

Exposition of Noise Fraction Adjustments for Integrated Noise Modeling of Rotorcraft

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The noise fraction adjustment is one of several adjustments to noise/power/distance data that are used to estimate sound exposure in integrated noise modeling. The noise fraction adjustment relates the sound exposure due to an infinitely long flyover to that generated by a finite segment using a fourth-power dipole model. This paper elucidates the origins and derivation of the noise fraction adjustment. Alternative formulations of the noise fraction adjustment are offered that may be better suited for different helicopter and urban air mobility vehicles and their different operational modes, that is, departure, overflight, and approach. These different formulations can alter noise fraction estimates by several decibels.

Nomenclature

E	=	total sound exposure, $\text{Pa}^2 \cdot \text{s}$
F	=	noise fraction
L	=	sound pressure level, dB
$\mathcal{L}$	=	finite flight-path segment length, ft, m
L_E	=	sound exposure level, dB
L_{EPN}	=	effective perceived noise level, EPNdB (Effective Perceived Noise Level in decibels)
L_{PNT}	=	tone-corrected perceived noise level, PNdB (Perceived Noise Level in decibels)
PCPA	=	perpendicular closest point of approach
p^2	=	mean square pressure, Pa^2
$\mathbb{R}$	=	set of real numbers
$\mathcal{S}$	=	power model order coefficient
s	=	distance between flight path and observer at perpendicular closest point of approach, ft, m
t	=	time, s
V	=	airspeed, ft/s, m/s
x	=	observer location, ft, m
$\mathbb{Z}$	=	set of integers
τ	=	time difference between aircraft position and perpendicular closest point of approach, s

Subscripts

A	=	A-weighted
mx	=	maximum value
o	=	reference value
v	=	arbitrary flight-path segment

I. Introduction

THE integrated noise modeling method, as recommended for fixed-wing air vehicles in International Civil Aviation Organization (ICAO) Doc. 9911 [1] and as implemented in the Federal Aviation Administration (FAA) Aviation Environmental Design Tool (AEDT) [2], is used to estimate community noise exposure

in the vicinity of airports. The AEDT also applies a similar methodology in the analysis of noise exposure due to helicopter operations. Recent work by Rizzi and Rafaelof [3] using the AEDT demonstrated the modeling of rotary-wing vehicles, specifically types being developed for urban air mobility (UAM) operations, in both AEDT fixed-wing and helicopter modes, irrespective of their actual vehicle architectures. Subsequent work by Letica and Rizzi [4] focused on investigating best practices for modeling UAM vehicle noise using the AEDT in fixed-wing and helicopter modes. A comparative study [5] between simulation, using the NASA Aircraft Noise Prediction Program 2 [6] Mission Analysis Tool (AMAT), and integrated noise modeling, using the FAA AEDT, was conducted for the NASA Quadrotor reference vehicle [7]. It was found that the differences between the AEDT fixed-wing and helicopter mode analyses were due to several factors. These included 1) the lack of an explicit lateral directivity adjustment LD_{ADJ} in the AEDT fixed-wing mode (see Sec. II.B); 2) a limitation in the number of unique helicopter mode noise/power/distance (NPD) data that could be used in departure, approach, and overflight; and 3) apparent differences in the noise fraction adjustment applied to fixed-wing and helicopter modes in the landing and takeoff area. Note that the lateral directivity adjustment referred to here is separate from the lateral attenuation adjustment, which includes engine installation, refraction-scattering (air to ground), and ground effect (ground to ground) propagation effects [1]. It should be noted that the noise fraction adjustment in Doc. 9911 was developed to represent the sound pressure level time history for large, jet-powered commercial transports [8], so the applicability of the adjustment to UAM vehicles is unknown.

The purpose of this paper is to elucidate the formulation and function of the noise fraction adjustment as currently recommended in Doc. 9911. To that end, in Sec. II.B, a short review of the integrated noise modeling method is offered to provide context for the noise fraction adjustment among several other adjustments used for noise exposure estimation. Simple examples of departure, overflight, and approach operations are used to demonstrate that exposure estimates in the AEDT fixed-wing and helicopter modes can be made practically equivalent by modeling operations in a way that minimizes differences between the various adjustments. Following that, a thorough treatment of the noise fraction adjustment is made to explain both its origin and its application. Formulations alternative to that recommended in Doc. 9911 are derived to explore the possibility of selecting different forms for different aircraft and operations. Finally, the fitness of each of several formulations to different helicopters and UAM concept vehicles is assessed using data derived from helicopter acoustic flight tests [9–11] and midfidelity analyses [12], respectively. This work is aligned with a recommendation of a recent white paper [13] that research “be conducted to more fully explore limitations in methods for assessing community noise impact of UAM vehicles in their operational environments, and to generate a software development plan that addresses the limitations of current models over time.”

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II. Review of Integrated Noise Modeling

This section reviews the contemporary integrated noise modeling method, that is, using flight-path segmentation, for estimation of sound exposure at a set of ground observers. It discusses differences between modeling the aircraft as fixed-wing and helicopter types, starting with the NPD data that serve as input to those analyses.

A. Noise-Power-Distance Data

NPD data express measures of noise at a ground observer as a function of a noise-related engine power parameter and the slant distance between the source and ground observer. The noise-related engine power parameter specified in fixed-wing NPD data is the corrected net thrust per engine, that is, the net thrust referenced to standard air pressure at mean sea level. There is no noise-related power parameter for helicopter NPD data. Instead, helicopter NPD data are provided for a set of operational modes, for example, approach at constant speed. Each noise measure corresponds to an infinitely long, straight-line flight trajectory under steady conditions, at a specified reference speed, atmospheric condition, and configuration. They are provided over a range of reference distances and power levels (for fixed-wing aircraft) and operational modes (for helicopters). NPD measures include maximum and time-integrated (exposure) noise metrics. Maximum metrics include the maximum A-weighted sound pressure level $L_{A_{\text{mx}}}$ and the maximum tone-corrected perceived noise level L_{PNTmx} . Sound exposure metrics include the A-weighted sound exposure level L_{A_E} and the effective perceived noise level L_{EPN} . As will be shown in Sec. III.A, both maximum level and exposure metrics are needed to estimate noise exposure when using (finite) flight-path segmentation.

The NPD data are provided by original equipment manufacturers. For fixed-wing aircraft, SAE-AIR-1845A [14] provides standardized methods to derive NPD data from measured flyover noise levels and known engine and flight conditions. There is no standard for calculating helicopter NPD data.

In some cases, sets of manufacturer-provided NPD data may lack one or more maximum level metrics. These missing data can be approximated by an empirical method discussed in Sec. III.A.3.

B. Segmentation Method

The internationally recommended segmentation modeling method for fixed-wing aircraft is detailed in ICAO Doc. 9911 [1] (see also ECAC/CEAC Doc. 29 [15]). In this approach, the flight path is divided into a contiguous set of straight-line segments of finite length. The noise exposure at each ground observer is computed by summing the noise exposure from all flight-path segments. The maximum level at each ground observer is computed as the maximum of all segment maxima, which may be from a segment other than the closest segment.

Exposure noise metrics are calculated at each segment's perpendicular closest point of approach (PCPA), or slant range, and are further described in Sec. III.A. For fixed-wing aircraft, noise exposure metrics at a given distance are calculated by interpolating and/or extrapolating the NPD data between power settings and between reference distances. Although helicopters are not addressed by Doc. 9911 and Doc. 29, they are included in some computer implementations, notably the AEDT helicopter mode. The AEDT interpolates/extrapolates helicopter NPD data between reference distances only and not between operational modes.

After the NPD data are interpolated for each segment of the flight path, several adjustments must be made to account for various factors that determine the sound exposure at each observer. All adjustments for sound exposure estimates due to a single path segment v of a flight operation are given for fixed-wing aircraft as

$$10 \log_{10}(E_v) = L_{E,P,d-\text{ADJ}} + F_{\text{ADJ}} + \text{DUR}_{\text{ADJ}} - L_{A_{\text{ADJ}}} + \text{TR}_{\text{ADJ}} + \text{DIR}_{\text{ADJ}} \quad (1)$$

and for helicopters as

$$10 \log_{10}(E_v) = L_{E,P,d-\text{ADJ}} + F_{\text{ADJ}} + \text{DUR}_{\text{ADJ}} - L_{A_{\text{ADJ}}} + \text{MN}_{\text{ADJ}} + \text{LD}_{\text{ADJ}} \quad (2)$$

In Eqs. (1) and (2), the terms describing the sound exposure and adjustments are defined as follows:

$L_{E,P,d-\text{ADJ}}$: Sound exposure, L_{A_E} or L_{EPN} , in decibels, interpolated for power P (fixed-wing only) and slant range s (both fixed-wing and helicopter) from the receptor to the PCPA on the flight-path segment or extended flight-path segment, and adjusted for atmospheric absorption and acoustic impedance (to account for differences between the reference-day condition associated with the NPD data and that of the particular study).

F_{ADJ} : Noise fraction adjustment, in decibels (see Sec. III)

DUR_{ADJ} : Duration adjustment = $10 \log_{10}[V_0/V]$, in decibels, in which V_0 is the reference speed for the operation and V is the segment speed. The reference speed may be different for helicopter departure, overflight, and approach operations, but is 160 kt for all fixed-wing operations.

$L_{A_{\text{ADJ}}}$: Lateral attenuation adjustment, in decibels

TR_{ADJ} : Thrust reverser adjustment, in decibels (fixed-wing only, not currently implemented in Doc. 9911)

DIR_{ADJ} : Directivity adjustment, in decibels, (fixed-wing only, applied only if segment is part of takeoff ground roll)

MN_{ADJ} : Advancing tip Mach number adjustment, in decibels (helicopters in level flight only)

LD_{ADJ} : Lateral directivity adjustment, in decibels (helicopters only) Additional information on each of the adjustments can be found in Ref. [2].

This work is focused on F_{ADJ} , the noise fraction adjustment. NPD data measurements (or simulations) are provided assuming an infinitely long flyover. As each segment is treated as a finite part of the infinitely long flyover used in the generation of the NPD data, an adjustment must be made to the interpolated sound exposure to determine the fraction of the infinite path sound exposure that is attributable to the finite segment. A semi-empirical relationship called the noise (or energy) fraction is used to apportion the noise exposure data of the infinite segment to each finite segment. The noise fraction adjustment is discussed in detail in Sec. III.

C. Simplified Departure, Overflight, and Approach Operations

Analyses of three simplified operations (departure, overflight, and approach) were performed in the AEDT to demonstrate that the fixed-wing and helicopter mode adjustments in Eqs. (1) and (2) can either be made equal, that is, the same for fixed-wing and helicopter modes, or eliminated. This results in practically identical noise exposure estimates for the two modeling approaches. Doing so allows differences in the noise fraction adjustment between fixed-wing and helicopter modes to be isolated, for example, landing and takeoff rolls; see Sec. III.A.5. Simplified operations were modeled primarily to avoid the AEDT limitation of allowing only one helicopter operating state (determined by a combination of airspeed and climb angle) to represent a departure at constant speed (operational mode procedural step D) and another to represent an approach at constant speed (operational mode procedural step A). Furthermore, fixed-point flight profiles were used when modeling the aircraft in AEDT fixed-wing mode [16], thus allowing identical operating states for fixed-wing and helicopter analyses without use of a nonexistent UAM performance model.

To the greatest extent possible, the same operating states for fixed-wing and helicopter were specified for the simplified departure, overflight, and approach operations. These are summarized in Table 1 for the fixed-wing mode and in Table 2 for the helicopter mode. The fixed-wing and helicopter NPD data used were taken from those generated in Ref. [12]. The operating states for which NPD data were chosen included 20 kt, 10 deg climb for all departure steps; 90 kt, 0 deg climb for all overflight steps; and 20 kt, -10 deg climb for all approach steps.

With respect to Eq. (1), fixed-wing types were specified as propeller-driven aircraft to set 1) the thrust reverser adjustment to zero and 2) the engine installation portion of the lateral attenuation

Table 1 Fixed-point flight profile data for modeling simplified operations in fixed-wing mode

Operation mode	Distance along track, ft	Altitude, ^a ft	Speed, kt
Departure	0	15	20
	15,000	2660	20
	15,001	2660	20
Overflight	0	1000	90
	31,680	1000	90
	0	2660	20
Approach	1	2660	20
	15,001	15	20

^aAbove field elevation (departure and approach), mean sea level (overflight).

Table 2 Operational procedural steps for modeling simplified operations in helicopter mode

Operation mode	Operational procedural step (AEDT)	Segment length, ft	Ending altitude ^a , ft	Ending speed, kt	Duration, s
Departure	G	—	0	—	0.001
	H	—	0	—	0.001
	V	—	15	—	0.001
	E	1	15	20	—
	D	14,999	2660	20	—
	L	1	2660	20	—
Overflight	S	—	1000	90	—
	L	31,680	1000	90	—
Approach	S	—	2660	20	—
	L	1	2660	20	—
	A	14,999	15	20	—
	B	1	15	0	—
	Y	—	0	0	0.001
	H	—	0	—	0.001
	G	—	0	—	0.001

^aAbove field elevation (departure and approach), mean sea level (overflight).

adjustment to zero. The remaining portions of the lateral attenuation adjustment are ground reflection and refraction effects, which are common between fixed-wing and helicopter analyses. The special cases of noise fraction adjustments for receptors before the start of takeoff roll and receptors after the end of landing roll (to be discussed in Sec. III.A.5) and for the takeoff roll directivity adjustment (DIR_{ADJ}, all particular to fixed-wing mode, were avoided by not including takeoff and landing rolls. With respect to Eq. (2), the advancing tip Mach number adjustment was eliminated by setting the B coefficients that are used to tune the adjustment to zero [2], and the lateral directivity adjustment was eliminated by setting the lateral (± 45 deg) NPD data to be identical to the centerline NPD data. Further, the noise exposure from static helicopter operational mode procedural steps (G, H, V, Y) [2], for which there is no fixed-wing equivalent, was minimized by specifying a minimal duration for each. These modes are required according to the mandatory operational mode procedural step sequences for helicopters. More general practices for modeling UAM vehicles in AEDT fixed-wing and helicopter modes can be found in Refs. [3,16].

A-weighted sound exposure level estimates for each operation are shown in Fig. 1. In all cases, the differences between fixed-wing and helicopter mode results were negligible, with a maximum average difference of <0.004 dBA.

III. Noise Fraction Adjustment

The noise fraction represents the fractional relationship between the sound exposure associated with an infinitely long flyover under steady conditions and that associated with a finite segment of that flyover. It can be written as

$$F_{12} = E_{12}/E_{\infty} \quad (3)$$

in which E_{12} is the sound exposure associated with the finite flight-path segment and E_{∞} is the sound exposure associated with the infinite flight path. The noise fraction for a given flight-path segment is based on both the geometrical relationship between the segment and the observer [8] and the sound exposure level and maximum sound level interpolated from the NPD data at the observer location[‡]. The derivation parallels Ref. [1], which follows from a private memorandum[§] with a few extra steps to assist the reader. Additionally, a general form allowing for arbitrary powers beyond the fourth-power model is provided in Sec. III.B. In the following, E is assumed to be A weighted total sound exposure.

A. Fourth-Power Model

Figure 2 shows a straight, level flyover of a vehicle on a finite flight-path segment extending from point P_1 to point P_2 within an infinite flight path extending to $\pm\infty$. An observer is positioned at location x , q_1 is the distance from P_1 to the PCPA, and the time difference between them is $\tau_1 = t_1 - t_s$. For a constant segment flyover speed V , q_1 is given by

$$q_1 = -V\tau_1 \quad \text{for } q_1 > 0 \quad (4)$$

The total sound exposure associated with an arbitrary flight-path segment and an arbitrary observer is

$$E_v = \int_{\tau_1}^{\tau_2} p^2(\tau) d\tau \quad (5)$$

in which $p^2(\tau)$ is the mean square sound pressure at the observer at time τ . The fourth-power 90 deg dipole model of sound radiation uses the following formulation of $p^2(\tau)$,

$$p^2(\tau) = p_s^2 \left(\frac{s^2}{r^2} \right) \sin^2 \theta \quad (6)$$

in which p_s^2 is the mean square sound pressure at the observer when the vehicle is at the PCPA, s is the positive distance from the flight path to the observer (or from the extended flight path to the observer for points behind P_1 and ahead of P_2) at the PCPA, and r is the distance from point P_1 to the observer ($r > 0$). Note that r and θ are functions of τ . The mean square sound pressure $p^2(\tau)$ is assumed to be a maximum when the vehicle is at the PCPA, that is,

$$\max(p^2(\tau)) = p_s^2 \quad (7)$$

In Eq. (6), the quantity (s^2/r^2) represents spherical spreading loss and the 90 deg dipole expression $\sin^2 \theta$ approximates other physical phenomena including atmospheric attenuation, source directivity, Doppler shift, etc.[¶]. The source directivity given by the sin squared term is discussed more fully in Sec. III.B.

1. Behavior of Fourth-Power Model

From Fig. 2, it is seen that $\sin^2 \theta = s^2/r^2$. This reduces Eq. (6) to

$$p^2(\tau) = p_s^2 \left(\frac{s^4}{r^4} \right) \quad (8)$$

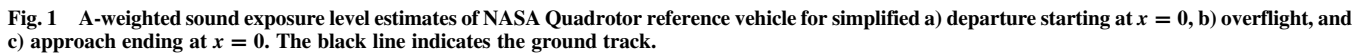
in which the mean square pressure is seen to decrease as $\sim 1/r^4$ (hence *fourth-power model*). The maximum A-weighted sound pressure level L_{Amx} is defined as

$$L_{\text{Amx}} = 10 \log_{10} \left[\frac{\max(p^2(\tau))}{p_o^2} \right] \quad (9)$$

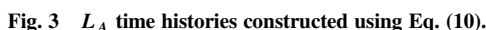
[‡]Private communication with J. Olmstead, ATAC Corporation, December 1998.

[§]Private communication with J. Olmstead, ATAC Corporation, October 1994 and December 1998.

[¶]Private communication with J. Olmstead, ATAC Corporation, October 1994.


$$L_A(\tau) = L_{\text{Amx}} + 10 \log_{10} \left[\frac{s^4}{r^4(\tau)} \right] \quad (10)$$

2. Noise Fraction Based on Geometry Only

$$r^2 = s^2 + q_1^2 = s^2 + (-V\tau)^2 \quad (11)$$
$$\frac{r^2}{s^2} = 1 + \left(\frac{V\tau}{s}\right)^2 \quad (12)$$

$$\sin^2 \theta = s^2/r^2 = 1/\left(1 + \left(\frac{V\tau}{s}\right)^2\right) \quad (13)$$
$$\alpha = \frac{V\tau}{s}, \quad d\alpha = \frac{V}{s} d\tau \quad (14)$$
$$E_v = p_s^2 \frac{s}{V} \int_{\alpha_1}^{\alpha_2} \frac{1}{(1 + \alpha^2)^2} d\alpha \quad (15)$$
$$E_v = p_s^2 \frac{s}{V} \frac{1}{2} \left[\frac{\alpha}{1 + \alpha^2} + \tan^{-1} \alpha \right] \Big|_{\alpha_1}^{\alpha_2} \quad (16)$$
$$E_{12} = p_s^2 \frac{s}{V2} \left[\frac{\alpha_2}{1 + \alpha_2^2} + \tan^{-1} \alpha_2 - \frac{\alpha_1}{1 + \alpha_1^2} - \tan^{-1} \alpha_1 \right] \quad (17)$$
$$E_{\infty} = p_s^2 \frac{s \pi}{V 2} \quad (18)$$
$$F_{12} = \frac{E_{12}}{E_\infty} = \frac{1}{\pi} \left[\frac{\alpha_2}{1 + \alpha_2^2} + \tan^{-1} \alpha_2 - \frac{\alpha_1}{1 + \alpha_1^2} - \tan^{-1} \alpha_1 \right] \quad (19)$$
$$\alpha_1 = -\frac{q_1}{s}, \quad \alpha_2 = \frac{\mathcal{L} - q_1}{s} \quad (20)$$
$$F_{\text{ADJ}} = 10 \log_{10}(F_{12}) \quad (21)$$
$$L_{\text{AE}} = 10 \log_{10} \left[\frac{E_v}{p_o^2 t_o} \right] \quad (22)$$

in which $p_o = 20 \mu\text{Pa}$ and $t_o = 1 \text{ s}$ are the reference pressure and time, respectively. In essence, L_{AE} represents the total sound energy of the event *compressed* into the reference time. An *effective* value of the mean squared pressure p_{eff}^2 represents a value that produces the same sound exposure level as the original event when applied at a constant level over a period of 1 s. In other words, Eq. (5) gives

$$E_v = \int_{t_1}^{t_2} p^2(\tau) d\tau = p_{\text{eff}}^2 t_o \quad (23)$$

Consider the sound pressure time history $p^2(\tau)$ for an idealized flyover shown by the blue triangle in Fig. 4. The area under the triangle represents the total sound exposure due to the flyover event. Equation (23) states that the area under the dark blue triangle is equal to the area of the light blue rectangle. Analogous to the effective pressure, a useful means of expressing the relationship between L_{AE} and L_{Amx} is through the *effective duration* Δt_{eff} (see footnote ¶), shown by the red rectangle in Fig. 4. Here, the L_{AE} associated with the red rectangle is the same as both the blue triangle and blue rectangle.

Mathematically, the total sound exposure represented by the red rectangle is

$$E_v = \max(p^2(\tau)) \Delta t_{\text{eff}} \quad \text{or} \quad \Delta t_{\text{eff}} = \frac{E_v}{\max(p^2(\tau))} \quad (24)$$

Adding a unity factor on the right-hand side and converting to decibel referenced to $t_o = 1 \text{ s}$ gives

$$\begin{aligned} 10 \log_{10} \left[\frac{\Delta t_{\text{eff}}}{t_o} \right] &= 10 \log_{10} \left[\frac{E_v}{\max(p^2(\tau)) t_o} \frac{1}{p_o^2} \right] \\ &= 10 \log_{10} \left[\frac{E_v}{p_o^2 t_o} \right] - 10 \log_{10} \left[\frac{\max(p^2(\tau))}{p_o^2} \right] \\ &= L_{\text{AE}} - L_{\text{Amx}} \end{aligned} \quad (25)$$

Thus, we find that the relationship between L_{AE} and L_{Amx} can be represented by Δt_{eff} , a value with units of time. This relationship is important because it identifies the key principles by which sound energy is incorporated into the geometric noise fraction Eq. (19). These two quantities are those typically provided by aircraft manufacturers and are key to the noise prediction methodology.

a. Where's My L_{Amx} ? Several fixed-wing aircraft and nearly all helicopters in the AEDT aircraft noise and performance (ANP) database lack maximum noise level (L_{Amx} and L_{PNTmx}) NPD data. Although it is alluded to in the context of the recommended method for aircraft substitution, there is no explicit provision for making up for the lack of those data in Doc. 9911 [1]. The provision in AEDT for doing so approximates maximum noise level data using empirical equations as a function of distance and L_{AE} . The approximation was developed from statistical analysis of NPD data containing all

four of the NPD metrics defined in Sec. II.A. Given that nearly all helicopters lack the four NPD metrics, it is surmised that the approximation is based either solely or largely on data from fixed-wing aircraft. Nevertheless, the same approximation is applied to both helicopters and fixed-wing aircraft. The approximation is given as [2]

$$L_{\text{Amx}} = L_{\text{AE}} - 7.19 - 7.73 \log_{10} \left(\frac{s}{1000} \right) \quad (26)$$

in which the distance at the PCPA s is given in feet. Under this approximation, the effective duration is given by

$$\Delta t_{\text{eff}} = 10^{-\frac{7.19 + 7.73 \log_{10} \left(\frac{s}{1000} \right)}{10}} \quad (27)$$

In practice, Eq. (26) is used to approximate L_{Amx} at all 10 NPD distances preceding its interpolation to the observer distance.

4. Noise Fraction Based on Geometry and Sound Energy

Olmstead (see footnote ‡) recognized a deficiency in the noise fraction that is based solely on geometry. In demonstrating this, he considered the case of a finite segment of 270.05 ft flown at the reference speed of 160 kt [1]. This resulted in a flight time of $\Delta \tau = 1 \text{ s}$. When the PCPA lies somewhere along this flight segment, L_{AE} and L_{Amx} should be equal according to Eq. (25). However, Olmstead showed that the fourth-power model given by Eq. (19) underpredicts the value of L_{AE} relative to the known value of L_{Amx} at all observer distances, with the discrepancy growing larger with increasing distance. Thus, the purely geometric fourth-power model does not adequately capture all the physics of sound exposure from a flight-path segment, and the sound energy associated with the noise exposure and maximum level must both be accounted for in the noise fraction.

To incorporate the known values of L_{AE} and L_{Amx} into the geometry noise fraction Eq. (19), the relationship based on Eqs. (22) and (9) must hold [2],

$$L_{\text{AE},0} - L_{\text{Amx}} = 10 \log_{10} \left[\frac{V}{V_o} \frac{E_{\infty}}{p_o^2 t_o} \right] - 10 \log_{10} \left[\frac{\max(p^2(\tau))}{p_o^2} \right] \quad (28)$$

in which $L_{\text{AE},0}$ and L_{Amx} represent the NPD data for the segment's operational mode procedural step, interpolated for distance with reference speed V_o . Note that L_{Amx} is the interpolated maximum level at the PCPA on the extended flight path (see Fig. 2), not the interpolated maximum level at the closest point of approach. The factor of V/V_o is included in the L_{AE} term to correct the sound exposure level from the segment airspeed V to the reference airspeed of the NPD V_o . The NPD data represent an infinite flyover, so E_{∞} is used to represent the sound exposure. Substituting Eqs. (7) and (18) from the fourth-power model into Eq. (28) yields

$$L_{\text{AE},0} - L_{\text{Amx}} = 10 \log_{10} \left[\frac{V}{V_o} \frac{p_s^2 \frac{s}{V} \frac{\pi}{2}}{p_o^2 t_o} \right] - 10 \log_{10} \left[\frac{p_s^2}{p_o^2} \right] \quad (29)$$

which simplifies to

$$10^{\frac{L_{\text{AE},0} - L_{\text{Amx}}}{10}} = \frac{\pi}{2} \frac{s}{V_o t_o} \quad (30)$$

Note that from Eq. (25) the left-hand side of Eq. (30) is the effective duration $\Delta t_{\text{eff}}/t_o$. Solving for s yields

$$s = \frac{2}{\pi} t_o V_o 10^{\frac{L_{\text{AE},0} - L_{\text{Amx}}}{10}} \quad (31)$$

This s represents the slant distance at which calculation of the noise fraction correctly reflects the unadjusted, interpolated noise

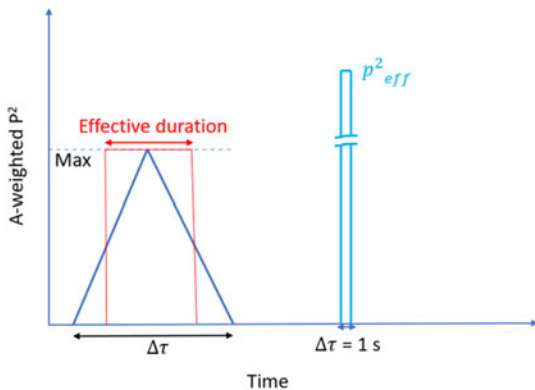


Fig. 4 Relationship between L_{AE} , L_{Amx} , and Δt_{eff} .

exposure and maximum level values in the NPD database. As it is essentially a scaling factor, it is called the *scaled distance* s_L , and Eq. (31) may be rewritten as

$$s_L = s_o \frac{\Delta t_{\text{eff}}}{t_o}, \quad s_o = \frac{2}{\pi} t_o V_o \quad (32)$$

This particular form of s_o , like the form of the effective duration in Eq. (25), is a consequence of the fourth-power model. Both the scaled distance and effective duration indicate how L_{AE} and L_{Amx} are related for a given event.

Finally, Eq. (32) can be substituted into Eq. (20) to obtain α_1 and α_2 in terms of s_L giving

$$\alpha_1 = -\frac{q_1}{s_L}, \quad \alpha_2 = \frac{\mathcal{L} - q_1}{s_L} \quad (33)$$

Equations (19) and (33) constitute the fourth-power noise fraction formulae that are specified in Doc. 9911 [1].

The noise fraction adjustments for the NASA Quadrotor reference vehicle for single segment departure, overflight, and approach operations are shown in Fig. 5. The departure segment consists of a 20 kt, 10 deg climb starting at an altitude of 15 ft at $x = 0$, over a track length of 15k ft. The 90 kt, level overflight segment at 500 ft altitude extends from $-1000 \leq x \leq 1000$ ft. The approach segment consists of a 20 kt, 10 deg descent ending at an altitude of 15 ft at $x = 0$, over a track length of 15k ft. All NPD data are taken from Ref. [12].

5. Special Cases for Takeoff and Landing Ground Roll Segments

The noise fraction differs for takeoff and landing ground roll segments. In the special case of the takeoff ground roll segment, Eqs. (19) and (33) are still used, but with the caveat that, for this segment only, all observers at points for which $q_1 < 0$, that is, observers behind the takeoff roll, are treated as $q_1 = 0$. This leads to Eqs. (19) and (33) taking new, simplified forms (for these observers only) as

$$F_{12,d} = \frac{1}{\pi} \left[\frac{\alpha_2}{(1 + \alpha_2^2)} + \tan^{-1}(\alpha_2) \right], \quad \alpha_2 = \frac{\mathcal{L}}{s_L} \quad (34)$$

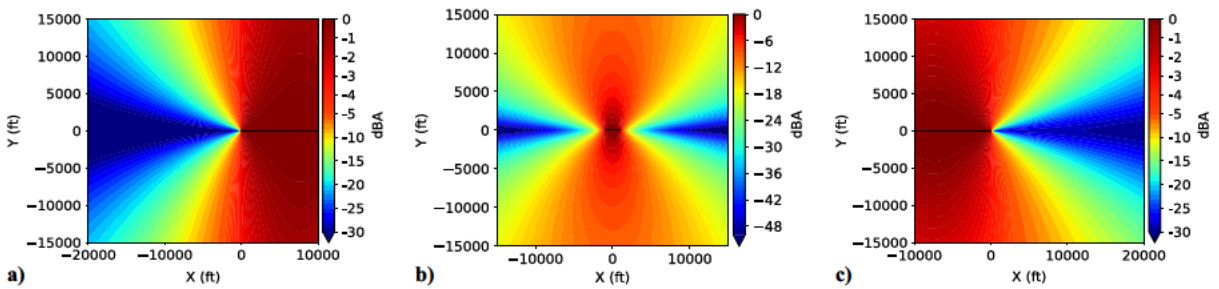


Fig. 5 Noise fraction adjustment (in dBA) of NASA Quadrotor reference vehicle for a) departure, b) overflight, and c) approach. The black line indicates the ground track.

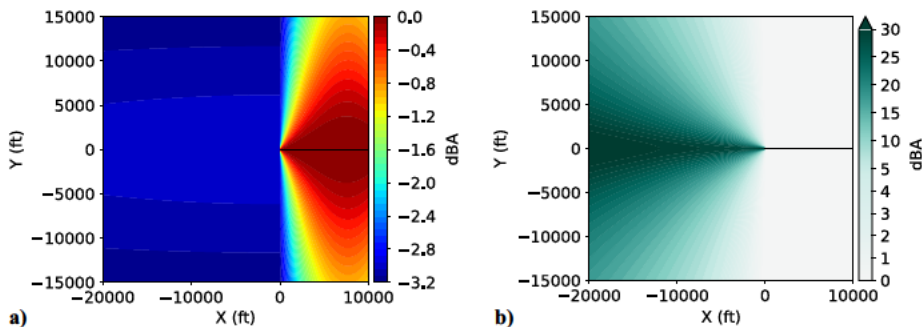


Fig. 6 Special case of noise fraction adjustment (in dBA) for takeoff ground roll of the NASA Quadrotor reference vehicle. The black line indicates the ground track.

Likewise, in the special case of the landing ground roll segment, all observers at points for which $q_1 > \mathcal{L}$, that is, observers beyond the landing roll, are treated as $q_1 = \mathcal{L}$, leading to

$$F_{12,a} = \frac{1}{\pi} \left[-\frac{\alpha_1}{(1 + \alpha_1^2)} - \tan^{-1}(\alpha_1) \right], \quad \alpha_1 = \frac{-\mathcal{L}}{s_L} \quad (35)$$

There is no specific justification offered by Refs. [1,2,15] for using these forms. However, Eqs. (34) and (35) are those used in current practice when modeling vehicles as fixed-wing aircraft. This form is not used when modeling vehicles as helicopters (AEDT only), as ground roll segments cannot be used when modeling in AEDT helicopter mode. In addition, when a takeoff ground roll segment is present, it is accompanied by the takeoff roll directivity adjustment DIR_{ADJ} .

The noise fraction adjustment for the departure with takeoff ground roll is shown in Fig. 6a. The noise fraction shown does not account for the takeoff ground roll directivity adjustment. Figure 6b indicates the difference between Eq. (19) using the scaled distance and Eq. (34), that is, the difference between Figs. 5a and 6a. This special case adjustment for takeoff ground roll ($x \leq 0$) replaces the large attenuation seen in Fig. 5a with a minimum attenuation of 3 dBA (at the origin) which slowly increases with increasing slant range.

The noise fraction adjustment for the approach with landing ground roll is shown in Fig. 7a. Figure 7b indicates the difference between Eq. (19) using the scaled distance and Eq. (35), that is, the difference between Figs. 5c and 7a. As in Fig. 6, the special case adjustment for landing ground roll ($x \geq 0$) replaces the large attenuation seen in Fig. 5c.

B. Alternative Power Models

Powers of the sine-squared term, other than those in the fourth-power model, can be derived in an attempt to better represent the physical phenomena embedded in the measured NPD data. These relationships can be summarized by writing the approximation of the physical phenomena as $\sin^{n-2} \theta$, in which n is the desired power. Figure 8 shows the directivity for several powers of n , with that of a monopole given by $n = 2$. Figure 9 shows an example of how the chosen power affects the time history of a flyover, keeping the altitude and speed constant. Increasing the power of the model decreases the area under the sound pressure

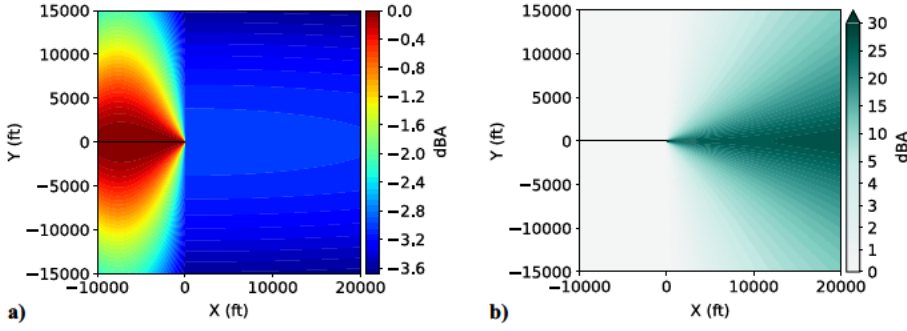


Fig. 7 Special case of noise fraction adjustment (in dBA) for landing ground roll of Quadrotor reference vehicle. The black line indicates the ground track.

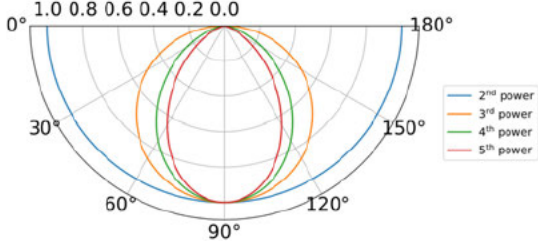


Fig. 8 Power model directivity for different integer values of n .

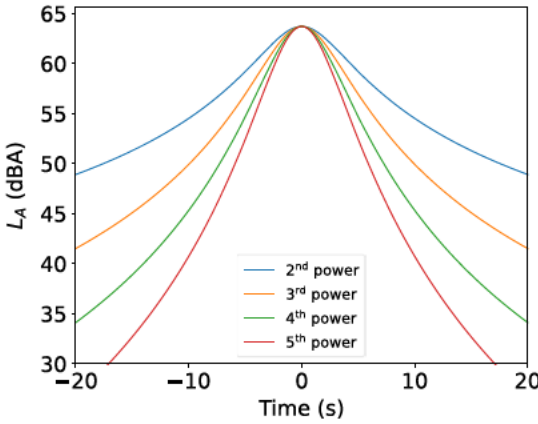


Fig. 9 The n -th-power models of L_A time history for constant speeds and altitudes.

level time history curve. In other words, it decreases the predicted difference between L_{AE} and $L_{A_{mx}}$ and thereby decreases the effective duration Δt_{eff} . Note that $n > 0$ is required for the maximum sound pressure at the observer to occur when the vehicle is at the PCPA.

New relationships for quantities of interest can be derived by starting with the substitution of $\sin^{n-2} \theta$ in Eq. (6), giving

$$p^2(\tau) = p_s^2 \left(\frac{s^2}{r^2} \right) \sin^{n-2} \theta = p_s^2 \left(\frac{s^n}{r^n} \right) \quad (36)$$

After some algebra, Eq. (36) can be used to rederive Eq. (14), shown in its indefinite form as

$$E_v = p_s^2 \frac{s}{V} \int \frac{1}{(1 + \alpha^2)^{n/2}} d\alpha \quad (37)$$

1. Real-Valued Power Models

The solution to Eq. (37) for $n \in \mathbb{R}$ is given as [17]

$$E_v = p_s^2 \frac{s}{V} \alpha_2 F_1 \left(\frac{1}{2}, \frac{n}{2}; \frac{3}{2}; -\alpha^2 \right) \quad (38)$$

in which ${}_2F_1$ is the Gaussian hypergeometric function. Equation (38) is defined for all $\alpha \in \mathbb{R}$. The improper integral for E_∞ can be evaluated using the known solution [17]

$$E_\infty = p_s^2 \frac{s}{V} \int_{-\infty}^{\infty} \frac{1}{(1 + \alpha^2)^{n/2}} d\alpha = p_s^2 \frac{s}{V} B \left(\frac{1}{2}, \frac{n-1}{2} \right) \quad (n > 1) \quad (39)$$

in which $B(z_1, z_2)$ is the beta function. The power-specific effective duration Δt_{eff} and s_o may then be obtained by evaluating Eq. (28) using Eq. (39), giving

$$s_o = S t_o V_o \quad \frac{\Delta t_{eff}}{t_o} = \frac{s}{V S} \quad (40)$$

in which S is a power model order coefficient defined by

$$S = \frac{1}{B \left(\frac{1}{2}, \frac{n-1}{2} \right)} \quad (41)$$

The final form of the noise fraction becomes

$$F_{12} = \frac{E_v}{E_\infty} = S \left[\alpha_2 {}_2F_1 \left(\frac{1}{2}, \frac{n}{2}; \frac{3}{2}; -\alpha_2^2 \right) - \alpha_1 {}_2F_1 \left(\frac{1}{2}, \frac{n}{2}; \frac{3}{2}; -\alpha_1^2 \right) \right] \quad (42)$$

with α_1 and α_2 defined by Eq. (33) and the scaled distance defined by

$$s_L = S t_o V_o 10^{\frac{L_{AE,0} - L_{A_{mx}}}{10}} \quad (43)$$

Equation (42) reduces to elementary functions for some integer values of n .

2. Integer Power Models

An alternate form of Eq. (37) for $n \geq 2$ and $n \in \mathbb{Z}^+$ using recursion can be written as [17]

$$E_{v,n}(\alpha) = p_s^2 \frac{s}{V} \frac{\alpha}{(n-2)(1 + \alpha^2)^{(n-2)/2}} + \frac{n-3}{n-2} E_{v,n-2}(\alpha) \quad (44)$$

with

$$E_{v,2}(\alpha) = p_s^2 \frac{s}{V} \arctan \alpha, \quad E_{v,3}(\alpha) = p_s^2 \frac{s}{V} \frac{\alpha}{\sqrt{1 + \alpha^2}} \quad (45)$$

The noise fraction for different integer power models, obtained through evaluation of Eqs. (39), (44), and (45), are provided in Table 3. Each power model yields a different expression for each of the four quantities in Table 3. They also each reflect a unique implicit relationship between L_{AE} and $L_{A_{mx}}$, which is most clearly seen through the effective duration Δt_{eff} .

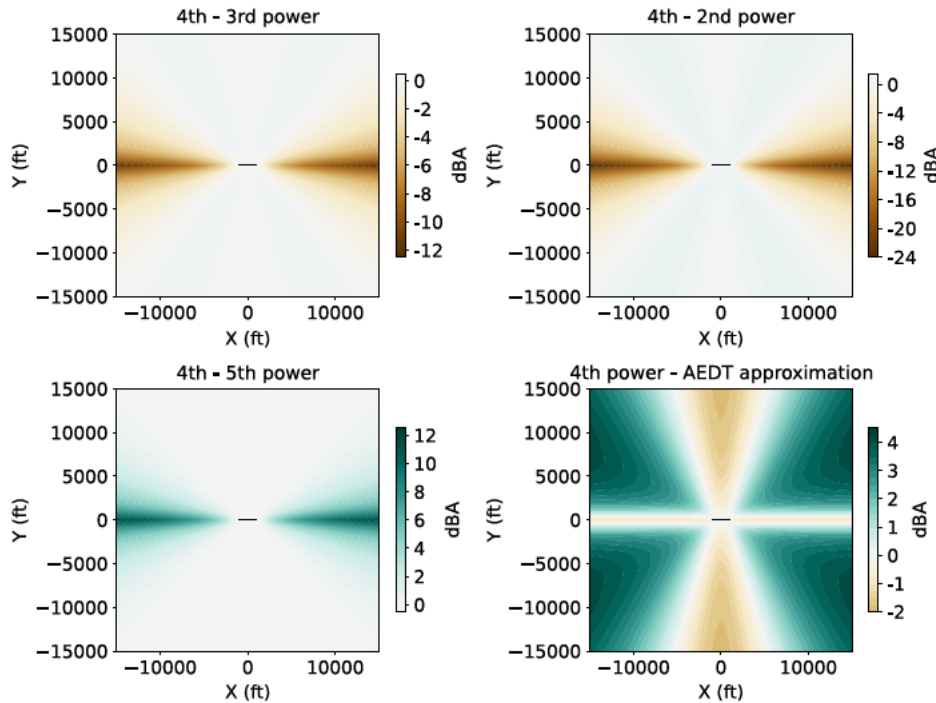
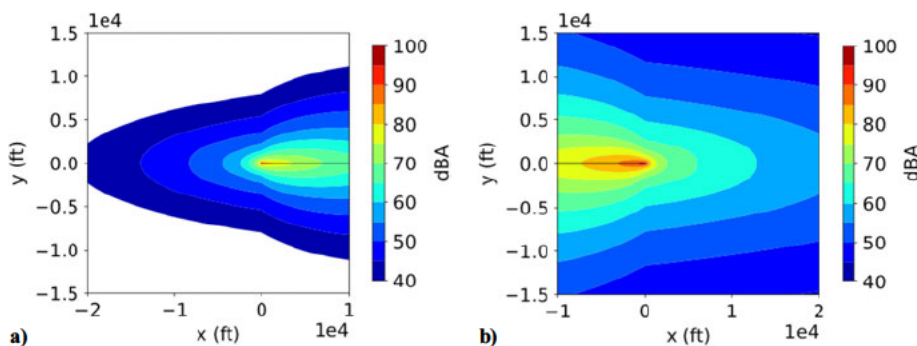
Table 3 E_{∞} , F_{12} , $\mathcal{S}$, Δt_{eff} , and s_o for different model powers

Power	E_{∞}	F_{12}	$\mathcal{S}$	Δt_{eff}	s_o
2	$\pi \frac{s}{V} p_s^2$	$\frac{1}{\pi} [\tan^{-1} \alpha_2 - \tan^{-1} \alpha_1]$	$\frac{1}{\pi}$	$\pi \frac{s}{V}$	$\frac{1}{\pi} t_o V_o$
3	$2 \frac{s}{V} p_s^2$	$\frac{1}{2} \left[\frac{\alpha_2}{\sqrt{1+\alpha_2^2}} - \frac{\alpha_1}{\sqrt{1+\alpha_1^2}} \right]$	$\frac{1}{2}$	$2 \frac{s}{V}$	$\frac{1}{2} t_o V_o$
4	$\frac{\pi s}{2V} p_s^2$	$\frac{1}{\pi} \left[\frac{\alpha_2}{1+\alpha_2^2} - \frac{\alpha_1}{1+\alpha_1^2} + \tan^{-1} \alpha_2 - \tan^{-1} \alpha_1 \right]$	$\frac{2}{\pi}$	$\frac{\pi s}{2V}$	$\frac{2}{\pi} t_o V_o$
5	$\frac{4s}{3V} p_s^2$	$\frac{1}{4} \left[\frac{3\alpha_2 + 2\alpha_2^3}{(1+\alpha_2^2)^{3/2}} - \frac{3\alpha_1 + 2\alpha_1^3}{(1+\alpha_1^2)^{3/2}} \right]$	$\frac{3}{4}$	$\frac{4s}{3V}$	$\frac{3}{4} t_o V_o$

For the level flyover scenario depicted in Fig. 5 (center), the difference between the fourth-power model with $\Delta t_{\text{eff}} = (\pi/2)(s/V)$ and the other power models is shown in Fig. 10. Differences in the noise fraction adjustment between the fourth- and third-power models are generally negative and up to 12 dBA over the range of observers shown. Note that negative differences between the baseline fourth-power model and the queried models indicate less attenuation by the queried model than that of the baseline. Small positive differences are seen along roughly 60 deg side lobes from the segment endpoints.

Greater negative differences of up to 24 dBA are seen between the fourth- and second-power models, with small positive differences along the 60 deg side lobes. Mostly positive differences of up to 12 dBA are seen between the fourth- and fifth-power models, with small negative differences along the 60 deg side lobes. The difference between the fourth-power model noise fraction and that computed using Eq. (27), the AEDT approximation, is shown in the lower right plot of Fig. 10, in which smaller positive (about 4 dBA) and negative (about 2 dBA) differences are observed compared with the differences seen between power models.

It should be noted that the segment reference speed V_o used for calculating the scaled distance in Eq. (40) must be consistent with that used for $L_{\text{AE},0}$ or the L_{AE} NPD data. This is unambiguous in the case of fixed-wing aircraft in the AEDT because all NPD data are provided for a common reference speed of 160 kt. However, in the case of the helicopter mode, departure, overflight, and approach may have different reference speeds. Consequently, there is potential to provide inconsistent data in the scaled distance calculation. This can have a dramatic effect on noise exposure estimates. For example, if erroneously using a 160 kt reference speed with 20 kt L_{AE} NPD data, the noise exposure contours take on an elongated shape (compare those in Fig. 11 with those in Fig. 1).

**Fig. 10** Difference in noise fraction adjustment (in dBA) between different power models for overflight. The black line indicates the ground track.**Fig. 11** Example of sound exposure level estimates for a) departure and b) approach when using reference speeds that are inconsistent with the NPD data. The black line indicates the ground track.

IV. Assessment of n th-Power Models for Helicopters and UAM Vehicles

The fitness of each n th-power model to represent the effective duration Δt_{eff} of different helicopters and UAM concept vehicles was assessed using available NPD data derived from helicopter acoustic flight tests [9–11] and midfidelity analyses [12], respectively. Simulations of maximum and noise exposure metrics for departure, overflight, and approach operations were performed using the AMAT according to the method developed in Ref. [12]. Each simulation used source noise hemispheres corresponding to a single operating state defined by a unique pair of flight speeds and climb angles. The AEDT database for helicopters was not useful for this purpose because it lacks L_{Amx} data, forcing it to use the empirical model in Eq. (26).

A. Helicopters

Source noise hemisphere data derived from helicopter flight tests were selected from a set of light helicopter weight class data, including the Robinson R44, Robinson R66, Bell 206L3, Bell 407, AS350B3, and EC130B4 [10], and medium helicopter weight class data, including the Bell 205, AW129, and S76D [9,11]. Source noise hemispheres for all the helicopters were available for approach and constant airspeed level flight, typically between 40 kt and V_H , the maximum speed at which an aircraft can fly in level flight at maximum continuous power. V_H varies depending on helicopter model from about 130 to 155 kt. A limited number of departure operating states are available for the Bell 205 and S76D. A list of operating states for which NPD data were generated is provided in Table 4.

Comparisons of the effective duration computed using the NPD data per Eq. (30) and the various models computed per Table 3 are summarized in Figs. 12–15. The AS350B3 overflight mode L

Table 4 Helicopter operating states used for NPD data generation

Vehicle	Operating state: speed, kt; climb angle, deg		
	Departure	Overflight	Approach
R44	—	100/0	60/−10.5
R66	—	100/0	60/−9
B206L3	—	100/0	60/−10.5
B407	—	100/0	60/−10.5
AS350B3	—	100/0	60/−10.5
EC130B4	—	100/0	60/−10.5
B205	70/11.5	100/0	60/−9
AW129	—	100/0	60/−10.5
S76D	75/9.3	100/0	60/−9

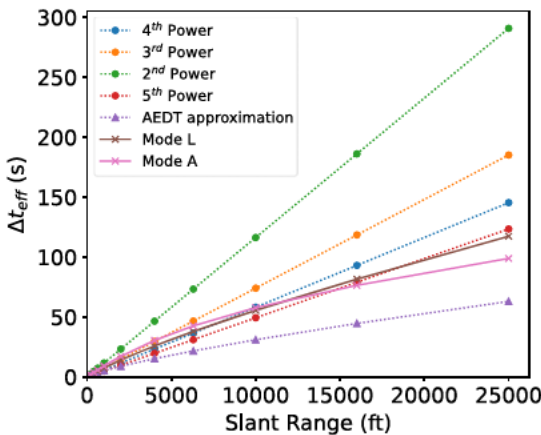


Fig. 12 Comparison of effective duration of AS350B3 with model variants.

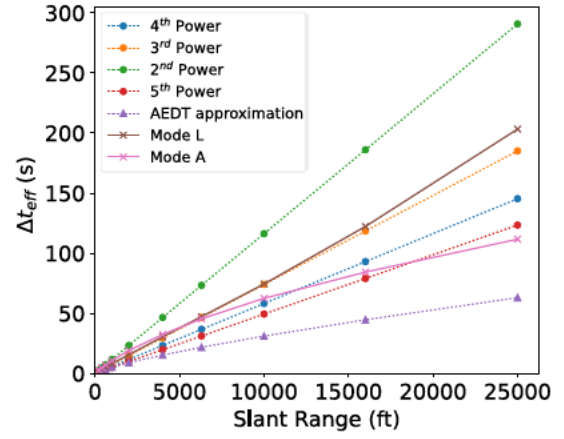


Fig. 13 Comparison of effective duration of EC130B4 with model variants.

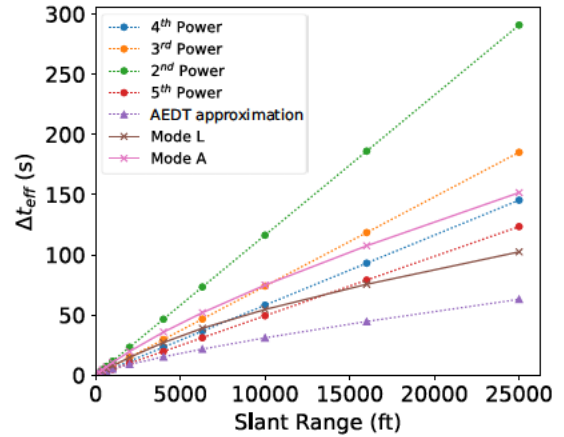


Fig. 14 Comparison of effective duration of R44 with model variants.

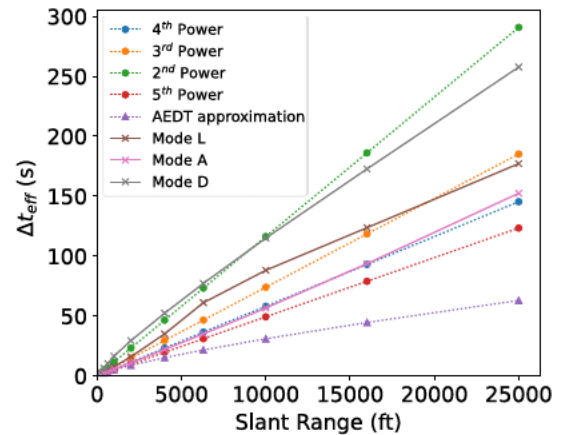


Fig. 15 Comparison of effective duration of B205 with model variants.

closely follows the fifth-power model with approach mode A falling somewhat below the fifth-power mode, as shown in Fig. 12. The AW139, B206L3, and B407 helicopters (all omitted for brevity) exhibit similar behaviors. It should be noted that Δt_{eff} for all power models is linear with slant range, except for the AEDT approximation model using Eq. (27). However, the effective durations from the flight-test-derived NPD data are not linear with slant range and are generally more (sideways) parabolic relative to slant range. Lastly, as noted in Sec. III.A.3, most helicopters in the AEDT ANP database lack manufacturer-provided L_{Amx} data. In such cases, Eq. (27) is used, which forces the effective duration to follow the AEDT

approximation curve, causing a maximal difference relative to the fourth-power model. The EC130B4 (shown in Fig. 13) and R66 (not shown) show a different trend, with overflight mode L more closely following the third-power model and approach mode A more closely following the fourth- to fifth-power model.

In contrast to the data shown in Figs. 12 and 13, the relation of the overflight mode L to the approach mode A for the R44 helicopter is reversed, with mode A more closely following the third- to fourth-power models and with mode L closest to the fifth-order model as shown in Fig. 14. For the two helicopters with all three operational modes (B205 and S76D), the departure mode D most closely follows the lower-power models (second- to third-power), with overflight mode more closely following the third- to fourth-power models, and the approach mode more closely following the fourth- to fifth-power model. Data for the B205 are shown in Fig. 15, with those for the S76D omitted for brevity.

Given the fact that there are areas of large differences in the noise fraction adjustment between different power models (Fig. 10), the helicopter data suggest that use of a vehicle-specific and operational mode-specific power model would be beneficial versus the current practice of exclusive use of the fourth-power model. Further, if different power models are not implemented in a future version of AEDT, then provision of L_{Amx} data by manufacturers as part of the NPD data would eliminate the use of Eq. (26) and would minimize differences with the fourth-power model.

B. Urban Air Mobility Vehicles

Source noise hemisphere data [12], derived from source noise predictions of NASA UAM reference vehicles including the Quadrotor and Lift+Cruise vehicles [7], were used in simulations of departure, overflight, and approach operations. A list of operating states for which NPD data were generated is provided in Table 5.

Comparisons of the effective duration computed using the NPD data and the models are shown in Figs. 16 and 17 for the Quadrotor and Lift + Cruise reference vehicles, respectively.

The overflight mode L and approach mode A of the Quadrotor vehicle closely follow the fifth-power model, while the departure mode D closely follows the AEDT approximation. The departure mode D for the Lift + Cruise vehicle also closely follows the AEDT approximation. Below the 10,000 ft reference distance, the overflight mode L and approach mode A also closely follow the AEDT

Table 5 UAM vehicle operating states used for NPD data generation

Reference vehicle	Operating state: speed, kt; climb angle, deg		
	Departure	Overflight	Approach
Quadrotor	20/10	90/0	20/ - 10
Lift + Cruise	20/10	110/0	20/ - 10

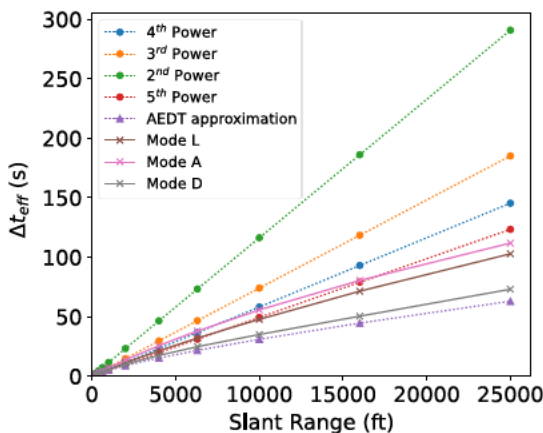


Fig. 16 Comparison of effective duration of NASA Quadrotor reference vehicle with model variants.

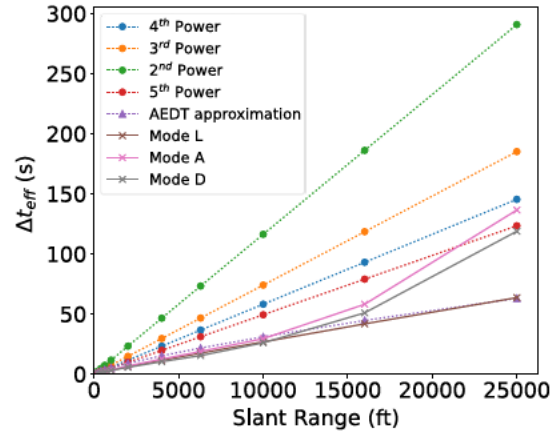


Fig. 17 Comparison of effective duration of NASA Lift + Cruise reference vehicle with model variants.

approximation but rise to the fifth- and fourth-order model curves, respectively, with increasing distance. This reflects an increasing difference between L_{Amx} and L_{AE} with increasing distance. Like the helicopter data, the UAM vehicle data suggest that use of a vehicle-specific and operational mode-specific power model would be beneficial versus the current practice of exclusive use of the fourth-power model.

V. Conclusions

In an effort to understand differences between integrated noise modeling using AEDT fixed-wing and helicopter modes, analyses of simplified departure, overflight, and approach operations were performed. These analyses demonstrated near-identical noise exposure estimates in both modes when adjustments, including the noise fraction adjustment, are made equivalent. However, it is imperative that the reference speed used in the scaled distance calculation of the noise fraction adjustment be consistent with the speed associated with the sound exposure level metric specified as part of the NPD data. Significant distortions of noise contours occur when inconsistent data are used.

A review of the fourth-power noise fraction adjustment model showed that the noise fraction for a given flight-path segment is based on both the geometrical relationship between the segment and the observer and the sound exposure level and maximum sound level interpolated from the NPD data at the observer location. Other power models, including second-, third-, and fifth-power models, were offered following the fourth-power model formulation. Significant differences in the noise fraction adjustment between different power models were observed in some areas. An assessment of NPD data for helicopters and UAM reference vehicles indicated that differences in the effective duration, used in the noise fraction adjustment, were both vehicle and operational-mode dependent. This suggests that improved noise exposure estimates could be made if alternative power models were made available within AEDT. The choice of power model for a particular vehicle/operation can be based on an analysis of the relevant NPD data set, specifically the relationship between the effective duration and observer distance. Comparisons with measured and/or simulated sound exposure data would be worthwhile to confirm this observation.

Ultimately, the AEDT aircraft mode used, that is, fixed wing or helicopter, will be dependent on several factors. These include what type of NPD data are provided (rarely is it the case that both fixed-wing and helicopter NPD data are specified for the same vehicle), how the takeoff and landing are modeled (with or without ground roll), and how the various other adjustments sum to produce sound exposure estimates. Limitations associated with each mode, both those identified herein with respect to the noise fraction adjustment and others in Ref. [3], indicate that modifications to the AEDT would be beneficial to the integrated noise modeling of rotary-wing vehicles.

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