining are a porous face sheet that interfaces with the acoustic field and flow at the inlet duct surface, a porous septum that with the face sheet creates a porously backed outer cavity, and an inner cavity, coupled via the septum to the outer cavity and rigidly backed. As shown in Figure 3.1 there are two coupled plane wave acoustic systems in the lining denoted by arrows showing right-running and left-running waves. The details of the standing waves depend on the acoustic frequency, the cavity depths and the acoustic properties of the face sheet and septum. Both the face sheet and septum can be conveniently pictured as perforated plates that principally provide resistance to acoustic transmission, though other porous materials are in use.

With this model, the liner has several physical parameters that must be properly manufactured for the optimal attenuation to occur. These parameters include:

1. Face sheet fraction open area – the percentage of the inlet wall surface area open to the acoustic liner face sheet cavity.
2. Face sheet hole diameter – diameter of the holes leading to the face sheet cavity from the inlet flow.
3. Face sheet thickness – thickness of the face sheet material that makes up the inlet wall (on far left side of liner in Figure 3.1).
4. Septum insertion depth – the distance between the face sheet and the beginning of the septum (or the depth of the face sheet cavity).
5. Septum fraction open area – the percentage of the septum face open to the face sheet cavity.
6. Septum hole diameter – diameter of the holes in the septum face separating the septum cavity from the face sheet cavity.
7. Septum thickness – thickness of the septum face separating the septum cavity from the face sheet cavity.
8. Septum backing depth – the termination depth of the entire cavity into the hard wall structure of the engine nacelle.

The lining components are subject to the current state-of-the-art manufacturing processes, but manufacturing tolerances exist. It is expected that the physical parameters noted above will vary somewhat from design values. The resulting realized attenuation achieved by a liner subjected to manufacturing tolerances is the topic of research conducted by Burd and Eversman [9]. The present research provides a tool that allows the study of the effect of two-DOF liner tolerances on Effective Perceived Noise Levels of aircraft flyovers.

Detailed analysis of the acoustic fields suggested in Figure 3.1 leads to a model for the impedance of the two-DOF lining in terms of physical parameters,

$$Z = Z_1 + \frac{Z_s \dfrac{\cos(kh_1)\sin(kh_2)}{\sin(kh)} - i\cot(kh)}{1 + iZ_s \dfrac{\sin(kh_1)\sin(kh_2)}{\sin(kh)}} \tag{18}$$

The impedance of the assembled liner, Z, is described by geometric and flow parameters including the wave number,

$$k = 2\pi f/c, \tag{19}$$

where f is the frequency in Hz and c is the speed of sound, h_1 and h_2, the face sheet and septum cavity depths that sum to equal h, the total cavity depth. Z_1 and Z_s are the face sheet and septum impedances, respectively.

The acoustic liner is structurally integrated into the turbofan nacelle inlet. It is commonly composed of a composite or metal honeycomb structure with a porous face sheet, a permeable septum separating the two cavities and a hard acoustically reflective surface at the bottom of the second cavity. The physical parameters cavities are chosen to achieve optimal attenuation of sound intensity incident on the lining. Several test cases have been considered that represent practical examples: (1) Two engines with four tones superposed on broadband noise with the maximum tone at 150 dB without acoustic treatment, (2) Two engine with four tones superposed on broadband noise with the maximum tone at 150 dB with acoustic treatment and (3) Two engine with four tones superposed on broadband noise with the maximum tone at 140 dB with acoustic treatment. A comparison between cases (1) and (2) will show the clear difference in the resulting aircraft effective perceived noise contour plots when the acoustic liner is included in case (2), but not in case (1). Similarly, a difference is seen when the maximum tone level considered is reduced by 10 dB. The parameters of the liner used in the cases studied are listed in Table 3.1.

Table 3.1. Two-degree-of-freedom liner dimensional parameters for Cases 1-3.

Lining Parameters	Values
Face sheet fraction open area	0.06
Face sheet hole diameter, in.(cm)	0.043 (0.109)
Face sheet thickness, in.(cm)	0.04 (0.102)
BL momentum thickness, in.(cm)	0.079 (0.200)
Septum insertion depth, in.(cm)	0.10 (0.254)
Septum fraction open area	0.023
Septum hole diameter, in.(cm)	0.008 (0.020)
Septum thickness, in.(cm)	0.03 (0.076)
Septum backing depth, in.(cm)	0.28 (0.71)

Another case, (4), is considered in which one of the liner parameters is varied sub-optimally; the septum insertion depth is increased by 50% to 0.15 inches, thus reducing the septum cavity depth as well. This changes the fundamental frequency at which the cavities tend to resonate, which in turn changes the realized attenuation of the liner. This could be due to a poor liner design or the effect of realistic manufacturing tolerances precluding the accuracy necessary for optimum attenuation. Table 3.2 shows the liner parameters for case (4).

Table 3.2. Two-DOF liner dimensional parameters for sub-optimal case (Case 4).

Lining Parameters	Values
Face sheet fraction open area	0.06
Face sheet hole diameter, in.(cm)	0.043 (0.109)
Face sheet thickness, in.(cm)	0.04 (0.102)
BL momentum thickness, in.(cm)	0.079 (0.200)
Septum insertion depth, in.(cm)	0.15 (0.381)
Septum fraction open area	0.023
Septum hole diameter, in.(cm)	0.008 (0.020)
Septum thickness, in.(cm)	0.03 (0.076)
Septum backing depth, in.(cm)	0.28 (0.71)

An inlet noise source radiation code written by Eversman has been significantly modified to generate the table of dimensionless mean-square acoustic pressures as a function of the 1/3-octave-band center frequencies, polar directivity angle and azimuth angle required as a noise source module in ANOPP. The modified Fortran code, referred to as **radcrhs_nl5_tones_scaled**, was written to calculate the propagation and radiation of noise at multiple frequencies from a fan source located in a duct with acoustic treatment. The code calculates acoustic radiation directivity at a finite number of user specified frequencies. The code is used to interface with ANOPP in such a way that it produces the output that would have been produced by the module HDNFAN it is intended to replace, but with the inclusion of acoustic liner effects on attenuation in the fan duct.

ANOPP requires input of the 1/3-octave-band spectrum at 0.5 second intervals to calculate EPNL. In considering the set of 1/3-octave-band frequencies, any pure tone contributions that do not happen to correspond to a center frequency must be merged with that center frequency. This is done by adding the intensities, or dimensionless mean-square acoustic pressures, of each tone contribution within the band corresponding to the 1/3-octave-band center frequency. The same process applies to contributions from broadband noise, except that the sound intensity level for broadband noise is representative of a much larger band with no distinguishable tonal content.

4. TEST CASE

A sample case is studied for the purpose of demonstrating the functionality of the ANOPP code with noise propagation and acoustic liner-related attenuation provided by the Eversman code. The case considered demonstrates the code's capability of translating a practical example with multiple pure tones in addition to the 24 1/3-octave-band center frequencies typically considered by ANOPP. Engine shaft rotational speed is 6000 RPM. With 22 fan blades blade passage frequency is 2200 Hz. A set of multiple pure tones is considered at 9, 11, 16 and 22 times the shaft speed in circumferential modes 9, 11, 16 and 22. The tones are at 900, 1100, 1600 and 2200 Hz and include three sub-harmonics of the blade passage frequency of 2200 Hz. The sub-harmonic at 1600 Hz happens to correspond to a 1/3-octave-band center frequency. The tones at 900, 1100, and 2200 Hz do not correspond with 1/3-octave-band center frequencies. The resulting source spectrum is taken as 1/3-octave-band levels plus one tone that corresponds to a standard center frequency and three tones that must be allocated to standard 1/3-octave-bands.

The input parameters are chosen to represent reasonable flight condition for a flyover at constant altitude of 3000 m. The aircraft is traveling at a Mach number of 0.2 and the effective perceived noise level is calculated from -5000 m to 5000 m along the runway centerline, where the runway midpoint is the zero point. There are observer locations defined along the runway centerline and along the sidelines parallel and offset to the runway centerline at five locations each for a total of 15 observation points at which Effective Perceived Noise Level calculated. The observer locations are symmetric with respect to the runway centerline and the locations range from -1000 m to 1000 m parallel to the runway as well as along the sideline locations at 1000 m from the runway centerline and -1000 m. Figure 4.1 represents the observer locations used for calculation. In the contour plotting routine, the locations were mirrored about the runway centerline to show the y = -500 m and y = -1000 m observers. The results show a comparison in EPNL at observer locations for an inlet duct without acoustic treatment and an acoustically lined inlet duct. In each case, all other parameters remain the same including the spectrum considered. The frequency spectrum, shown in Figure 4.2, consists of tones of 80 dB intensity (representing the broadband noise) at most of the frequencies in the 1/3-octave-band except for the dominant tones at 900, 1100, 1600 and 2200 Hz. At these frequencies the tonal sound pressure levels are 140, 150, 140 and 150 dB, respectively. The other spectrum, that of Figure 4.5, has tones with sound pressure levels at 130, 140, 130 and 140 dB, respectively.

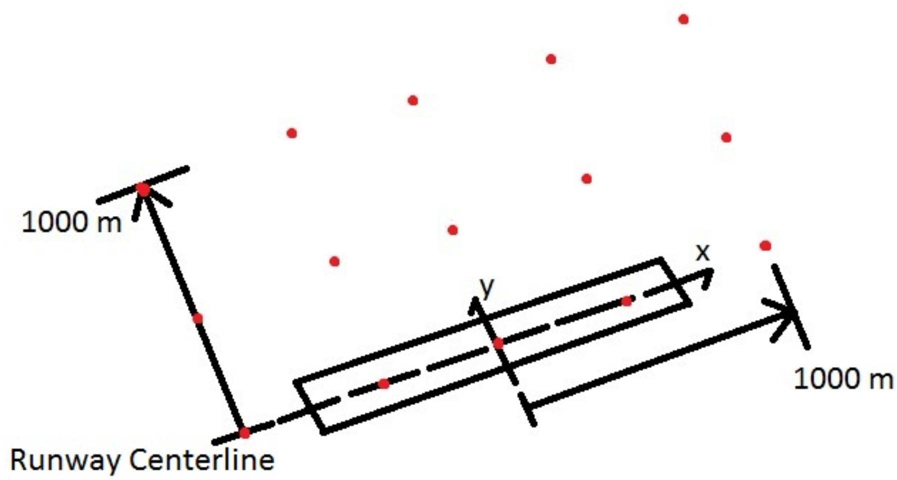

Figure 4.1. Observer locations used for ANOPP calculation of EPNL.

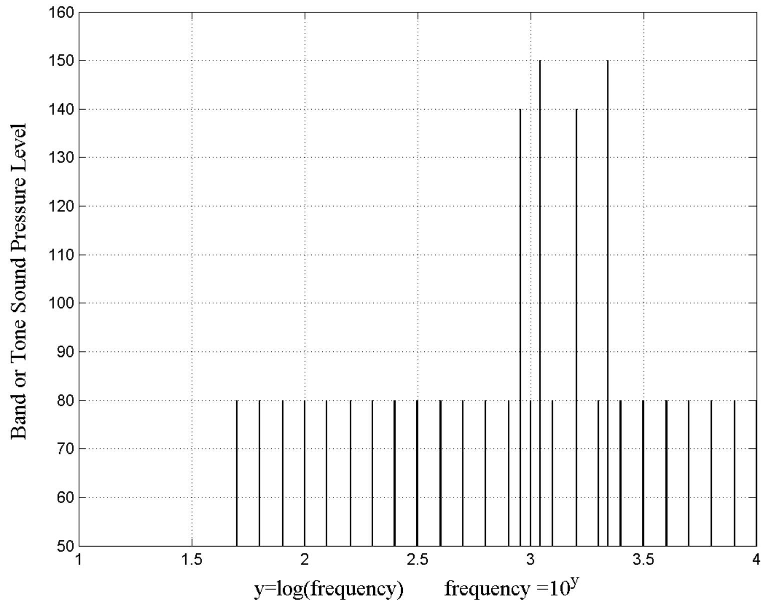

Figure 4.2. Frequency content for cases (1,2,4) considered, unlined and lined ducts. Maximum tone SPL is 150 dB and the spectrum is the same in cases 1,2 and 4.

Figure 4.3 is the resulting contour plot of the EPNL resulting from a flyover of an aircraft with two engines without acoustic treatment. Such is typical of legacy aircraft that received certification before Stage 3 noise requirements were implemented. Although many of these aircraft are now being decommissioned, in part due to their noncompliance with noise regulations.

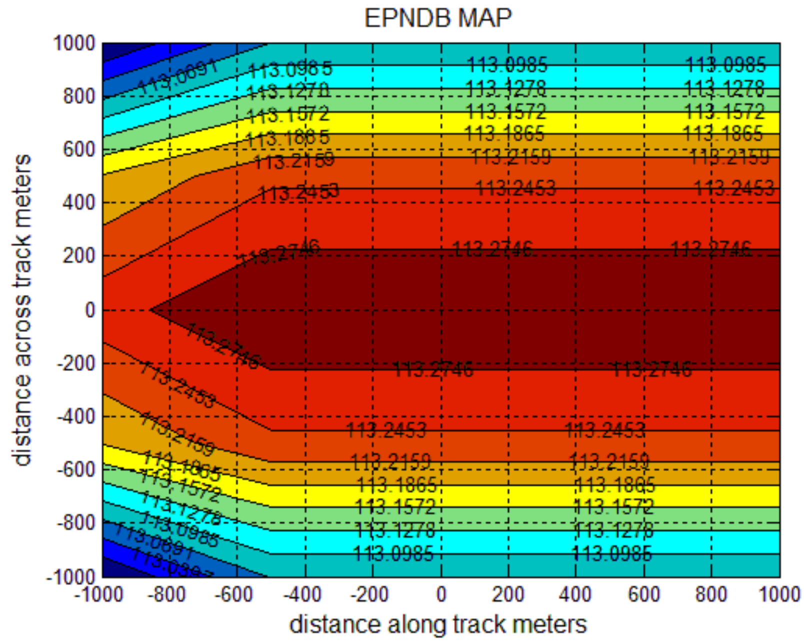

Figure 4.3. Unlined case with maximum tone sound intensity level of 150 dB.

Figure 4.4 is an example of how the inclusion of acoustic treatment in the calculation of noise propagation can significantly impact both the resulting intensity and directionality of the Effective Perceived Noise Level. Particularly, the impact on intensity level is on the order of 14 EPNdB.

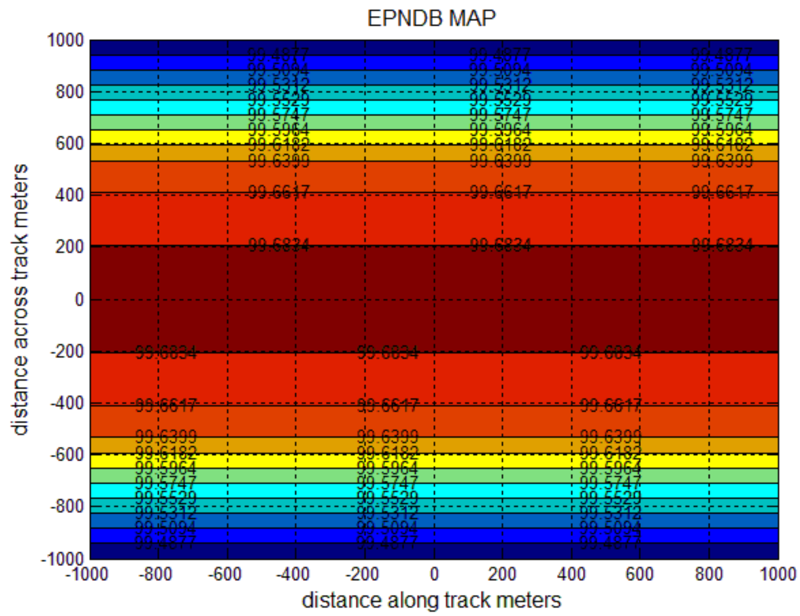

Figure 4.4. Acoustically lined engine inlets with maximum tone at 150 dB and frequency content represented by Figure 4.2.

The results above show that directivity is impacted in addition to the intensity level of the EPNL that reaches the airport neighbor. Furthermore, the code can be used to determine the effect of changes in frequency content from the noise source and changes in the effective impedance of the liner as a result of design changes or manufacturing tolerance variations. Figure 4.5 represents a different spectrum, namely a lower maximum tone level (140 dB). This has a noticeable effect on the EPNL contours.

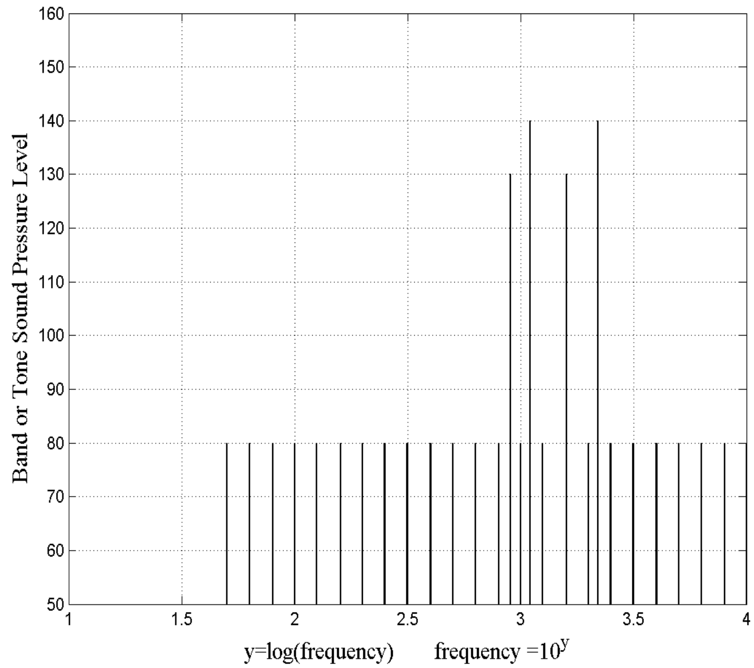

Figure 4.5. Frequency spectrum with reduced maximum tone at 140 dB to demonstrate the effect on EPNL.

The change in maximum tone intensity level is clear in comparing the EPNL contours from the previous lined case with that of Figure 4.6. The overall EPNdB values are decreased as a direct result of the lower tone levels prevalent in the frequency spectrum.

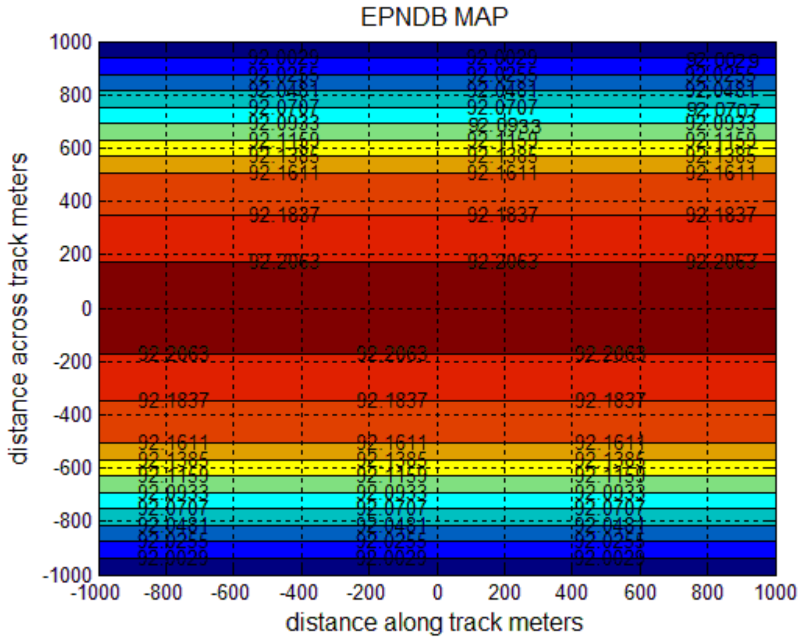

Figure 4.6. Acoustically lined inlet with maximum tone sound intensity level of 140 dB. EPNL is clearly impacted by the reduction of maximum level tones.

The acoustic liner has many physical parameters that can either be sub-optimally designed or subject to manufacturing tolerances that can achieve only a sub-optimal fidelity, resulting in an attenuation that is less than design intent. Such a case is presented in Figure 4.7 below, where the septum insertion depth is 150% of the previous cases. Specifically, case (4) is compared to case (2), whereby both have the same frequency content, shown in Figure 4.2, but due to the change in liner physical parameters, the resulting contour plot of EPNL for case (4) shows a clear degradation of liner performance in the form of a higher EPNL at each observer location.

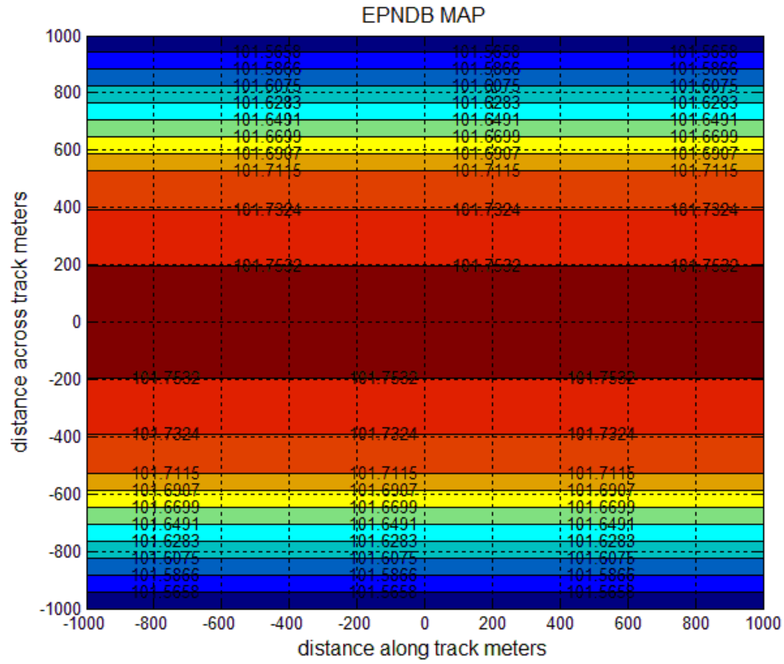

Figure 4.7. Acoustically lined inlet with maximum tonal sound intensity level of 150 dB and sub-optimal liner parameters shown in Table 3.2.

5. CONCLUSIONS

The Aircraft Noise Prediction Program and the Eversman code have shown their merit as research tools for independently studying the noise produced by an aircraft flying a typical approach, takeoff or flyover and the attenuation of noise due to inlet acoustic treatment. However, to enable researchers to advance aircraft noise suppression to meet the next generation of regulatory airport noise requirements, a new tool must exist that takes advantage of resources such ANOPP and Eversman's code. This tool is currently being used by industry partners to study the effects of various designs and manufacturing tolerances on the realized attenuation achieved with acoustic treatment. Burd and Eversman [6] investigated the effects of manufacturing tolerances on the realized attenuation of acoustic liners. This work exposes the realistic attenuation from such liners when they are mass-produced, as they must be to become commercially viable.

A more accurate tool for noise prediction of commercial turbofan-equipped aircraft is essential in meeting Stage 4 noise requirements. Manufacturers and airlines are responsible for complying with noise standards and do so either through retrofitting the existing fleet or through research using prediction tools and models for newly developed attenuation devices.

The research objective has been successful in terms of Eversman's code modification to produce an output that will replace the HDNFAN module of ANOPP in order to account for an acoustic liner model in the final noise metric calculations done by ANOPP. This process has been passed to industry researchers for several facets of their own research, including the study of the effects liner design and manufacturing tolerance specifications on total vehicle noise footprint. This is important because no matter how much analysis is done on an optimized liner, it will still be subject to the manufactured and installed final product that will contain imperfections and deviations from the specifications around which the acoustic treatment was optimized. This means that the liner manufacturer must know the result of these performance changes in order to deliver a suitable product to the aircraft manufacturer.

APPENDIX A.

EXAMPLE ANOPP TEMPLATE

```
$
$  TEMPLATE 11.1---STEADY FLYOVER USING A SINGLE NOISE SOURCE
$                  USING HDNFAN MODULE
$
$
ANOPP JECHO=.TRUE. $    (1)
STARTCS $
$
$      Load SAE table from the ANOPP permanent data base LIBRARY
$
LOAD /LIBRARY/ SAE $
$
$  Specify the frequency and directivity angles
$
UPDATE NEWU=SFIELD SOURCE=*  $      (2)
   -ADDR OLDM=* NEWM=FREQ FORMAT=4H*RS$ $
          50.     63.     80.    100.    125.    160.
         200.    250.    315.    400.    500.    630.
         800.   1000.   1250.   1600.   2000.   2500.
        3150.   4000.   5000.   6300.   8000.  10000.  $
   -ADDR OLDM=* NEWM=THETA FORMAT=4H*RS$ $
          10.   30.   50.   70.   90.   110.   130.   150.   170.  $
   -ADDR OLDM=* NEWM=PHI FORMAT=4H*RS$ $
           0. $
   END* $
$
$  These two input parameters will be used by every module executed
$      in this template.  Since they will not be modified, they are
$      defined once before any module is executed.
$
PARAM IUNITS   = 2HSI  $  define input units to be SI       (3)
PARAM IPRINT   =   3   $  printed output option code
$

$======================================================================
$  Atmospheric Module - ATM        (4)
$
$  The purpose of this module is to build a table of atmospheric model
$  data as functions of altitude.  Input required includes the user
$  parameters listed below and the unit member ATM(IN).  Output
$  consists of the table ATM(TMOD) which is a table of atmospheric
$  model values in dimensionless units.  The model values include
$  pressure, density, temperature, speed of sound, average speed of
$  sound, humidity, coefficient of viscosity, coefficient of thermal
$  conductivity, and characteristic impedance all as a function of
$  altitude.  This table will be used as input to several modules that
$  will be subsequently executed.
$
$---------------------------------------------------------------------
$
$  Define the input unit member ATM(IN).  Each record defines the
$      temperature and relative humidity at a specific altitude.
$
UPDATE NEWU=ATM SOURCE=* $
   -ADDR OLDM=* NEWM=IN FORMAT=4H3RS$ $
           0.   288.2    70.  $
        1000.   281.7    70.  $
```

```
        2000.   275.2    70.  $
        3000.   268.7    70.  $
        4000.   262.2    70.  $
        5000.   255.7    70.  $
    END* $
$
$      Define input user parameters for the Atmospheric Module
$
PARAM DELH      =       1000.   $  altitude increment for output, m
PARAM H1        =          0.   $  ground level altitude, m
PARAM NHO       =          6    $  number of altitudes for output
PARAM P1    =   101325. $  atmospheric pressure at ground level, N/m^2
$
$  Execute the Atmospheric Module
$
EXECUTE ATM  $
$

$=======================================================================
$  Steady Flyover Module - SFO     (5)
$
$   The purpose of this module is to provide flight dynamics data in
$   the case of a steady state flyover.  One record of trajectory data
$   is written to a unit member at each time step.  This module
$   requires the user parameters listed below and the unit member
$   generated by the Atmospheric Module, ATM(TMOD), as input.  SFO
$   generates two unit members as output.  FLI(PATH) contains the
$   following flight trajectory data: time, aircraft position (x,y,z),
$   Euler angles from vehicle-carried to body axis and Euler angles
$   from body to wind axis.  FLI(FLIXXX) contains flight data in the
$   following order: time, Mach number, power setting, speed of sound,
$   density, viscosity, landing gear indicator, flap setting, and
$   humidity.
$
$----------------------------------------------------------------------
$
$  Define input user parameters for the Steady Flyover Module
$
PARAM ZOPT      =          2    $  use THW and disregard ZF
PARAM J         =          1    $  initial time step
PARAM TSTEP     =        0.5    $  time interval between step, sec
PARAM ZGR       =       0.0   $  altitude of runway above sea level, m
PARAM ENGNAM    =      3HXXX    $  engine identifier name
PARAM DELTA     =        0.0    $  engine inclination angle, deg
PARAM TI        =        0.0    $  initial time, sec
PARAM VI        =       67.8    $  aircraft velocity, m/sec
PARAM VF        =         VI    $ final aircraft velocity, m/sec
PARAM XI        =    -5000.0    $  initial distance from origin, m
PARAM YI        =    0.0    $  initial lateral distance from origin, m
PARAM ZI        =     3000.0    $  initial altitude, m
PARAM THW       =   0.0   $  inclination of flight vector with respect
                                $  to horizontal, deg
PARAM PLG       =       4HUP    $  initial landing gear position
PARAM TLG       =        0.0    $  time at which landing gear position
                                $  was reset, sec
PARAM TF        =      100.0    $  final time limit, sec
PARAM XF        =     5000.0    $  final distance limit, m
```

```
 PARAM ZF        =     3000.0    $  final altitude limit, m
 PARAM ALPHA     =        2.0    $  angle of attack, deg
 PARAM THROT     =        1.0    $  power setting
 $
 $  Execute the Steady Flyover Module
 $
 EXECUTE SFO $
 $

$======================================================================
 $  Geometry Module – GEO     (6)
 $
 $  The purpose of the Geometry Module is to calculate the source
 $  to observer geometry.  Input parameters are given below.  Input
 $  data units include ATM(TMOD), FLI(PATH), and OBSERV(COORD).
 $  ATM(TMOD) is generated by the Atmospheric Module.  FLI(PATH) is
 $  generated by one of the flight dynamics modules - Steady Flyover
 $  Module (SFO), Jet Takeoff Module (JTO), or Jet Landing Module
 $  (JLD).  OBSERV(COORD) contains the observer locations where the
 $  noise sources will be propagated and is generated using the
 $  UPDATE control statementas shown below.  The value of the user
 $  parameter ICOORD determines the output generated by this module.
 $  In this example, ICOORD has a value of 1 which indicates that
 $  geometry associated with the body axis will be output in a table
 $  called GEO(BODY).  Body axis calculations used for all of the
 $  engine noise sources while wind axis calculations are used for
 $  the airframe noise sources.
 $
 $---------------------------------------------------------------------
--
 $
 $  Define the observer coordinates
 $
 UPDATE NEWU=OBSERV SOURCE=* $
    -ADDR OLDM=* NEWM=COORD FORMAT=4H3RS$ $
        -1000.      0.   1.2  $
        -1000.    500.   1.2  $
        -1000.   1000.   1.2  $
         -500.      0.   1.2  $
         -500.    500.   1.2  $
         -500.   1000.   1.2  $
            0.      0.   1.2  $
            0.    500.   1.2  $
            0.   1000.   1.2  $
          500.      0.   1.2  $
          500.    500.   1.2  $
          500.   1000.   1.2  $
         1000.      0.   1.2  $
         1000.    500.   1.2  $
         1000.   1000.   1.2  $
    END* $
 $
 $  Define input user parameters for the Geometry Module
 $
 PARAM AW        =        1.0    $  reference area, m^2
 PARAM CTK       =        0.1    $  characteristic time constant
 PARAM DELDB   =    20.0    $  limiting noise level down from peak, dB
```

```
PARAM MASSAC    =      416.8    $  reference mass of aircraft, kg
PARAM START =   0.0    $  initial flight time to be considered, sec
PARAM STOP   =   1000.0    $  final flight time to be considered, sec
PARAM DELT      =        0.5    $  reception time increment, sec
PARAM DELTH   =  10.0    $  maximum polar directivity angle limit, deg
PARAM ICOORD    =          1    $  generate body axis output
PARAM DIRECT    =    .FALSE.    $  interpolate from FLI(PATH) observer
                          $  reception times based on user parameters
                                $  start, stop, delth, and delt
$
$  Execute the Geometry Module
$
EXECUTE GEO  $
$
$=======================================================================
$ Procedure HDNFAN     (7)
$
TABLE ENG(FAN1) 1 SOURCE=* $
 INT= 0 1 2
 IND1= RS 2 2 2  0.50  1.00
 IND2= RS 4 2 2  0.00  0.30  0.35 0.50
 IND3= 0  6 0 0
 DEP = RS
      0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
      0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
      0.3228  0.4916  0.3843  0.5251  0.4154  0.5473  0.4580  0.5851
      0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
      1.0     1.0     1.0180  1.0180  1.0320  1.0320  1.0501  1.0501
      0.3476  0.5198  0.3785  0.5255  0.3891  0.5274  0.4079  0.5405
END* $
TABLE ENG(FAN2) 1 SOURCE=* $
 INT= 0 1 2
 IND1= RS 2 2 2  0.50  1.00
 IND2= RS 4 2 2  0.00  0.30  0.35 0.50
 IND3= 0  6 0 0
 DEP = RS
      0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
      0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
      0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
      0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
      1.0777  1.1631  1.1009  1.1806  1.1154  1.1936  1.1386  1.2188
      0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
END* $
$
 PARAM AE = 2.0                  $  Engine reference area, m^2
 PARAM HDNMTH    = 1 $ Prediction method flag:
                     $   =1; Original Heidmann method,
                     $   =2; AlliedSignal small fan method,
                     $   =3; General Electric revised method
 PARAM AFAN  = 2.0   $ Fan face cross sectional annular flow area, m^2
                   $   (i.e., between the hub and tip at the fan face)
 EVALUATE AFAN  = AFAN/AE $ Fan inlet cross sectional flow area, Re AE
 PARAM DIAM      =         1.63  $ Fan diameter, m
 EVALUATE DIAM   = DIAM/SQRT(AE) $ Fan diameter, Re sqrt(AE)
 PARAM MD  = 1.25 $ Fan aerodynamic design relative (helical) tip Mach
                  $ number.  Note this is a fixed number given at
                                 $ the machine's aero design point.
```

```
 PARAM RSS   =   3.0  $ Rotor-stator axial spacing at the tip,
                      $   Re tip rotor axial chord
           $   Note: this is expressed as a fraction, not a percentage
 PARAM IGV      =             1 $ Inlet guide vane index;
                                $   =1, no IGVs
                                $   =2, IGVs
 PARAM NENG      =            2 $
 PARAM NB        =           24 $ Number of rotor blades
 PARAM NV        =           54 $ Number of vanes
 PARAM NBANDS    =     0 $ #1/3 octave bands for tone frequency shift
 PARAM INDIS  = .FALSE. $ Do not calculate inlet flow distortion tones
 PARAM IOUT      =            3
$
EXECUTE HDNFAN $

$=======================================================================
 $  Propagation Module - PRO        (8)
 $
 $  The Propagation Module takes noise data which has been generated by
 $   the noise source module(s) in the source frame of reference and
 $   applies all of the appropriate computations to transfer it to the
 $   observer frame of reference.  Input user parameters required by
 $   this module are listed below.  Input data base units include the
 $   following:
 $      ATM(TMOD)      -  generated as output from the Atmospheric
 $                        module
 $      ATM(AAC)       -  generated as output from the Atmospheric
 $                        Absorption Module and used only if
 $                        atmospheric absorption effects are requested
 $      GEO(GEOM)      -  generated as output from the Geometry Module
 $      FLI(FLIXXX)    -  generated as output from a flight dynamics
 $                        module - SFO in this template
 $      YYYYYY(XXXNNN) -  output generated by the noise source
 $                        module(s) where YYYYYY is the unit name
 $                        associated with the noise module(s) used to
 $                        calculate the source noise - SGLJET in this
 $                        example
 $   Output generated by this module includes the data unit
 $   PRO(PRES) which contains dimensionless mean-square pressure
 $   at the observer as a function of frequency and time.
 $
 $---------------------------------------------------------------------
 $
 $  Define input parameters for the Propagation Module
 $
 PARAM IOUT      =          3   $  print output in both SPL (dB) and
                                $  mean-square acoustic pressure
 PARAM SIGMA     =      2.5E05   $  specific flow resistance of the
                                $  ground kg/(sec m^3)
 PARAM NBAND    =         5   $  number of subbands per 1/3-octave band
 PARAM SURFACE  =   4HSOFT $  type of surface to be used in calculating
                                $  ground effects
 PARAM COH       =        0.01   $  incoherence coefficient
 PARAM PROTIME  =   3HXXX   $  3 letter id from unit member FLI(FLIXXX)
 PARAM PROSUM   =   6HHDNFAN  $  name(s) of source unit(s) to be summed
 $
 $  In order to include atmospheric absorption and ground effects,
```

```
$  these two input parameters are given a value of TRUE
$
PARAM ABSORP   =   .FALSE.   $  include atmospheric absorption effects
PARAM GROUND    =      .FALSE.   $  include ground effects
PARAM RS    =  0.8862    $  radius of arc for source noise directivity
$  Execute the Propagation Module - a name override is used to inform
$  the Propagation Module that the Geometry Module generated the unit
$  member GEO(BODY) while the Propagation Module is expecting
$  GEO(GEOM)
$
EXECUTE PRO GEOM=BODY  $
$

$======================================================================
$  Noise Levels Module – LEV       (9)
$
$   The Noise Levels Module computes overall sound pressure level,
$   A-weighted sound pressure level, D-weighted sound pressure level
$   perceived noise level, and tone-corrected perceived noise level as
$   a function of time and observer as requested by the user.  The
$   input user parameters required by this module are listed below.
$   The Noise Levels Module uses the data unit PRO(PRES), which was
$   generated by the Propagation Module, as input.  Also required as
$   input are the data units SFIELD(FREQ) and OBSERV(COORD) which both
$   were generated using the UPDATE control statement earlier in this
$   input deck.  If tone-corrected perceived noise levels calculations
$   are requested then the data unit LEV(PNLT) is generated as output.
$
$---------------------------------------------------------------------
$
$  Define input parameters for the Noise Levels Module
$
PARAM IAWT    =    .TRUE.   $  A-weighted sound pressure level option
PARAM IDWT    =    .FALSE.   $  D-weighted sound pressure level option
PARAM IOSPL   =      .TRUE.   $  overall sound pressure level option
PARAM IPNL    =      .TRUE.   $  perceived noise level (PNL) option
PARAM IPNLT   =      .TRUE.   $  tone-corrected PNL option
PARAM MEMSUM  = 4HPRO 4HPRES $  unit name and member name of the noise
                                $  member to be summed
$
$  Execute the Noise Levels Module
$
EXECUTE LEV $

$======================================================================
$  Effective Noise Module – EFF    (10)
$
$   The Effective Noise Module computes the effective perceived
$   noise levels (EPNL) as a function of observer location.  The input
$   user parameter required by this module is listed below.  Required
$   input data units include OBSERV(COORD), which has been previously
$   defined using the UPDATE control statement, and LEV(PNLT), which
$   has been generated by the Noise Levels Module (LEV) by setting the
$   value of the user parameter IPNLT to TRUE.  The output member
$   EFF(EPNL) is generated by this module.  EPNL values are printed in
$   the output listing if the user parameter IPRINT has a value of
$   either 2 or 3.
```

```
$
$-------------------------------------------------------------------
$
$  Define input parameter for the Effective Noise Module
$
PARAM DTIME    =        0.5    $  reception time increment, sec
$
$  Execute the Effective Noise Module
$
EXECUTE EFF $
$
PARAM IPRINT = 3 $
PARAM IOUTPUT = 2 $
PARAM IOPT = 1 $
PARAM FILNAME = 4HTEST $
$
EXECUTE CNT $    (11)
$
$
ENDCS $
```

APPENDIX B.

EXAMPLE TABLE PRODUCED BY HDNFAN

```
                                ***********************************
                                * TABLE OF MEAN-SQUARED PRESSURES *
                                ***********************************

0.6055E-16 0.6134E-16 0.6214E-16 0.6295E-16 0.6378E-16 0.6462E-16
0.6547E-16 0.6633E-16 0.6721E-16
0.6055E-16 0.6134E-16 0.6214E-16 0.6295E-16 0.6378E-16 0.6462E-16
0.6547E-16 0.6633E-16 0.6721E-16
0.6055E-16 0.6134E-16 0.6214E-16 0.6295E-16 0.6378E-16 0.6462E-16
0.6547E-16 0.6633E-16 0.6721E-16
0.6055E-16 0.6134E-16 0.6214E-16 0.6295E-16 0.6378E-16 0.6462E-16
0.6547E-16 0.6633E-16 0.6721E-16
0.6055E-16 0.6134E-16 0.6214E-16 0.6295E-16 0.6378E-16 0.6462E-16
0.6547E-16 0.6633E-16 0.6721E-16
0.6055E-16 0.6134E-16 0.6214E-16 0.6295E-16 0.6378E-16 0.6462E-16
0.6547E-16 0.6633E-16 0.6721E-16
0.6055E-16 0.6134E-16 0.6214E-16 0.6295E-16 0.6378E-16 0.6462E-16
0.6547E-16 0.6633E-16 0.6721E-16
0.6055E-16 0.6134E-16 0.6214E-16 0.6295E-16 0.6378E-16 0.6462E-16
0.6547E-16 0.6633E-16 0.6721E-16
0.6055E-16 0.6134E-16 0.6214E-16 0.6295E-16 0.6378E-16 0.6462E-16
0.6547E-16 0.6633E-16 0.6721E-16
0.6055E-16 0.6134E-16 0.6214E-16 0.6295E-16 0.6378E-16 0.6462E-16
0.6547E-16 0.6633E-16 0.6721E-16
0.6055E-16 0.6134E-16 0.6214E-16 0.6295E-16 0.6378E-16 0.6462E-16
0.6547E-16 0.6633E-16 0.6721E-16
0.6055E-16 0.6134E-16 0.6214E-16 0.6295E-16 0.6378E-16 0.6462E-16
0.6547E-16 0.6633E-16 0.6721E-16
0.6055E-16 0.6134E-16 0.6214E-16 0.6295E-16 0.6378E-16 0.6462E-16
0.6547E-16 0.6633E-16 0.6721E-16
0.2900E-14 0.3028E-14 0.3160E-14 0.3296E-14 0.3437E-14 0.3582E-14
0.3732E-14 0.3886E-14 0.4045E-14
0.6055E-16 0.6134E-16 0.6214E-16 0.6295E-16 0.6378E-16 0.6462E-16
0.6547E-16 0.6633E-16 0.6721E-16
0.2167E-14 0.2265E-14 0.2365E-14 0.2469E-14 0.2576E-14 0.2687E-14
0.2801E-14 0.2919E-14 0.3040E-14
0.4433E-14 0.4632E-14 0.4838E-14 0.5051E-14 0.5270E-14 0.5496E-14
0.5729E-14 0.5970E-14 0.6218E-14
0.6055E-16 0.6134E-16 0.6214E-16 0.6295E-16 0.6378E-16 0.6462E-16
0.6547E-16 0.6633E-16 0.6721E-16
0.6055E-16 0.6134E-16 0.6214E-16 0.6295E-16 0.6378E-16 0.6462E-16
0.6547E-16 0.6633E-16 0.6721E-16
0.6055E-16 0.6134E-16 0.6214E-16 0.6295E-16 0.6378E-16 0.6462E-16
0.6547E-16 0.6633E-16 0.6721E-16
0.6055E-16 0.6134E-16 0.6214E-16 0.6295E-16 0.6378E-16 0.6462E-16
0.6547E-16 0.6633E-16 0.6721E-16
0.6055E-16 0.6134E-16 0.6214E-16 0.6295E-16 0.6378E-16 0.6462E-16
0.6547E-16 0.6633E-16 0.6721E-16
0.6055E-16 0.6134E-16 0.6214E-16 0.6295E-16 0.6378E-16 0.6462E-16
0.6547E-16 0.6633E-16 0.6721E-16
0.6055E-16 0.6134E-16 0.6214E-16 0.6295E-16 0.6378E-16 0.6462E-16
0.6547E-16 0.6633E-16 0.6721E-16
```

Note: The table is a 24-by-9 table that doesn’t fit in its original format, resulting in the last three columns of each row dropping to the next row.

APPENDIX C.
MATLAB CONTOUR PLOTTING ROUTINE

```
% Routine used to plot EPNL contours from ANOPP

clear all, close all, clc

load CNT.OUT
%first column is distance from origin (x)on track
%second column is distance (y) across the track
%third column is the metric

%mm is the number of on track locations
mm=5;
%nn is the number of cross track points for each on track location
nn=5;

bb=CNT;

%ON TRACK (X) AXIS
for ii=1:mm
    X(ii)=bb((ii-1)*nn+1,1);
end

%CROSS TRACK (Y) AXIS
Y=bb(1:nn,2);

%METRIC
Z=bb(1:mm*nn,3);

%TABLE WITH COLUMNS REPRESENTING Y (varying (jj))
%AND ROWS REPRESENTING X (varying (ii))
icount=0;
for ii=1:mm
    for jj=1:nn
        icount=icount+1;
        F(ii,jj)=Z(icount);
    end
end
%TRANSPOSE F SO THAT RESISTANCE BECOMES THE COLUMNS, REACTANCE BECOMES
%THE ROWS
G=F';
[C,h]=contourf(X,Y,G,10);
grid
clabel(C,h);
xlabel('distance along track meters','fontsize',12)
ylabel('distance across track meters','fontsize',12)
title('EPNDB MAP','fontsize',12)
pause
print -dbitmap EPNDB_Map.bmp
```

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VITA

Devin Kyle Boyle was born in Saint Louis, Missouri on 24 April 1987. Devin received his Bachelor of Science Degree in Aerospace Engineering, Magna Cum Laude, in May 2010, from Missouri University of Science and Technology (formerly University of Missouri-Rolla), Rolla, Missouri. He interned during the summer of 2007 at the Boeing Company in Long Beach, California, working in Flight Test Engineering for the C-17 Globemaster III cargo aircraft operated primarily by the United States Air Force. Following his summer tour at the Boeing Company, he worked during the fall of 2007 at NASA Dryden Flight Research Center (DFRC) at Edwards AFB, California. Devin continued to work in varying roles at NASA DFRC during the summers of 2008, 2009, 2010 and 2011.

He has been a member of the American Institute of Aeronautics and Astronautics (AIAA) since 2007. He was inducted into the Sigma Gamma Tau National Aerospace Engineering Honor Society in 2010.

Presently, Devin is a Propulsion Engineer at NASA DFRC working on various projects, including Vehicle Integrated Propulsion Research (VIPR). VIPR is a joint project with several NASA centers, the USAF/AFRL, other government entities and industry partners. The project is focused on numerous research opportunities involving engine and vehicle health monitoring and management.