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Community noise exposure is an integral factor in vertiport placement

Acoustic footprint of EC/VTOL aircraft will dictate approach and departure air-corridors

Current noise prediction methods fall on the extremities of the computational cost-accuracy spectrum

There is a need for a tool for iterative conceptual design

Currently, the Federal Aviation Administration (FAA) is using the Day-Night Av- erage A-weighted Sound Pressure Level (DNL) to quantify aircraft noise induced annoyance in the communities around airports. Here, the 65 DNL contour is used as a criterion to determine qualification for noise insulation programs. DNL is an equivalent continuous A-weighted sound pressure level with an addition

of 10 dB during the night-time (2200-0700) (ANSI S3.23-1980, 1980). The addition of 10 dB during the night-time reflects the fact that people are more sensitive to noise during the night. This is mainly because the background noise level is reduced at night which causes aircraft events to be more noticeable. DNL as a single number measure for predicting the effects of the long-term ex-

posure of environmental noise was widely accepted. However, some of its drawbacks, mainly the penalty factor for night-time events (10 dB) are often questioned. Also it is felt that the effects of sharpness, tonal- ness, roughness and fluctuation strength

are not adequately accounted for by DNL

A weighting schemes are based on equal loudness contours (ISO 226, 1987, 2003) at different pressure levels. A-weighting weighting factors (wi) related to the different frequency bands are given in Table 2.1. These are derived from the 40 phon equal loudness contour. Although A-weighted sound level is universally accepted for community noise measurement, Fidell, Pearsons, Tabachnick, and Howe (2000b) mentioned that it is inadequate in assessing aircraft noise impact on a community. This inadequacy is because it de- emphasizes low-frequencies below 400 Hz and high-frequencies above 4000 Hz. If a sound component is around 40 phon then A-weighted sound pressure level may be appropriate.

\textcolor{red}{A Weigting PLot}

## Noise Prediction From A Frequency Domain Approach

An acoustic analogy formulation for moving sources in uniformly moving media

Applicability of Early Acoustic Theory for Modern Propeller Design

fowkes williams and hawkins

green function

advantages and disadvanates

There exist several assessment methods to quantify aircraft noise annoyance in communities around airports. A few noteworthy ones are weighted sound pressure level based ratings, computed loudness and annoyance based ratings, noise level and event-based ratings and statistical centennial based rating. The rationale behind the development of several noise ratings stemmed from the purpose of using a different noise rating that adequately predicts human response to noise \cite{schultz1982community}. Different occasions led to a slightly different rating in each case. More \cite{more2010aircraft} outlines some of their respective advantages and disadvantages. For the purposes of this study, the A-weighted Maximum Noise Level, $SPL\_{Amax}$, measured in dBA is used. This is an instantaneous peak noise level measured at an observer location during the time period in consideration.

The computational approach to predict aircraft noise in SUAVE is a post-processing technique and is not a part of the iterative mission-solving routine. That is to say, the radiated sound pressure level is not repeatedly computed at each control point but one time after the kinematics of each flight segment are fully resolved. There are two commonly used methods for computing noise from aerodynamic loads, pressure distributions on the surfaces of the vehicle and turbulent wake: Time-domain methods and frequency-domain methods. Time-domain methods require large time histories of the pressures from the loading on each blade to compute radiated noise. Despite demonstrating higher accuracy, these methods are a few orders of magnitude more expensive in terms of wall clock computing time and memory than frequency-domain methods. On the other hand, frequency-domain approaches reconstruct the governing equations using a Fourier transform but have been known to suffer from loss of information as a result of the oversimplification of the blade geometry. This loss however is less significant for capturing higher harmonics, as pointed out by Hubbard \cite{Hubbard1991a}. A frequency-domain approach was therefore preferred for the scope of this study.

Excluding the motor, the primary sources of acoustic noise of electric aircraft are (1) rotational noise -- occurring at integer multiples of the blade passing frequency and includes thickness noise due to finite blade thickness and loading noise due to thrust generation; (2) blade vortex interaction noise -- created when rotors blades pass through the wake emanating from another blade; (3) broadband noise -- due to turbulent flow impinging on the rotating blades as well as blade self-generated turbulence interacting with the blade trailing edge. Mathematical formulations for both the steady harmonic or tonal sources which dominate the noise spectrum and the broadband component are presented below.

### Harmonic Noise

harmonic

Influence of Propeller Design Parameters on Far-Field Harmonic Noise in Forward Flight

Sound from a propeller at angle of attack: a new theoretical viewpoint

Helicoidal surface theory for harmonic noise of propellers in the far field

Influence of Propeller Design Parameters on Far-Field Harmonic Noise in Forward Flight

Helicoidal surface theory for harmonic noise of propellers in the far field

Hanson's formation \cite{hanson1995sound} of harmonic propeller noise in the frequency domain was implemented. Extending from early work by \cite{deming1937noise,gutin1948sound,garrick1953theoretical,arnoldi1956propeller,barry1971noise}, this approach encompasses the effects of airfoil thickness, non-axial propeller inflow and blade sweep. The acoustic prediction of the aircraft is confined to rotating blades and excludes fluctuating loads on wings and noise generated in the quasi-steady wake. Starting with a definition of coordinate systems in Figure \ref{fig:noise\_coordinate\_diagram} below, $\theta$ and $\phi$ denote radiation angles of an arbitrary propeller in a freestream at an angle of attack, $\alpha$ relative to the observer. These two angles are defined in Equation \ref{eq:theta\_phi} along with other geometrical expressions required to fully interpret the diagram.

\begin{figure}

\centering

\mbox{\subfigure[Isolated rotor in forward flight. \label{fig:Noise\_Coordinate\_Diagram\_}]

{\includegraphics[width=0.9\linewidth]

{FIGURES/04\_Images/Noise\_Coordinate\_Diagram\_1.png}}}\qquad

\mbox{\subfigure[Azimuth radiation angle.\label{fig:Noise\_Coordinate\_Diagram\_2}]

{\includegraphics[width=.4\linewidth]

{FIGURES/04\_Images/Noise\_Coordinate\_Diagram\_2.png}}}

\caption[Figure Title]{Sound emission reference frames.}

\label{fig:noise\_coordinate\_diagram}

\end{figure}

\begin{equation}

\textrm{where } \theta = cos^{-1}\left(\frac{x}{S}\right) \quad, \quad

\phi = tan^{-1}\left(\frac{z}{y}\right)\quad, \quad S = \sqrt{x^2 + y^2 + z^2} \quad , \quad Y = \sqrt{y^2 + z^2} \label{eq:theta\_phi}

\end{equation}

\noindent Applying the required transformation from the visual frame to the retarded frame using Equations \ref{eq:coordinate\_transformation\_1} and \ref{eq:coordinate\_transformation\_2} result in the corrected distance and radiation angles from the point of emission.

\begin{subequations}

\begin{align}

\theta\_{r} &= cos^{-1}\left(cos(\theta)\sqrt{1 - M\_x^2 sin^2\theta} + M\_x sin^2\theta\right)\label{eq:coordinate\_transformation\_1} \\

S\_r &= \frac{Y}{sin\theta\_r} \label{eq:coordinate\_transformation\_2}

\end{align}

\end{subequations}

Finally, modification of the propeller from the inertial frame to the body-fixed frame oriented $\alpha$ relative to the freestream as shown in Figure \ref{fig:noise\_coordinate\_diagram} yields the following:

\begin{subequations}

\begin{align}

\cos \theta\_{r}^{\prime}&=\cos \theta\_{r} \cos \alpha+\sin \theta\_{r} \sin \phi \sin \alpha \label{eq:theta\_r\_p} \\

\cos \phi^{\prime}&=\frac{\sin \theta\_{r}}{\sin \theta\_{r}^{\prime}} \cos \phi \label{eq:phi\_p}

\end{align}

\end{subequations}

With these definitions, the thickness and loading noise components of the root mean squared pressure of the $n$\textsuperscript{th} rotor is be expressed as:

\begin{multline}

P\_{T{m}\_n} = \frac{-\rho a^{2} B \sin \theta\_{r} \exp \left[i m B\left(\frac{\Omega S\_{r}}{a}+\left(\phi^{\prime}-\frac{\pi}{2}\right)\right)\right]}{4 \sqrt{2} \pi(Y / D)\left(1-M\_x \cos \theta\_{r}\right)} \ldots\\

{} \int\_{h u b}^{t i p} M\_{s}^{2}(h / b) \exp \left(i \phi\_{s}\right) J\_{m B} k\_{x}^{2} \Psi\_{V} d r \label{eq:thickness\_noise}

\end{multline}

\begin{multline}

P\_{L{m}\_n} = \frac{i m B M\_{t} \sin \theta\_{r} \exp \left[i m B\left(\frac{\Omega S\_{r}}{a}+\left(\phi^{\prime}-\frac{\pi}{2}\right)\right)\right]}{2 \sqrt{2} \pi Y r\_{t}\left(1-M\_x \cos \theta\_{r}\right)} \ldots\\

{} \int\_{h u b}^{t i p}\left[\frac{\cos \theta\_{r}^{\prime}}{1-M\_x \cos \theta\_{r}} \frac{d T}{d r}-\frac{1}{r^{2} M\_{t} r\_{t}} \frac{d Q}{d r}\right] \exp \left(i \phi\_{s}\right) J\_{m B} \Psi\_{L} d r \label{eq:loading\_noise}

\end{multline}

where

\begin{equation}

J\_{m B}=J\_{m B}\left(\frac{m B r M\_{t} \sin \theta\_{r}^{\prime}}{1-M\_x \cos \theta\_{r}}\right)

\end{equation}

\noindent

$J\_{m B}$ denotes Bessel functions of the first kind of order $m$ and comes through manipulation of the governing Ffowcs Williams-Hawking equation in the time domain. $m$ is the harmonic number and $B$ is the number of blades. $k\_x$, the ratio of the blade passing frequency to the speed of the aircraft or wavenumber for short is given as:

\begin{equation}

k\_{x}=\frac{2 m B b M\_{t}}{M\_{s}\left(1-M\_x \cos \theta\_{r}\right)}

\end{equation}

\noindent

The phase lag due to the sweep of the propeller, $\phi\_s$, is defined as:

\begin{equation}

\phi\_{s}=\frac{2 m B M\_{t}}{M\_{s}\left(1-M\_x \cos \theta\_{r}\right)} \frac{M C A}{D}

\end{equation}

\noindent $\phi\_{s}$ will be of particular interest in future research as blade sweep has a significant impact on the phase of radiated sound and the onset of the critical blade tip Mach number. The effect of chordwise non-compactness is captured through non-dimensional source transforms $\Psi\_V$ and $\Psi\_L$, which will be examined in succeeding studies. Given below in Equation \ref{eq:psi\_v} and \ref{eq:psi\_l}, the first term approximates the chordwise thickness as a parabolic distribution with maximum thickness at unity while the second represents a uniform lift distribution. Though suitable for conceptional design, a reformulation to accommodate more accurate shape functions will enable topology optimization using a frequency-domain acoustic prediction approach.

\begin{equation}

\hspace\*{2.3cm}\Psi\_{V}\left(k\_{x}\right)=\left\{\begin{array}{cc}

2 / 3 & \text { if } k\_{x}=0 \\

\frac{8}{k\_{x}^{2}}\left[\frac{2}{k\_{x}} \sin \left(\frac{k\_{x}}{2}\right)-\cos \left(\frac{k\_{x}}{2}\right)\right] & \text { if } k\_{x} \neq 0

\end{array}\right.\label{eq:psi\_v}

\end{equation}

\begin{equation}

\Psi\_{L}\left(k\_{x}\right)=\left\{\begin{array}{cc}

1 & \text { if } k\_{x}=0 \\

\frac{2}{k\_{x}} \sin \left(\frac{k\_{x}}{2}\right) & \text { if } k\_{x} \neq 0

\end{array}\right. \label{eq:psi\_l}

\end{equation}

\noindent The total unweighted harmonic sound pressure level from a single rotor is determined through decibel arithmetic of the thickness and loading terms as follows:

\begin{equation}

SPL\_{har\_{{n}\_n}} = 20 log \left(\frac{ P\_{T{m}\_n}+ P\_{L{m}\_n} }{P\_0}\right). \label{eq:raw\_noise}

\end{equation}

The A-weighting scaling to account for human perception is then applied. This expression provided in Equation \ref{eq:A\_weight} was developed by first fitting the A-weighting standard to a continuous polynomial. It is then summed to the sound pressure level of the corresponding frequencies to produced a re-scaled noise spectrum.

\begin{subequations}

\begin{align}

R\_{A}(f) &=\frac{12194^{2} f^{4}}{\left(f^{2}+20.6^{2}\right) \sqrt{\left(f^{2}+107.7^{2}\right)\left(f^{2}+737.9^{2}\right)}\left(f^{2}+12194^{2}\right)} \\

A(f) &= 20 \log \_{10}\left(R\_{A}(f)\right)-20 \log \_{10}\left(R\_{A}(1000)\right) \\

SPL\_{har\_{{m}\_n}}(dBA) &= SPL\_{har\_{{m}\_n}} + A\_f(f)

\end{align} \label{eq:A\_weight}

\end{subequations}

\noindent where $f$ denotes the vector of frequencies of the first 20 harmonics, that is, $f = 2 \pi m \Omega B$, $m = 1,2...20$. The sound pressure level of one rotor can now be similarly computed by logistically summing over the A-weighted harmonic spectrum using Equation \ref{eq:spl\_rot\_harmonic} and again over the total number of rotors using Equation \ref{eq:spl\_tot\_harmonic}.

\begin{subequations}

\begin{align}

SPL\_{\text{har}\_{n}} = 10 log\left( \sum\_{i = 1}^{i = m} 10^{\frac{ SPL\_{\text{har}\_{{i}\_n}}}{10}} \right) \label{eq:spl\_rot\_harmonic} \\

SPL\_{\text{har}\_{\text{tot}}}= 10 log\left( \sum\_{j = 1}^{j = n} 10^{\frac{ SPL\_{\text{har}\_{\_j}}}{10}} \right). \label{eq:spl\_tot\_harmonic}

\end{align} \label{eq:spl\_harmonic}

\end{subequations}

### Broadband Noise

\textcolor{red}{

Broadband trailing-edge noise predictions— overview of BANC-III results

A frequency domain numerical method for airfoil broadband self-noise prediction

Empirical wall-pressure spectral modeling for zero and adverse pressure gradient flows

Prediction of rotorcraft broadband trailing-edge noise and parameter sensitivity study

Broadband

Rotor broadband noise prediction with comparison to model data

Prediction of rotorcraft broadband trailing-edge noise and parameter sensitivity study

brooks and burley

Helicopter Rotor Trailing Edge Noise

Broadband trailing-edge noise predictions— overview of BANC-III results

A frequency domain numerical method for airfoil broadband self-noise prediction

Frequency-Domain Method for Rotor Self-Noise Prediction

The Effect of Airfoil Shape on Trailing Edge Noise

Wall-pressure spectral model including the adverse pressure gradient effects

}

As alluded to before, broadband noise is a culmination of noise generating phenomena including blade wake interaction, aerodynamic pressure fluctuations at the leading and trailing-edges, turbulence on the surface and shed vortices. A more detailed examination of these source is provided in \cite{Brooks2001}.

Ref [Rotor broadband noise prediction with comparison to model data by Brooks and Burley] provides a comprehensive summary of the broadband noise. These are Blade-Wake Interaction (BWI) noise due to a rotor blades' interaction with the turbulent wakes emulating from preceding blades and self-noise which is generated as a result of the development and shedding of turbulence within the rotor blades' boundary layers. As noted by Burley [ref] the flow details of the turbulence in the wake and within the boundary layers are non-deterministic and thus approached analytically in a statistical wave-number or spectral fashion. There is also impulsive blade vortex interaction (BVI) noise produced by the rotor blade’s interaction with the strong tip vortex, a phenomenon of finite wings, resulting in distinguishable jumps in pressure disturbance at blade passing frequencies. These three major categories of sources are shown in Figure {reproduced below} reproduced from the original paper.

\texstcolor{red}{[figure of flow field encounted by rotor ]}

Self-noise itself is a combination of noise-generation phenomena shown in Figure [ref]. These are briefly summarized below:

\begin{itemize}

\item Trailing edge noise is caused by the scattering of the turbulence pressure field on both the upper and lower surfaces of the rotor blade. This component is one of the more significant noise spectra contributions to the overall self-noise generated.

\item Laminar Boundary Layer - Vortex Shedding (LBL-VS) noise generated at conditions conducive to laminar boundary layer flow on the surfaces of the blade. The rarity of such flow conditions on the blade makes this component of self-noise not a significant component of self-noise.

\item Blunt Trailing Edge (BTE) noise is due to vortex shedding from a less-than-sharp trailing edge.

\item Tip noise due to the finite nature of the lifting surface resulting in the formation and shedding of a tip.

\end{itemize}

In Figure [next figure below ], we see the contributions of each of these broadband noise-generating components to the overall broadband noise prediction methodology outlined in [Helicopter Rotor Trailing-Edge Noise] along with a comparison to experimental data. These tests were conducted on a BO-105 model rotor in 1994 in the Geerman Duch Wind Tunnel as part of the [The data employed in this paper is that of an

international cooperative rotor noise research study by researchers from the US Army Aeroflightdynamics Directorate (AFDD), NASA Langley, the German-Dutch Wind Tunnel (DNW), and the Aerospace Research Establishments of France (ONERA) and Germany (DLR). The HART43 (Higher-harmonic control Aeroacoustic Rotor Test) program was conducted in 1994 in the German-Dutch Wind Tunnel

(DNW). Details of the test program and major results are reported by Splettstoesser, et al44 and Kube et al4

]. The rotor blade was 4 m in diameter had a constant chord length of 0.121 m and RPM of 1040 or a tip Mach around 0.6. This is important to note because through this was a scaled model of a helicopter blade (typically diameters of ), it is the scale of most eVTOL lift-rotor blades (Joby = Dia, Archer = , Vertical = , Wisk). Self-noise models used in this study were based on previous experimental work examining self-noise generated from airfoils by [ Airfoil self-noise and prediction ]. From the figure, we see that there is generally good agreement of this total prediction acoustic spectra with measured data. Here is the perfect point to highlight the limitations of the broadband noise models implemented in SUAVE’s Fidelity One framework. The only component modeled in the broadband noise spectra is trailing edge noise. That is the laminar boundary layer vortex shedding noise, blunt trailing edge noise, tip vortex noise and blade wake interaction nose components of self. are omitted in the formulation. For the purposes of this work, three, two is justified given that their contributions are insignificant. The BWI is however significant contributor to the overall broadband spectrum as shown in the image, particularly in the region of the frequency spectrum that is emphasized in an A-weighting spectrum. Blade vortex interactions are not considered in this study. Together BWI and BVI are two components that are significant in the total acoustic spectra of EVTOL aircraft, whose numerous configurations possess distributed rotors about the airframe rotors operate in edgewise flight and emulate helical wakes that interact with blades near the rear end of the aircraft.

\texstcolor{red}{[figure for noise spectra]}

In the context of rotor blade acoustics, the rotors of UAM aircraft are expected to operate around tip Mach numbers of 0.4-0.7. Within this range, tonal noise is expected to dominate in the lower frequencies of a vehicle's noise signature. In the mid to high frequency range however, trailing-edge noise dominates and thus its contribution to the overall power spectrum density cannot be overlooked. In this study, this component of broadband noise is modeled using an extension of Amiet's \cite{Amiet1976NoiseEdge} model for predicting trailing-edge noise on an airfoil. This extension includes the modified wall pressure spectrum proposed by Li and Lee \cite{Li2019PredictionStudy,KevinLi2021PredictionUCD} which accounts for adverse pressure gradient flows on the airfoil. The process begins with the discretized loads and local flow incidence angles of all sections of the rotating blades obtained from BEVF routine described in Chapter \ref{C:03\_SUAVE}. A viscous panel method code is then used to compute the boundary layer properties. This evaluation of the surface pressure distribution and the magnitude of the displacement and momentum thicknesses at the trailing edge using a combination of potential theory and laminar and turbulent boundary layer models from Thwaites \cite{thwaites1949approximate} and Head \cite{head1981new} respectively is a departure from the simplifications made by Brooks, Pope and Marcolini \cite{Brooks2016AirfoilPrediction} whose model assume symmetric airfoil sections and utilize empirical estimations for boundary layer properties. The computed variables along the surface are rotor blade are then used in Lee’s wall pressure spectrum model. A more detailed methodology is now presented below.

We start the mathematical formation by examining a section of the blade shown in Figure \ref{fig:Propeller\_Noise\_Rotor\_Diagram}. The local coordinate system located at the midspan of each blade segment is shown in the figure, with both the x and y axes lying on the rotor disk plane if the blade segment is not pitched with respect to the rotor disk. Additionally, the blade pitch angle, $\alpha\_p$, is the angle between the rotor plane and the local blade chord.

\begin{figure}[!h]

\centering

\includegraphics[width=0.6\textwidth]{ ./FIGURES/04\_Images/Propeller\_Noise\_Rotor\_Diagram}

\caption{Local blade section coordinate system.}\label{fig:Propeller\_Noise\_Rotor\_Diagram}

\end{figure}

Starting with Amiet’s model for power spectral density at an observer location with respect to the upper and loser surfaces of the airfoil can be written as:

\begin{equation}

S\_{p p(U / L)}=\left(\frac{\omega}{a}\right)^{2} c^{2} dr\left(\frac{1}{32 \pi^{2}}\right) \frac{N\_{B}}{2 \pi} \int\_{0}^{2 \pi} D\_{\phi}\left|L\right|^{2} l\_{r} \Phi\_{p p} d \phi

\end{equation}

where $U$ and $L$ represent the upper and lower surfaces of an airfoil, respectively and

\begin{subequations}

\begin{align}

\epsilon^{2}&=X^{2}+\beta^{2}\left(Y^{2}+Z^{2}\right) \\

\beta^{2}&=1-M^{2} \\

\frac{\omega\_{d}}{\omega} &= \frac{1}{1+M\_{r}\left(\frac{X}{R\_{s}}\right)} \\

M\_r &= \frac{\Omega r}{a}.

\end{align}

\end{subequations}

\noindent $D$ is the spectrum directivity as defined in the appendix of \cite{KevinLi2021PredictionUCD}, $\epsilon$ is the doppler shifted frequency and $c$ is the chord length of the blade section. This paper also provides a comprehensive review of the coordination transformation from the observer to the blade section surface, including any out of plane flapping motion of the blade thus the authors refer the reader to this reference. Schlinker and Amiet's model \cite{Schlinker1981HelicopterNoise} for the loading term, $L$ is used in the above formulation. It is given as follows:

\begin{multline}

|L|= \frac{1}{\Lambda} \Biggl| e^{i 2 \Lambda} \biggl[ 1-(1+i) E^{\*}\left(2\left(\bar{K}+\bar{\mu} M+\bar{\gamma} \right) \right) + e^{-i 2 \Lambda} \sqrt{\frac{K+\mu M+\gamma}{\mu x \epsilon+\gamma}}(1+i) + \ldots\\

{}E^{\*}\left(2\left(\frac{\bar{\mu} x}{\epsilon} +\bar{\gamma} \right) \right) \biggr] \Biggr|\end{multline}

where

\begin{subequations}

\begin{align}

\Lambda&=\bar{k}\_{x}- \frac{\bar{\mu} x}{\epsilon} +\bar{\mu} M \\

K&= \frac{\omega\_{d}}{U\_{c}} \\

\mu&= \frac{\omega\_{d} M}{ U \beta^{2}} \\

\gamma^2 &= \left( \frac{\mu}{\epsilon}\right)^{2}\left(x^{2}+\beta^{2} z^{2}\right).

\end{align}

\end{subequations}

\noindent Here, $k\_x$ is the chordwise wave number denied by $\omega/U$ and $mu = M k\_x / beta^2$ and $E^\*$ represents the the complex conjugate of a Fresnel integral defined by

\begin{equation}

E(x) \equiv \frac{1}{\sqrt{2 \pi}} \int\_{0}^{x} e^{i t} \frac{d t}{\sqrt{t}}.

\end{equation}

\noindent The bar over the variables indicated normalization by the semichord of the blade section. Lastly, the wall pressure is given by

\begin{equation}

\frac{\Phi\_{pp}(\omega) U\_{e}}{\tau\_{w}^{2} \delta^{\*}}=\frac{\max \left(a,\left(0.25 \beta\_{c}-0.52\right) a\right)\left(\frac{\omega \delta^{\*}}{U\_{e}}\right)^{2}}{\left.\left[4.76\left(\frac{\omega \delta^{\*}}{U\_{e}}\right)^{0.75}+d^{\*}\right]^{e}+\left(8.8 R\_{T}^{-0.57}\right)\left(\frac{\omega \delta^{\*}}{U\_{e}}\right)\right]^{h^{\*}}}. \label{eq:phi\_broadband}

\end{equation}

Table \ref{tab:spectrum\_properties} below documents the parameters used within the Equation \ref{eq:phi\_broadband}.

\begin{table}[!h]

\caption{Parameters for wall pressure spectrum model.} \label{tab:spectrum\_properties}

\centering

\begin{tabular}{cc}

\hline

\textbf{Parameter} & \textbf{Value} \\ \hline \hline

$\beta\_{c}$ & $ \left(\Theta / \tau\_{w}\right)|d p / d x|$ \\

$a$ & $ 2.28 \Delta^{2}\left(6.13 \Delta^{-0.75}+d\right)^{e}[4.2(\Pi /\Delta)+1]$ \\

$\Delta$ & $\delta / \delta^{\*}$ \\

$\Pi$ & $0.8\left(\beta\_{c}+0.5\right)^{3 / 4}$ \\

$e$ & $3.7+1.5 \beta\_{c}$ \\

$d$ & $4.76(1.4 / \Delta)^{0.75}[0.375 e-1]$ \\

$R\_{T}$ & $\left(\delta / U\_{e}\right)\left(v / u\_{\tau}^{2}\right)$ \\

$ h^{\*}$ & $\min (3,(0.139+ \left.\left.3.1043 \beta\_{c}\right)\right)+7$\\

$d^{\*}$ & if $\left(\beta\_{c}<0.5\right)$, = $\max (1.0,1.5 d)$ , otherwise = d \\ \hline

\end{tabular}

\end{table}

Finally, the far-field SPL for one side of the $i^{th}$ section on the $n$th rotor blade is calculated from the acoustic power spectral density $S\_{pp}$ as

\begin{equation}

\mathrm{SPL}\_{\text {bb}\_{i(U,L)}}=10 \log \_{10}\left(\frac{2 \pi S\_{p p(U,L)}}{P\_0^2 } \right).

\end{equation}

The rotor’s total SPL can now be computed through decibel arithmetic

\begin{equation}

\mathrm{SPL}\_{\text {bb}\_n}=10 \log \_{10} \sum\_{i=1}^{n\_{S}}\left(10^{0.1 \mathrm{SPL}\_{\text {bb}\_{i,U}}}+10^{0.1 \mathrm{SPL}\_{\text {bb}\_{i,L}}}\right)

\end{equation}

\noindent where $n\_S$ is the total number of sections. Likewise, the total SPL of a vehicle with multiple rotors is given in Equation \ref{eq:total\_broadband} below:

\begin{equation}

\mathrm{SPL}\_{\mathrm{bb}\_{\text{tot}}}=10 \log \_{10} \sum\_{j=1}^{n}\left(10^{\left.0.1 \mathrm{SPL}\_{\mathrm{bb}, j}\right)}\right). \label{eq:total\_broadband}

\end{equation}

### Total Noise

The final step of the noise prediction methodology is the summation of the tonal and broadband components around the aircraft through decibel arithmetic.

Observer or microphone locations where the sound is computed are positioned in the inertial frame on the x-y plane beneath the aircraft, confined to the range of the aircraft in the longitudinal direction and maximum lateral distance of +/- 1000 feet in rectangular array as depicted in Figure \ref{fig:Observer\_Locations}. This suggests that as the aircraft gains altitude, the absolute distance from the noise sources on the aircraft each microphone.

Intro

 Aircraft Noise Characteristics and Metrics

 Community noise exposure is an integral factor in vertiport placement

Acoustic footprint of EC/VTOL aircraft will dictate approach and departure air-corridors

Current noise prediction methods fall on the extremities of the computational cost-accuracy spectrum

There is a need for a tool for iterative conceptual design

General Noise

History of noise prediction

Studie

Compitatin work

Propeller Noise

Limitationgs of prediciton

Layout

Propeller Noise Characteristics

Propeller noise car be classified into three categories: harmonic noise, broadband

noise, and narrow-band random noise. Harmonic noise is the periodic component, that is, its time signature can be represented by a pulse which repeats at a constant rate. If an ideal propeller with B blades is operating at constant rotational speed N, then the resulting noise appears as a signal with fundamental frequency BN The blade-passage period is I/BN. Typically the generated pulse is not a pure sinusoid, so that many harmonics exist These occur at integer multiples of the fundamental frequency. The first harmonic is the fundamental, the second harmonic occurs at twice the fundamental frequency. and so on. Figure 4 illustrates the characteristics of harmonic noise in both the time and frequency domains. Broadband noise is random in nature and contaiis components at all freq-iencies

A typical broadband noise signal for propellers is shown in figure 5. The frequency spectrum is continuous, although there may be a "shape" to it because not all frequencies have the same amplitude. Narrow-band random noise is almost periodic. However, examination of the

harmonies reveals that the energy is not concentrated at isolated frequencies, but rather it is spread out. As illustrated in figure 6 the signal may appear periodic, but certain components do not repeat exact!y with time. The frequency spectrum shows discrete components, but these spread out, particularly at the higher frequencies

Steady Sources Steady sources are those which would appear constant in time to an observer

on the rotating blade. They produce periodic noise because of their rotation Noise sources are usually divided into three categories linear thickness, linear loading, and (nonlinear) quadrupole Thickness noise arises from the transverse periodic displacement of the air by

the volume of a passing blade element. Tie amplitude of this noise component is proportional to tle blade volume, with frequency characteristics dependent on the shape of the blade cross section (airfoil shape) and rotational speed. Thickness noise can be represented by a monopole source distribution and becomes important at high speeds Thin blade sections and planforin sweep are used to control this noise.

Loading noise is a combination of thrust and torque (or lift and drag) components

which result from the pressure field that surrounds each blade as a consequence of its motion. This pressure disturbance moving in the medtum propagates as noise. Loading is an important mechanism at low to moderate speeds. For moderate blade section speed, the thickness and loading sources are linear and

act on the blade surfaces. When flow over the blade sections is transomc, nonlinear effects can become significant. In aeroacoustic theory these can be modeled with quadrupole sources distributed in the volume surrounding the blades. In principle, the quadrupole could be used to account for all the viscous and propagation effects not covered by the thickness and loading sources. However, the only practical application of this term to propeller acoustics has been its evaluation in the nonviscous flow close to the blade surface. At

Linear Theories As given by Farassat (ref. 5), the linear form of the Ffowcs Williams and Hawkings

equation is v2 1 02p I OpVnjVfj6(f)] ~ ~~~l()

1

where the left side is the well-known linear wave operator acting on the acoustic pressure p. The right side contains the source terms resulting from the motion of surfaces in the fluid: p is the ambient density, c is the ambient speed of sound, v. is the local velocity of the surface hormal to itself, 6(f) is the Dirac delta function, x% is the observer position, and 1, is the ith component of the iurface force. The first source term represents the effect of the blades parting the air and produces what is known as "thicknes noise." The second term represents the action of the blade forces on the air and produces "loading noise." In equation (1), the presence of the surfaces is accounted for by the factors

containing f, where f = 0 is the equation of the blade surface. Unless very high frequencies are considered (wavelengths of the order of blade thickness), details of the

airfoil section can be ignored. The source term is thus simplified, so that equation (1) becomes

v2p I 02pT2 5 T (2)

where now the thickness source can be thought of as being represented by a volume distribution of sources (and sinks) of strength q. The loading source is represented by

Time-domain methods-are used to solve equations (1) or (2) directly in terms

of the space-time variables. These methods are appealing because they can treat blade geometry with any desired level of precision., The result is the prediction of the acoustic pressure waveform p(t). If noise harmonics are needed, p(t) is Fourier transformed numerically.

FRequency-domain mnethods eliminate time from the wave equation by means of

Fourier transformation. Some precision in the representation of blade geometry is usually lost through the transformnatio 'n, but this loss is generally acceptable

for harmonics to a fairly high order. The transformation also gives rise to Bessel functions which are indicators of radiation efficiency. Harmonics are computed one

at a time and waveforms are generated by summing a Fourier series.

Time-Domain Methods The most prolific proponent of time-domain methods for propellers and rotors

has been Farassat. Papers listed in the References section can be used to trace the

derdot;-uof is formulations 1, IA, 2, and I. The preferred fornulations are coded in the Aircraft Noise Prediction Program (ANOPP, ref 9) and the Dum- Farassat-Padula Advanced Turboprop Prediction (DFP-ATP, reL 10) program and re described brily beow. Formulation IA, used in both ANOPP and DFP-ATP forsubsonic source regions,

gives the acoustic premure p(t) as foilowu

Frequency-Domain Methods A transformation to the frequency domain eliminates the need for computing

retarded blade locations and numerical derivatives. By representing blades as helicoidal surfaces, far-field noise formulas that are easily coded on a personal computer can be derived. Effective radius versions can even be computed by hand with the help of a Bessel function table. Furthermore, these formulas give direct insight to the influence of blade geometry and operating conditions on the sound harmonics. The first successful propeller noise theory by Gutin (ref. 15) was in harmonic

form. This theory was extended by various investigators; one of these was Hanson, whose versions included effects of thickness, forward flight, and blade sweep (refs. 16 to 18). Hanson's formulas are described below in enough detail for programming. To arrive at his simple results, the approximation is made that the thickness and loading sources act on the advance helix, that is, on the surface swept out by a radial line that rotates at angular speed 12 and translates at the flight speed V. Of course, the aerodynamic loading comes from the fact that blades are at an angle of attack relative to the helical surface. However, once the loading is determined from an aerodynamic analysis, the thickness and loading sources are transferred to the advance helix for the radiation calculation This transfer corresponds to linearization of the boundary condition to the free-stream direction in wing theory. With this simplification, the sources can be modeled with the terms on the right in equation (2), and the far-field pressure can be found from the free-space Green's function in the following form (refs. 16 and 17):