



**REPORT ON STANDARD METHOD OF COMPUTING
ROTORCRAFT NOISE CONTOURS**

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FOREWORD

Predicting rotorcraft noise is a complex task. It is highly non-linear and varies strongly with emission angle, which in turn depends on the rotorcraft's climb and descent angles. Consequently, although guidance on fixed-wing aircraft noise prediction has existed for several decades, it has not addressed rotorcraft noise. Various attempts have been made to adapt fixed-wing noise modelling methodologies for rotorcraft, but these have not been endorsed by ECAC.

This guidance details the development and application of a methodology for rotorcraft noise modelling. It responds to the need for accurate noise prediction in aviation, specifically addressing the complexities associated with rotorcraft noise. The guidance outlines the methodology's foundation, its practical steps for noise contour generation, and the rationale behind its approach.

The underlying methodology uses hemispheres to describe the rotorcraft noise source, which capture the complex and directive nature of its noise. It combines the theoretical background with empirical data, ensuring a balanced approach to rotorcraft noise modelling. This guidance therefore contributes to a more informed understanding of environmental noise prediction of rotorcraft, offering a reliable tool for strategic assessments of noise.

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EXPLANATION OF TERMS AND SYMBOLS

Some important **terms** are described here by the general meanings attributed to them in this document. The list of terms is not exhaustive; only expressions and acronyms used frequently are included. Others are described where they first occur.

The mathematical **symbols** (listed after the terms) include those that are predominantly used in equations in the main text. Other symbols used locally in both the text and the appendices are defined where they are used.

The reader is reminded periodically of the interchangeability of the words *sound* and *noise* in this document. Although the word *noise* has subjective connotations, it is usually defined by acousticians as “unwanted sound”. In the field of aircraft noise control, however, it is commonly taken to mean just sound - airborne energy transmitted by acoustic wave motion.

The “→” denotes cross references to other terms included in the list.

Terms

AIP	Aeronautical Information Publication
Rotorcraft movement	An arrival, departure or other rotorcraft action that affects noise exposure around an aerodrome or helipad.
Altitude	Height above mean sea level.
A-weighted sound pressure level, L_A	Sound level scale used for measuring environmental noise including that from rotorcraft and on which most noise contour metrics are based.
Backbone ground track	A representative or nominal ground track which defines the centre of a swathe of tracks.
Cumulative sound level	A decibel measure of the noise received over a specified period of time, from rotorcraft movements. It is calculated by accumulating the event sound levels occurring at that point.
Decibel sum or average	Sometimes referred to elsewhere as “energy” or “logarithmic” (as opposed to arithmetic) values. Used when it is appropriate to sum or average the underlying energy-like quantities, e.g. $decibel\ sum = 10 \cdot \lg \sum 10^{L_i/10}$.
Effective Perceived Noise Level	(Acronym EPNL). A scale that applies different weights to sound of different frequencies and the duration of the noise event to mimic human perception.
EPNL	→ <i>Effective Perceived Noise Level</i>
Equivalent (continuous) sound level, L_{eq}	A measure of long-term sound. The level of a hypothetical steady sound, which over a specified period of time, contains the same total energy as the actual variable sound.
Event noise level	A decibel measure of the finite quantity of noise received from a passing rotorcraft → <i>sound exposure level</i> .
Flight parameters	Rotorcraft climb or descent angle and speed.

Flight path	The path of a rotorcraft through the air, defined in three dimensions, usually with reference to the start or end of the flight.
Flight path segment	Part of a rotorcraft flight path represented for noise modelling purposes by a line of finite length.
Flight profile	Variation of rotorcraft height and speed along the ground track described by a set of → <i>profile points</i> .
Ground impedance	The characteristic of a ground surface that results in sound absorption as sound passes over a ground surface at shallow angles.
Ground plane	(Or Nominal Ground Plane) Horizontal ground surface through the study reference point on which the contours are normally calculated.
Ground speed	Rotorcraft speed relative to a fixed point on the ground.
Ground track	Vertical projection of the flight path onto the ground plane.
Height	Vertical distance between rotorcraft and → <i>ground plane</i> .
Integrated sound level	Otherwise termed → <i>single event sound exposure level</i> .
Maximum sound level	The maximum sound level reached during an event.
Noise	Noise is defined as unwanted sound. But metrics such as → <i>A-weighted sound level (L_A)</i> and → <i>effective perceived noise level (EPNL)</i> effectively convert sound levels into noise levels. The terms sound and noise are used interchangeably in this document, as elsewhere - especially in conjunction with the word <i>level</i> .
Noise contour	A line of constant value of a cumulative rotorcraft noise level or index.
Noise impact	The adverse effect(s) of noise on its recipients; importantly it is implied that noise metrics are indicators of noise impact.
Noise index	A measure of long-term, or cumulative sound exposure. The noise index may take some account of factors in addition to the magnitude of sound (especially time of day). An example is day-evening-night level, <i>L_{den}</i> .
Noise level	A decibel measure of sound on a scale which indicates its loudness or noisiness. For environmental noise from aircraft, two scales are generally used: A-weighted sound level and Perceived Noise Level (PNL). These scales apply different weights to sound of different frequencies to mimic human perception.
Noise metric	An expression used to describe any measure of noise at a receiver position, whether it be a single event or an accumulation of noise over extended time. There are two commonly used measures of single event noise: the → <i>maximum level</i> reached during the event, or its → <i>sound exposure level</i> , a measure of its total sound energy determined by time integration.
Observer	→ <i>Receiver</i>

Perceived Noise Level	(Acronym PNL) A scale that applies different weights to sound of different frequencies to mimic human perception.
PNL	→ <i>Perceived Noise Level</i>
Profile point	Height and speed of flight path segment end point - in a vertical plane above the ground track.
Receiver	A recipient of noise that arrives from a source; principally at a point on or near the ground surface.
Reference day	A set of atmospheric conditions on which the associated data are standardised.
Reference duration	A nominal time interval used to standardise single event sound exposure level measurements; equal to 1 second in the case of → <i>SEL</i> .
SEL	→ <i>Sound Exposure Level</i>
Single event sound exposure level	The sound level an event would have if all its sound energy were compressed uniformly into a standard time interval known as the → <i>reference duration</i> .
Sound	Energy transmitted through air by (longitudinal) wave motion which is sensed by the ear.
Sound attenuation	The decrease in sound intensity with distance along a propagation path. For rotorcraft noise, its causes include spherical wave spreading and atmospheric absorption.
Sound exposure	A measure of total sound energy immission over a period of time.
Sound Exposure Level, L_{AE}	(Acronym SEL) A metric standardised in ISO 1996-1, ref. [1.] = A-weighted single event sound exposure level referenced to 1 second.
Sound intensity	The strength of sound immission at a point related to noise energy (and indicated by measured sound levels).
Sound level	A measure of sound energy expressed in decibel units. Received sound is measured with or without "frequency weighting"; levels measured with a weighting are often termed → <i>noise levels</i> .
True airspeed	Actual speed of rotorcraft relative to air (equivalent to groundspeed in still air during level flight).
Weighted equivalent sound level, $L_{eq,W}$	A modified version of L_{eq} in which different weights are assigned to noise occurring during different periods of the day (for day-evening-night level, L_{den}).

Symbols

c	Speed of sound
d	Shortest distance from an observation point to a flight path segment
d_p	Perpendicular distance from an observation point to the flight path (slant distance or slant range)
$EPNL$	Effective Perceived Noise Level
f_c	Centre frequency
F_{fc}	Flight condition scaling factor
h	Rotorcraft altitude (above MSL)
L	Event noise level (scale undefined)
$L_{A,} L_A(t)$	Time-averaged A-weighted sound pressure level (at time t)
L_{AE}	(SEL) Sound Exposure Level [ref. [1.]]
L_{Amax}	Maximum value of $L_A(t)$ during an event
L_E	Single event sound exposure level
L_{eq}	Equivalent (continuous) sound level
$L_{id,j}$	Rotorcraft sound pressure level for class i and flight path index j
\tilde{L}_{id}	Rotorcraft hemisphere time-averaged sound pressure level for class id
L_o	Instantaneous sound pressure level at an observer
ΔL_p	Atmospheric propagation correction term, comprises those effects relating to spherical spreading, atmospheric attenuation and ground absorption
ℓ	Perpendicular distance from an observation point to the ground track
\lg	Logarithm to base 10
N	Number of segments or sub-segments
r	Hemisphere radius
R	Radius of turn
S	Standard deviation
s	Distance along ground track
t	Time
t_e	Effective duration of a single sound event
t_0	Reference time for integrated sound level
V	Groundspeed
\bar{V}	Normalised groundspeed
x, y, z	Local coordinates
x', y', z'	Rotorcraft coordinates
$X_{ARP}, Y_{ARP}, Z_{ARP}$	Position of study reference point in geographical coordinates
z	Height of rotorcraft above ground plane / study reference point
z'	Set of values of height of rotorcraft for sub-segmentation
γ	Flight path angle

$\bar{\gamma}$	Normalised flight path angle
φ	Azimuth angle between rotorcraft and ground observer
λ	Total segment length
ρ	Air density
θ	Polar angle between rotorcraft and ground observer
Δ	Change in value of a quantity, or a correction (as indicated in the text)

Subscripts

1, 2	Subscripts denoting start and end values of an interval or segment
<i>a</i>	atmospheric absorption
<i>A</i>	A-weighting or denoting airborne value of a parameter
<i>c</i>	centre
<i>e</i>	emission
<i>E</i>	Exposure
<i>g</i>	ground
<i>h</i>	hemisphere
<i>i</i>	frequency band index. The numerical indicator that denotes any one of the 30 one-third octave bands with nominal geometric mean frequencies from 10 to 10 000 Hz.
<i>id</i>	rotorcraft class index
<i>j</i>	time dependent flight path index
<i>k</i>	point summation index
<i>l</i>	interpolation index
<i>max</i>	maximum
<i>p</i>	propagation
<i>r</i>	recorded or noise receiver
<i>ref</i>	reference value
<i>s</i>	spherical
<i>seg</i>	segment specific value
<i>t</i>	time

1 INTRODUCTION

1.1 AIM AND SCOPE OF DOCUMENT

Noise contour maps are used to indicate the extent and magnitude of noise impact. A contour is a line along which the specified noise metric or index value is constant. The index value aggregates all the individual aircraft noise events that occur during a specified period of time, normally measured in days or months (see ECAC.CEAC Doc 29 **Volume 1** [2.] for a review).

Noise calculation methods in Europe developed for fixed-wing aircraft are described in ECAC Doc 29 [2.]. Unlike fixed-wing aircraft noise, rotorcraft noise emission is strongly dependent on flight conditions and varies heavily with emission angles. In order to obtain high-fidelity noise prediction, a dedicated method is required to model rotorcraft noise. This document describes a complementary method to model rotorcraft noise for strategic noise mapping purposes using hemispheres.

The guidance targets both *practitioners* and *modellers*. The guidance fully describes a specific noise contour modelling method which is considered by ECAC to represent current best practice. It does not prescribe a computer program but rather the equations and logic that need to be programmed to construct a physical “working model”. Any physical model that complies fully with the methodology described can be expected to generate contours of rotorcraft noise exposure with reasonable accuracy. The methodology is primarily designed to estimate long-term average noise exposure with multiple rotorcraft operations; whilst it can estimate time-varying sound pressure levels from a single rotorcraft movement, the uncertainties will be greater, and it should not be relied upon for that purpose.

Contours are generated by calculating surfaces of local noise index values mathematically. This document explains in detail how to calculate, at an observer point, the individual rotorcraft noise event levels, each for a specific rotorcraft flight or type of flight, which are subsequently averaged, or accumulated, to yield index values at that point. The required surface of index values is generated by repeating the calculations as necessary for different rotorcraft movements, taking care to maximise efficiency by excluding events that are not “noise-significant” (i.e. which do not contribute significantly to the total).

A linked Noise of Rotorcraft Assessed by a Hemisphere approach database (NORAH) is provided, and the recommended methodology is designed to make full use of this ECAC endorsed data source. The associated NORAH database includes rotorcraft trajectory and linked hemisphere data for an initial set of civil rotorcraft types that dominate rotorcraft noise in urban areas.

There are several local noise-generating activities on operational aerodromes and heliports which are excluded from the “air noise” calculation procedures given here. These activities typically include taxiing, engine testing, and use of auxiliary power units, and the noise of these activities generally comes under the heading of “ground noise” rather than “air noise”. In practice, the effects of these ground noise activities are unlikely to affect noise contours in regions beyond the aerodrome or heliport boundary, therefore assessments of ground noise are usually undertaken independently of air noise analyses.

1.2 OUTLINE OF THE DOCUMENT

It is assumed that users of this document are familiar with basic acoustic and noise modelling principles. A best practice *modelling methodology* is one of three requirements for valid noise contour modelling, the others are an accurate *rotorcraft noise hemisphere database* and a detailed understanding and description of the *rotorcraft operations*. All three requirements for valid noise contour modelling are covered in this document.

The noise contour generation process is illustrated in **Figure 1**. Noise contours are produced for various purposes, and these tend to control the requirements for sources and pre-processing of input data. Contours that depict historical noise impact might be generated from actual records of rotorcraft operations, for example, records of rotorcraft movements, rotorcraft types, or radar flight paths. Noise contours used for future planning and forecasting purposes rely on forecasts of traffic and flight tracks and the noise characteristics of future rotorcraft.

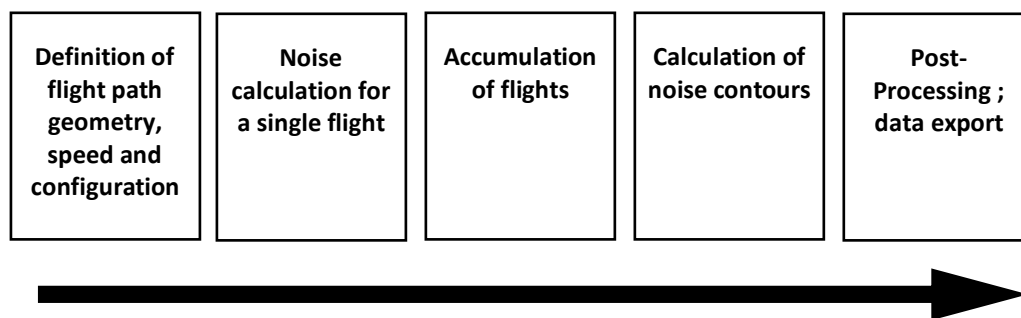


Figure 1: The noise contour generation process

Chapter 2 presents an overview and rationale for the recommended method. It sets out the rotorcraft classes based on the initial version of the NORAH database (i.e. NORAH Version 1 or NORAH1).

Chapter 3 outlines the input data requirements for producing a set of noise contours. Detailed specifications for the input data needed are set out in **Appendix A**.

Whatever the source of flight data, each different rotorcraft movement, arrival or departure, is defined in terms of its flight path geometry and the noise emission from the rotorcraft as it follows that path. Rotorcraft movements that are essentially the same in noise and flight path characteristics are represented by simple multiplication of operations. The noise emission depends on the characteristics of the rotorcraft and the trajectory it follows.

The calculation of the flight path segments from pre-processed input data is described in **Chapter 3**. Flight paths are subject to significant variability - rotorcraft often follow no predefined routes, and where they follow a route, they may be dispersed across a swathe due to a variety of factors.

Chapter 4 describes the acoustic source model which relies on linking flight path segment conditions to an associated noise hemisphere of the same or similar condition. The NORAH hemisphere format is described in **Appendix A**.

The recommended methodology involves dividing the flight path into segments, which are then further subdivided into time steps. **Section 4.3** outlines the elements of the methodology and explains the principle of segmentation on which it is based; that the observed event noise level is an aggregation of contributions from all "noise-significant" segments of the flight path, each of which can be calculated independently of the others. At present, the methodology is restricted to take-off (climb), flyover (level flight) and approach (descent) flight phases at different flight speeds and different climb and descent angles. All flight phases assume the rotorcraft is in level flight regardless of turns on ground

tracks. The methodology will be expanded to address bank angle during turning flight, and taxi and hover phases in a future edition.

Chapter 5 describes the adjustment of the reference hemisphere sound pressure levels for ground attenuation (ΔL_g), atmospheric attenuation (ΔL_a) and spherical spreading losses.

Chapter 6 describes the calculation of a single noise event. Unlike ECAC Doc 29, NORAH is not an integrated method, thus it calculates one-third octave band sound pressure levels at time t , from which the maximum noise level is calculated. Other noise metrics such as SEL and EPNL must be calculated using integration of the receptor time-based instantaneous noise levels.

Determining the noise event level for a single rotorcraft movement at a single observer point is the core calculation. It must be repeated for all aircraft movements at each of a prescribed array of points covering the expected extent of the required noise contours. At each point, the event levels are aggregated to arrive at a "cumulative level" or noise index value.

2 OVERVIEW AND RATIONALE OF THE METHOD

The rotorcraft noise modelling method allows the prediction of noise levels for standard rotorcraft operations targeting the most common types within the European helicopter fleet. The method starts by considering the noise levels at an observer location, \mathbf{x} . The observer location is a function of the time dependent rotorcraft location $\mathbf{y}(t)$ and centre frequency f_c associated with one-third octave band i :

$$L_o(f_c, \mathbf{x}, \mathbf{y}(t)) = L(f_c, \varphi, \theta, V, \gamma) + \Delta L_p \quad (1)$$

The observer noise level is decomposed in a source term L and an adjustment factor to account for atmospheric propagation ΔL_p . The latter term comprises those effects relating to spherical spreading, atmospheric attenuation and ground absorption.

For an accurate description of a given rotorcraft type, the method relies on sets of measured noise hemispheres, covering a broad range of lateral and polar emission angles and the relevant conditions in the flight envelope. Noise hemispheres provide a source description, given in one-third octave bands, from which SEL, EPNL, L_{ASmax} ¹ and other noise metrics can be derived.

A noise hemisphere approach is followed to describe the rotorcraft noise source. Next-generation rotorcraft noise models show a consensus that this hemisphere approach adequately captures the complex and highly directive nature of rotorcraft noise. Hemispheres are defined as a function of azimuth φ and polar angle θ , grouped in intervals of 10 degrees. This hemisphere approach differs from the Noise-Power Distance (NPD) methods for fixed-wing aircraft noise, allowing separate handling of the modelling of source and noise propagation and the detailed description of emission characteristics of rotorcraft noise.

To allow representation of a large portion of the European helicopter fleet based on a limited set of rotorcraft noise data, helicopter types with assumed similar noise characteristics are clustered together within a single class. The parameters considered to determine the classes are summarised in **Table 1**, where the premise is that noise caused by a specific rotorcraft type relates directly to these parameters. The resulting rotorcraft classes are specified in

Table 2, where only the classes comprising more than a single rotorcraft are given. In the source term $L_{id,j}$, id and j are, respectively, the rotorcraft class index and time dependent flight condition index.

Table 1: Parameter overview of collected configuration data and noise level information

Parameter	Explanation
Maximum Take-Off Weight [kg]	
Main rotor number of blades	
Main rotor direction of rotation (viewed from above)	CW = Clockwise, CCW = Counter-Clockwise, Co-ax = Coaxial rotors, Intermesh = intermeshing rotors
Tail rotor number of blades	
Tail rotor position	L = Left, R = Right, in fin = Fan-in-fin, NOTAR = No Tail Rotor
Engine type	P = Piston, T = Turbine
Engine number	
ICAO noise level, take-off [EPNdB]	for Chapter 8 helicopters

¹ The recommended data measurement method and hemisphere database definition assumes 0.5s time-averaged 1/3 octave band spectral data. Consequently, the method and data does not yield exponential time-weighted metrics, i.e. it is only an approximation of a measured L_{ASmax} , consequently, throughout this document, the maximum 0.5s time-averaged sound pressure level is used as a surrogate for L_{ASmax} .

ICAO noise level, overflight [EPNdB]	for Chapter 8 helicopters
ICAO noise level, approach [EPNdB]	for Chapter 8 helicopters
ICAO noise level, overflight [dBA]	for Chapter 11 helicopters

Table 2: Rotorcraft classes containing more than one rotorcraft type, types within square brackets denote geometrically mirrored configurations

Rotorcraft class	ATD	Included rotorcraft types
AS350 Ecureuil	AS50	AS50, ALO2, ALO3, LAMA, PSW4
Bell 206	B06	R66, B06, B06T, B47T, H12T
Bell 412	B412	B412, B430, S76
EC120 Colibri	EC20	EC20, EC30, GAZL
EC135	EC35	EC35, EC145T2
Robinson 22	R22	R22, CH7, V500, [A600], [BABY], [DRAG], [EXEC], [SCOR], plus homebuilts like EliSport CH-77 Ranabot, Cicaré CH-7T Spirit Tandem, BHR Mustang F260N, BHR Mustang F290, Hungarocopter HC-01, Italian Rotors T22, BHR Fandango F360, [LCA Helicopter LH212]
Robinson 44	R44	R44, B47G, B47J, ELTO, UH12
Schweizer 300	H269	H269, BRB2, EN28, [ZA6]

3 INPUT DATA GENERATION

3.1 OPERATIONAL DATA

To produce noise contour maps, an overview of the type of rotorcraft, a list of rotorcraft operations, and their associated flight tracks are required.

Radar track data is the most readily available source of information on actual rotorcraft flight paths and the recommendations on how to deal with this data source, as outlined in ECAC Doc.29, Vol.2, section 3.2.1 remains pertinent. The limitation described in the first paragraph of this subsection requires the user to adapt the vertical flight profiles to the noise hemisphere database. It is the role of the noise practitioner to define modelled trajectories which best match the radar data.

3.2 ROTORCRAFT MAPPING AND SUBSTITUTION

A categorisation into classes is adopted to model the European rotorcraft fleet. In case a rotorcraft type is modelled for which a noise database was established for another rotorcraft within its class, or when no noise database is established for its class at all, this needs further consideration.

To allow variations in sound pressure levels within a class, an offset of hemisphere levels based on the difference ($\Delta EPNL$) between registered certification levels [3.] of the class reference and the rotorcraft type under consideration is applied. The sound pressure level for a rotorcraft type in class i at flight condition j and emission angles φ and θ is then given by:

$$L(f_c, \varphi, \theta, V, \gamma) = \tilde{L}_{id}(f_c, \pm\varphi, \theta, V, \gamma) + \Delta EPNL \quad (2)$$

where $\tilde{L}_{id}(f_c, \varphi, \theta, V, \gamma)$ is defined by eq.5.

The correction is applied to the overall hemisphere noise levels based on the difference in certification noise levels. For Annex 16, Volume I to the Convention on International Civil Aviation "Chapter 8" certified helicopters, climb, level and descent conditions shall be corrected based on the take-off, overflight and approach certification levels.

Classes with more than one rotorcraft type are given in

Table 2. Several rotorcraft type indicators are within brackets, e.g. [A600] in the R22 class, to indicate that the main rotor configuration is mirrored with respect to the class reference. In this case, the hemisphere azimuth angle must be mirrored, hence the \pm symbol in eq. 2.

In the case that no hemisphere set is available for a given rotorcraft class, a dedicated hemisphere set is recommended to be acquired by conducting noise measurements. An intermediate solution is to temporarily group the rotorcraft type with a class for which a noise database is available. In this case, certification noise levels are decisive and should be lower than or within the range of the target rotorcraft class. In case no certification noise levels are available, or multiple classes can be selected based on this criterion, rotorcraft weight becomes the governing parameter. The class with the best matching weight that is still lower than the rotorcraft type considered is selected. $\Delta EPNL$ is set to zero to ensure a conservative estimate of sound pressure levels.

3.3 WEATHER CONDITIONS

Weather conditions (atmospheric pressure, temperature, wind speed and relative humidity) have an influence on the sound propagation through the atmosphere, affecting atmospheric attenuation, ground absorption and sound refraction. Atmospheric attenuation is influenced most significantly, whereas for ground absorption, weather conditions mainly influence the frequencies at which constructive or destructive interference occurs. Refraction (i.e. the curving of sound rays) is not covered by the present method. Modelling

refraction would require a detailed knowledge of atmospheric temperature and velocity profiles.

3.4 TERRAIN ELEVATION DATA

It is not possible to incorporate terrain elevation data at this time due to the way in which ground effects are modelled in **Section 5.3**. This is a reasonable approximation since terrain around most geographic regions where rotorcraft noise may be of interest is relatively flat. A future development to the guidance is expected to incorporate terrain elevation and ground effects in an integrated manner.

4 SOURCE MODEL

4.1 FLIGHT CONDITIONS

The rotorcraft noise source is described by a set of hemispheres covering a range of flight conditions. The flight condition is characterised by both airspeed and rate of flight angle.

Figure 2 shows the impulsive noise boundaries as a function of airspeed and Rate of Climb/Descent for the UH-1 series helicopter. Two distinct areas within the impulsive noise boundaries can be identified: firstly, an area related to Blade Vortex Interaction (BVI) that occurs mainly for descending operations; and secondly, another area associated with high-speed impulsive noise, which occurs when the rotorcraft is in fast forward flight. Although the exact location of noise boundaries will vary depending on rotorcraft type, this diagram is applicable to many rotorcraft types.

An example of the impact on noise emission is shown in **Figure 3**, presenting maximum A-weighted sound pressure levels as a function of climb and airspeed for the R22 helicopter type. A difference of up to 10 dB in noise levels is observed over the flight envelope. A second observation is that the noise levels generally vary within 1 dB as a function of rate of climb.

Figure 2 and **Figure 3** demonstrate that, for descending operations, rotorcraft noise will vary depending on airspeed and descent angle. These variations should be captured in the hemisphere data set that makes up the source model. Hemispheres at descent angle intervals of minimum 3 degrees and four different velocities are recommended to cover the operational range.

The climb region is sufficiently covered by considering a number of climb angles, at the best rate of climb speed (V_y) or a speed typically used in take-off procedures. It is recommended to: (i) include the maximum climb angle as stated in the rotorcraft flight manual; and (ii) keep level flight conditions at 90% of the speed at level flight for maximum continuous power (V_H) and +10 kts (or V_H whichever is the smallest), -15 kts and -30 kts increments on $0.9 V_H$.

At present there is no agreed method for the interpolation between hemispheres to reflect flight conditions not directly covered by specific hemispheres. Consequently, users will need to select the most appropriate hemisphere to assign to each flight path segment.

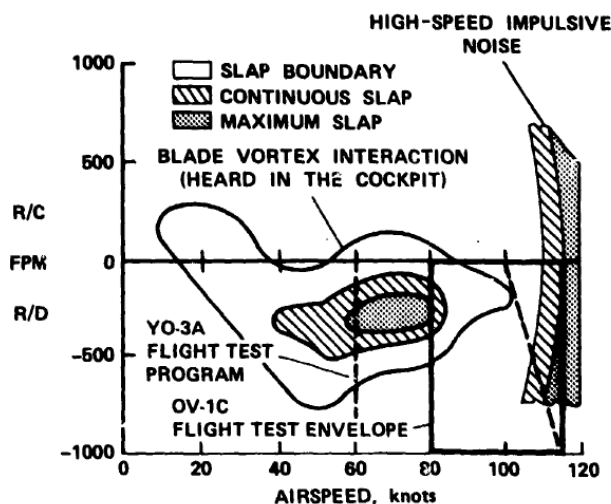


Figure 2: Impulsive noise boundaries for UH-1 series helicopter, from Schmitz et. al [4.]

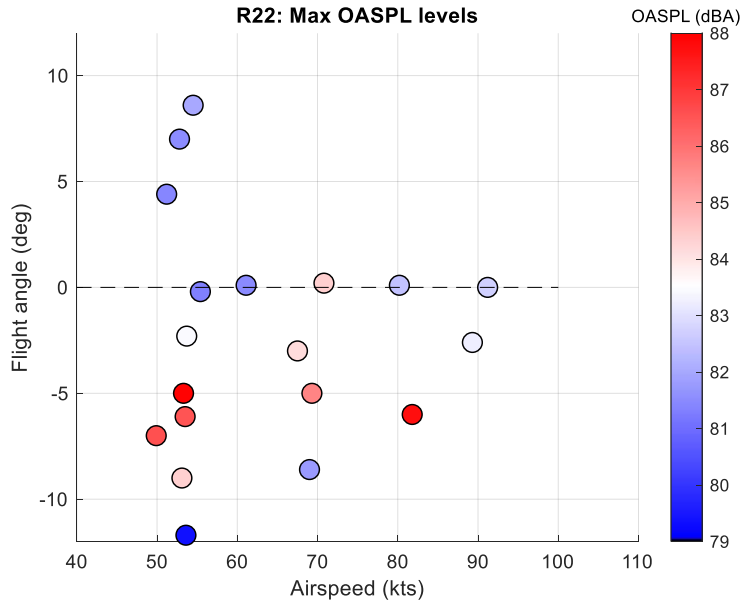


Figure 3: R22 maximum A-weighted sound pressure level at centre microphone, from the NORAH1 database.

4.2 NOISE HEMISPHERES

As a prerequisite to the method, the rotorcraft noise source needs to be described via a hemisphere (see **Appendix A** for hemisphere data format). Hemispheres provide an adequate manner to describe the complex and highly directive nature of rotorcraft noise. Notwithstanding this fact, it is noteworthy that noise measurements for the purpose of hemisphere derivation should be performed with great care and follow the relevant guidelines in ICAO Annex 16 Vol. 1 [19.].

Hemisphere sound pressure levels are defined at a fixed reference distance of 60 metres and include effects of atmospheric absorption under ICAO noise certification atmospheric reference conditions ($p_a = 101325 \text{ Pa}$, $T = 298.15 \text{ K}$ and $h_{rel} = 70\%$). This distance of 60 metres matches that used for the frequency extrapolation method outlined in ICAO Doc 9501[5.]. The latter is used to reconstruct masked one-third octave bands levels above 2 kHz, assuming a flat spectrum (equal energy) following the last good band. Hemispheres are composed of thirty 1/3 octave bands, i , for frequencies between 10 Hz ($i=1$) to 10 000 Hz ($i=30$).

Hemispheres are defined as a function of azimuth φ and polar angle θ , grouped in intervals of 10 degrees. The emission angles are related to Cartesian coordinates in the aircraft body axis system as follows:

$$\begin{aligned}
 x &= r_h \cos \theta \\
 y &= r_h \sin \theta \sin \varphi \\
 z &= r_h \sin \theta \cos \varphi
 \end{aligned}
 \tag{3}$$

in which $-90^\circ \leq \varphi \leq 90^\circ$ and $0^\circ \leq \theta \leq 180^\circ$.

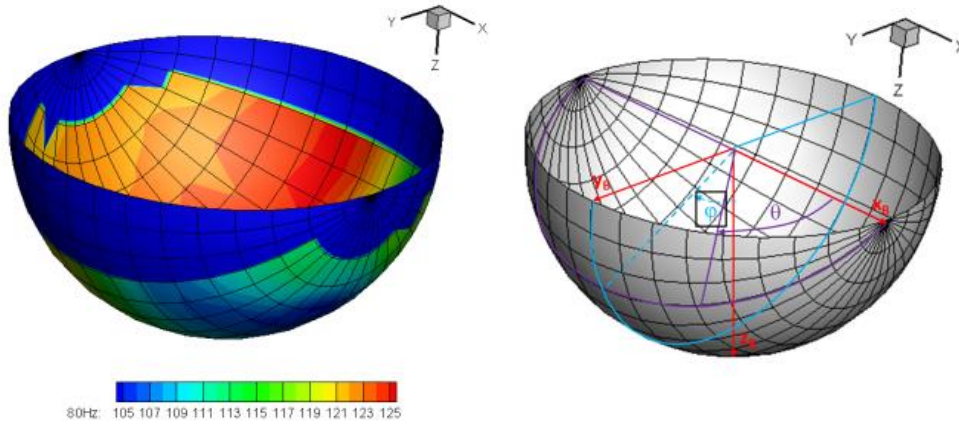


Figure 4: Example of a noise hemisphere (left), based on measurements of an R22 helicopter, 80 Hz 1/3 octave band frequency, given in aircraft body axis system (right)

Negative and positive azimuth angles correspond, respectively, to port and starboard of the rotorcraft. For polar angles, $\theta < 90^\circ$ noise emits in the forward direction, and for $\theta > 90^\circ$ in the rearward direction of the rotorcraft (see **Figure 4**).

The example hemisphere shows that its surface is not filled entirely with noise data. For both practical reasons and data quality-related issues, hemisphere data is required to cover at least the following emission angles:

$$\begin{aligned} -60^\circ \leq \varphi \leq 60^\circ \\ \theta_{t1} \leq \theta \leq \theta_{t2} \end{aligned} \quad (4)$$

where θ_{t1} and θ_{t2} correspond to the polar angles at 10 dB down time instance. Measurement of higher lateral angles or polar angles approaching $0^\circ/180^\circ$ is possible but requires complex measurement setups [6.],[7.].

To obtain source levels from stored hemispheres, a bilinear interpolation is applied as follows:

$$\tilde{L}_{id,j}(f_c, \varphi, \theta) = 10 \log_{10} \left(\begin{bmatrix} \frac{\varphi^{m+1} - \varphi}{\Delta\varphi} & \frac{\varphi - \varphi^m}{\Delta\varphi} \end{bmatrix} \begin{bmatrix} 10^{\frac{L_h(f_c)_{id,j}^{m,n}}{10}} & 10^{\frac{L_h(f_c)_{id,j}^{m,n+1}}{10}} \\ 10^{\frac{L_h(f_c)_{id,j}^{m+1,n}}{10}} & 10^{\frac{L_h(f_c)_{id,j}^{m+1,n+1}}{10}} \end{bmatrix} \begin{bmatrix} \frac{\theta^{n+1} - \theta}{\Delta\theta} \\ \frac{\theta - \theta^n}{\Delta\theta} \end{bmatrix} \right) \quad (5)$$

in which j is the time dependent flight path index and m and n are the azimuth and polar index respectively, with $\varphi^n < \varphi < \varphi^{n+1}$ and $\theta^n < \theta < \theta^{n+1}$.

When exceeding the range for which data is available, constant value extrapolation should be applied from the nearest filled data group, filling any gaps in the hemispheres. The nearest group is given by the subset of indices for which $\rho_{m,n}$ is minimized:

$$\underset{m,n}{\operatorname{argmin}} \{ \rho_{m,n} \} \quad (6)$$

In this equation, $\rho_{m,n}$ is the absolute angle between a group and target value φ, θ , defined by:

$$\rho_{m,n} = \cos^{-1}(\mathbf{x}(\varphi, \theta) \cdot \mathbf{x}_{m,n}) \quad (7)$$

The vectors \mathbf{x} and $\mathbf{x}_{m,n}$ are given by eq. 3, with $r_h=1$. In cases where there are multiple closest groups, the energetic average of all closest groups is taken.

4.3 FLIGHT PATH CONSTRUCTION

As mentioned previously, there is no agreed method for the interpolation between hemispheres to reflect flight conditions not directly covered by specific hemispheres. While this functionality is expected in a future edition of the guidance, the method currently only supports flight paths consisting of segments of constant speed and constant climb/descent angles, where both speed and climb/descent angle are aligned with the conditions in one of the available noise hemispheres. Users should model their flight paths using only these supported segments, to ensure that the acoustic data remains representative of modelled flight path segments.

Having determined flight path speeds and climb/descent angles from radar data or other data sources such as published procedures, this limitation presents a challenge because the flight conditions in the source data will not always match those available in the database. Users can choose to reconstruct the flight path data using supported segments only, at the cost of introducing position and duration errors relative to the source data. A second option is to maintain the original flight path segments and to assign the most appropriate hemisphere to each segment. Both approaches are, however, beyond the scope of the current guidance.

Regardless of the approach chosen, it is recommended that the flight path is output every 0.5 seconds using equations 9 and 10 to ensure that there is sufficient flight path data resolution to determine L_{ASmax} and to integrate the event time history to determine SEL (LAE). Radar track data includes a level of uncertainty with a typical accuracy of around 5 m to 10 m. Furthermore, time registration is often rounded to full seconds giving a maximum error of 0.5s. For typical rotorcraft speeds, this results in a positioning error of 10 m to 20 m. To derive velocity and climb angles, it is essential to apply smoothing to the radar data to filter out unrealistic oscillations. This can be achieved by spline interpolation, which has the added benefit of allowing the user to generate position data at higher sampling time Δt_s (e.g., every second).

At each timestep t of the refined and smoothed track the ground velocity is determined as:

$$V_g = \frac{\Delta S}{\Delta t_s} = \frac{\sqrt{(\Delta X^2 + \Delta Y^2)}}{\Delta t_s} \quad (8)$$

And:

$$V_A = \frac{\sqrt{(\Delta X^2 + \Delta Y^2 + \Delta Z^2)}}{\Delta t_s} \quad (9)$$

based on finite differences around t . The resulting velocity is defined with respect to the ground surface, which neglects wind.

The path angle is given by:

$$\gamma = \text{atan} \frac{\Delta Z}{\Delta S} \quad (10)$$

Note that the velocity V_A should be used to find the best matching hemisphere, not V_g .

5 PROPAGATION MODEL

5.1 SPHERICAL SPREADING, EMITTED AND RECORDED TIME

A time delay is experienced between emission and receiver of noise, related to the time taken for a sound wave to reach the observer. This relation between recorded time t_r and emitted time t_e is given by:

$$t_r = t_e + \frac{r}{c} \quad (11)$$

where c is the speed of sound and r is the distance between rotorcraft and observer. At ICAO reference atmospheric conditions ($p_a = 101325$ Pa, $T = 298.15$ K and $h_{rel} = 70\%$) the speed of sound is $c = 346.1$ m/s.

To evaluate time-integrated metrics, e.g. SEL or EPNL, it is required to express the predicted sound pressure levels as a function of recorded time.

The total noise attenuation due to propagation:

$$\Delta L_p = \Delta L_s + \Delta L_a + \Delta L_g \quad (12)$$

is governed by ground attenuation (ΔL_g), atmospheric attenuation (ΔL_a) and spherical spreading losses (ΔL_s):

$$\Delta L_s = -20 \log_{10} \frac{r}{r_h} \quad (13)$$

where $r_h = 60$ m is the hemisphere reference distance.

5.2 ATMOSPHERIC ATTENUATION

An unhindered propagating plane acoustic wave is attenuated due to atmospheric absorption. This is caused by losses due to shear viscosity, thermal effects and molecular relaxation. These losses vary with temperature, pressure, frequency and in the case of molecular (nitrogen and oxygen) relaxation losses, with humidity. A propagating plane wave attenuated by the atmosphere can be written as:

$$p(t, s) = p_0 e^{-as} e^{i(\omega t - ks)} \quad (14)$$

where p is the pressure amplitude at a distance s , p_0 is the initial wave amplitude and a is the atmospheric attenuation in Nepers per metre. This can be expressed in decibels by:

$$\Delta L_{a,t}(f) = -20 \log_{10} \frac{|p(t, s)|}{p_0} = -20 \log_{10} e^{-as} = -\alpha(f)(r - r_h) \quad (15)$$

where $\alpha (= 20/\ln 10 \cdot a)$ is the attenuation in dB/m.

The method described in SAE ARP5534 [8.] is followed to obtain α at ICAO reference conditions. The pure-tone mid-band attenuation coefficient given by:

$$\alpha = 8.686 f^2 \left\{ 1.8556 \cdot 10^{-11} + 6.6928 \cdot 10^{-6} \cdot \frac{f_{rO}}{f_{rO}^2 + f^2} + 1.3415 \cdot 10^{-6} \cdot \frac{f_{rN}}{f_{rN}^2 + f^2} \right\} \quad (16)$$

where f is the pure-tone frequency of sound in Hz and the variables $f_{rN} = 75\,692$ Hz and $f_{rO} = 630.7$ Hz represent the vibrational relaxation frequencies of oxygen and nitrogen respectively. Eq. 16 gives the attenuation in dB/m for a pure-tone frequency. To infer the atmospheric attenuation for a one-third octave band, the SAE method by Rickley et al. [9.] is applied.

5.3 GROUND ABSORPTION

The solution [10.],[11.],[12.] for a point source above an impedance surface is given by:

$$p(x) = \frac{e^{ikr_1}}{r_1} + Q \frac{e^{ikr_2}}{r_2} \quad (17)$$

where p is the complex pressure amplitude, k is the wavenumber, Q is the spherical reflection coefficient, and r_1 and r_2 are the direct and reflected path length respectively. Assuming Q is approximately constant within a one-third octave band, the ground attenuation as a function of centre frequency is given by [13.]:

$$\Delta L_g = 10 \log \left\{ 1 + \frac{r_1^2}{r_2^2} |Q|^2 + 2 \frac{r_1}{r_2} |Q| I \right\} \quad (18)$$

in which:

$$I = \frac{\sin\left(\frac{0.727 f_c \Delta R}{c}\right)}{\frac{0.727 f_c \Delta R}{c}} \cos\left(\frac{6.325 f_c \Delta R}{c} + \psi\right) \quad (19)$$

accounts for the interference patterns that occur within a band. ΔR is the path length difference between the direct and reflected ray, c is the speed of sound and ψ is the argument of the spherical reflection coefficient. Eq. 19 shows that in the high frequency limit, I tends to zero and eq. 18 reduces to a summation of two uncorrelated noise sources.

The spherical reflection coefficient Q is given by:

$$Q = R_p + (1 - R_p)F(d) \quad (20)$$

where:

$$R_p = \frac{Z_s \cos \xi - 1}{Z_s \cos \xi + 1} \quad (21)$$

is the planar wave reflection coefficient. In the latter expression, Z_s is the surface impedance and ξ is the angle of incidence of the incoming acoustic wave (0° corresponding to normal incidence). In eq. (22), F is a boundary loss factor, defined by:

$$F(d) = 1 + id\sqrt{\pi}e^{-d^2} \operatorname{erfc}(-id) \quad (22)$$

which is a function of numerical distance:

$$d = \frac{(1+i)}{2} \sqrt{kr_2} \left(\frac{1}{Z_s} + \cos \xi \right) \quad (23)$$

The complementary error function for complex arguments (erfc) is evaluated by numerical approximations [14.], [15.] (see **Appendix B**).

The surface impedance Z_s is modelled by a single parameter model by Delaney and Bazley [16.], which strikes a balance between ease of use and accuracy. The surface is assumed locally reacting so that the surface impedance Z_s is equal to the specific normalized impedance of the ground medium. The surface impedance is then given by

$$Z_s = \left\{ 1 + 0.0511 \left(\frac{f}{\sigma} \right)^{-0.754} \right\} + i \left\{ 0.0768 \left(\frac{f}{\sigma} \right)^{-0.732} \right\} \quad (24)$$

The variables f and σ are, respectively, the frequency and the flow resistivity of the material. The recommended surface types are either concrete ($\sigma = 65 \cdot 10^6 \text{ Pa} \cdot \text{s} / \text{m}^2$) for city areas or grass field ($\sigma = 200 \cdot 10^3 \text{ Pa} \cdot \text{s} / \text{m}^2$) for rural areas.

**Table 3: Flow resistivity data of common ground type classes
(from CNOSSOS EU Table G) [17.]**

Description	Class	(Pa·s/m ²)
Very soft (snow or moss-like)	A	12.5 x10 ³
Soft forest floor (short, dense heather-like or thick moss)	B	31.5 x10 ³
Uncompacted, loose ground (turf, grass, loose soil)	C	80 x10 ³
Normal uncompacted ground (forest floors, grass or pasture field)	D	200 x10 ³
Compacted field and gravel (compacted lawns, park area)	E	500 x10 ³
Compacted dense ground (gravel road, car park)	F	2 x10 ⁶
Hard surfaces (most normal asphalt, concrete)	G	20 x10 ⁶
Very hard and dense surfaces (dense asphalt, concrete, water)	H	200 x10 ⁶

6 NOISE CALCULATION

6.1 SINGLE NOISE EVENT

For a single noise event and a given observer position, the 1/3 octave band sound pressure levels as a function of recorded time shall be calculated by eq(1). As noted in **Section 5.1**, the time delay between noise emission and reception must be taken into account. The recorded time intervals will be irregular, however, for small time intervals, e.g. 0.5 to 1 second, the effect of varying recorded time intervals can be ignored.

The 1/3 octave band sound pressure level for band i at time t is calculated by eq. 1 and requires the frequency weighting A applied as specified in IEC 61672 [18.]:

$$L_{A_i}(t) = L_o(f_c, \mathbf{x}, \mathbf{y}(t)) + A_i \quad (25)$$

The overall A-weighted sound pressure level at time t is then calculated using:

$$L_A(t) = 10 \log \sum_{i=1}^{i=30} 10^{0.1 L_{A_i}} \quad (26)$$

Where $i=1$ to 30 for the thirty 1/3 octave bands from 10 Hz to 10 000 Hz, respectively as defined in IEC 61672.

From this any required time integrated metric may be calculated. The Sound Exposure Level (SEL), L_{AE} , [1.] is calculated using:

$$L_{AE} = 10 \log \frac{1}{t_0} \sum_{t_1}^{t_2} 10^{0.1 L_A(t)} \Delta t \quad (27)$$

where t_0 denotes the reference time, 1 second for SEL. A Δt value of 0.5 seconds is recommended to ensure values of L_{ASmax} and SEL are not underestimated.

Effective Perceived Noise Level (EPNL) is calculated in a similar manner, except that the input level is $PNLT(t)$ and the reference time, t_0 is ten seconds:

$$EPNL = 10 \log \frac{1}{t_0} \sum_{t_1}^{t_2} 10^{0.1 PNL T(t)} \Delta t \quad (28)$$

where t_0 denotes the reference time, 10 seconds for EPNL. Δt for EPNL calculation must be 0.5 seconds. The limits t_1 and t_2 are chosen as the times when the level $L_{PNLT}(t)$ is 10 dB below the maximum value of $PNLT(t)$. Calculation of L_{PNLT} is described in ICAO Annex 16 Volume I Appendix 2 Section 4 [19.]. Note that the times t_1 and t_2 for EPNL may be different to those for calculation of SEL and must be evaluated separately for each noise metric.

6.2 MULTIPLE EVENTS

For the calculation of cumulative noise levels, refer to ECAC Doc. 29, Vol. 2, Chapter 5 [2.].

6.3 NOISE CONTOURS

For the calculation of noise contours, refer to ECAC Doc 29, Vol. 2, Chapter 6 [2.].

Appendix A. Noise hemisphere format

This appendix presents the format of noise hemispheres used in the NORAH and HELENA (HELicopter Environmental Noise Analysis tool) models. The structure of a hemisphere file is given below:

```
[TITLE]
17      !      #      Table constants
POLDIST          60          ! Distance at which hemisphere is defined
FREEFIELD        2          ! Atmospheric absorption included in hemisphere
NOVALUE         -999       ! no value indicator
TAMB            298.1      ! Ambient temperature, deg Kelvin
RELHUM          70.0      ! Relative humidity, %
PAMB            101325.0   ! Ambient pressure, Pa
Tm              16.5      ! Measurement ambient temperature at 10m, deg Celsius
RHm             73.2      ! Measurement relative humidity at 10m, %
Pm              101079.2   ! Measurement ambient pressure at 10m, Pa
RmOmega         102.6     ! RotorRPM, rpm
ACSPEED         49.9      ! Indicated airspeed, kts
GAMM            -7.0      ! Path angle, deg
PITCH           -6.8      ! Pitch, deg
ROLL            3.4       ! Roll, deg
TW              5.2       ! Total wind, kts
CW              4.6       ! Cross wind, kts
HW              2.4       ! Head wind, kts
2 !      Number of axis
THETAOBSAC 19  0  3  0
           0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180
PHIOBSAC 19  0  3  0
          -90 -80 -70 -60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90
0 !      NPARAD: Additional point dependent parameters
NFREQ          31
           10 12.5 16 20 25 31.5 40 50 63 80 100 125 160 200 250 315 400 500 630 800 1000
           1250 1600 2000 2500 3150 4000 5000 6300 8000 10000
PHIOBSAC=     0.000
.... (DATABLOCK)
```

Where the data block contains the 1/3 octave band hemisphere data as function of polar angle (THETAOBSAC) for the given PHIOBSAC. When no data was collected for a given data group, the default value -999 is set. The first six table constants define the hemisphere reference distance (POLDIST), the content of the hemisphere (FREEFIELD), the no-value indicator (NOVALUE) and the hemisphere atmospheric conditions (TAMB, RELHUM and PAMB). The other nine parameters record the average conditions (over multiple runs) at which the hemisphere data was acquired. The metadata included in the merged hemisphere file are:

- Tm: Measurement of ambient temperature at 10m, deg Celsius
- RHm: Measurement of relative humidity at 10m, %

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- Pm: Measurement of ambient pressure at 10m, Pa
- RmOmega: Rotor RPM, %
- ACSPEED: Indicated airspeed, kts
- GAMM: Path angle, deg
- PITCH: Pitch, deg
- ROLL: Roll, deg
- TW: Total wind, kts
- CW: Cross wind, kts
- HW: Head wind, kts

Appendix B. Numerical Evaluation of Complementary Error Function for Complex Arguments (erfc)

The error function in the boundary loss factor is evaluated numerically. According to Abramowitz and Stegun [14.] (p.328) for $d_R > 3.9$ or $d_X > 3$,

$$(1) \quad e^{-d^2} \operatorname{erfc}(-id) = id \left(\frac{0.4613135}{d^2 - 0.1901635} + \frac{0.09999216}{d^2 - 1.7844927} + \frac{0.002883894}{d^2 - 5.5253437} \right)$$

with an absolute error of less than 2×10^{-6} . When $d_R > 6$ or $d_X > 6$,

$$(2) \quad e^{-d^2} \operatorname{erfc}(-id) = id \left(\frac{0.5124242}{d^2 - 0.2752551} + \frac{0.05176536}{d^2 - 2.724745} \right)$$

with an absolute error of less than 1×10^{-6} . For smaller values of d_R and d_X we resort to a formula by Matta and Reichel [15.]:

$$(3) \quad e^{-d^2} \operatorname{erfc}(-id) = K_1(d_X, d_R) + iK_2(d_X, d_R)$$

with

$$(4) \quad K_1 = \frac{hd_X}{\pi(d_X^2 + d_R^2)} + \frac{2hd_X}{\pi} \sum_{n=1}^{\infty} \frac{e^{-n^2 h^2} (d_X^2 + d_R^2 + n^2 h^2)}{(d_X^2 - d_R^2 + n^2 h^2)^2 + 4d_X^2 d_R^2} - \frac{d_X}{\pi} E(h)$$

$$+ P \text{ if } d_X < \frac{\pi}{h},$$

$$+ \frac{P}{2} \text{ if } d_X = \frac{\pi}{h}$$

+0 if $d_X > \frac{\pi}{h}$

$$(5) \quad K_2 = \frac{hd_R}{\pi(d_X^2 + d_R^2)} + \frac{2hd_R}{\pi} \sum_{n=1}^{\infty} \frac{e^{-n^2 h^2} (d_X^2 + d_R^2 - n^2 h^2)}{(d_X^2 - d_R^2 + n^2 h^2)^2 + 4d_X^2 d_R^2} + \frac{d_R}{\pi} E(h)$$

$$- Q \text{ if } d_X < \frac{\pi}{h},$$

$$- \frac{Q}{2} \text{ if } d_X = \frac{\pi}{h}$$

+0 if $d_X > \frac{\pi}{h}$

where

$$(6) \quad P = 2e^{-\left(d_R^2 + \frac{2d_X\pi}{h} - d_X^2\right)} \left[\frac{(A_1 C_1 - B_1 D_1)}{(C_1^2 + D_1^2)} \right]$$

$$(7) \quad Q = 2e^{-\left(d_R^2 + \frac{2d_X\pi}{h} - d_X^2\right)} \left[\frac{(A_1 D_1 + B_1 C_1)}{(C_1^2 + D_1^2)} \right]$$

in which

$$(8) \quad A_1 = \cos(2d_R d_X)$$

$$B_1 = \sin(2d_R d_X)$$

$$C_1 = e^{-2d_X\pi/h} - \cos(2d_R\pi/h)$$

$$D_1 = \sin(2d_R\pi/h)$$

By setting $h = 0.8$, the error $E(h)$ is less than 10^{-6} and generally the first five terms of the infinite series are sufficient to ensure the required accuracy.

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