CEAS Aeronautical Journal
https://doi.org/10.1007/s13272-019-00374-5

REVIEW PAPER

Aircraft noise immission modeling

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Received: 13 November 2017 / Revised: 1 June 2018 / Accepted: 11 February 2019

Abstract

This contribution to the CEAS special edition *Aircraft Noise Generation and Assessment* focuses on the simulation of the aircraft noise immission, i.e., the aircraft noise received on the ground. This process includes two steps, the description of the sound emission by the aircraft and the modeling of the sound propagation through the atmosphere. An overview is provided on how aircraft noise immission can be described and assessed by noise descriptors. These quantities can be derived from measurable and computable quantities like maximum sound levels, time-integrated sound levels and the number of aircraft movements. Moreover, a generation of novel noise indices which relate human reactions to noise is presented. Fundamentals of aircraft noise modeling are explained. First, this includes a classification of aircraft noise models into best practice and scientific models and their applicability to the noise mitigation measures described by ICAO's Balanced Approach to Aircraft Noise Management. Furthermore, the overall workflow of a noise modeling task is explained as well the special role of noise model databases and the simulation of aircraft flight paths. The most common methods used to describe the sound propagation process through the atmosphere are introduced. This covers the modeling of the fundamental propagation effects which are used by all noise model types as well as a description of propagation effects which are of importance only for special modeling tasks and which normally require sophisticated physical approaches. The fundamental difference between best practice and scientific aircraft noise models—i.e., the source modeling—is described in detail thereafter. Best practice models are based on a simple source description. Moreover, a common approach is to combine emission and propagation using pre-calculated noise–power–distance tables. In contrast, scientific models are of multi-source type, i.e., they differentiate between particular noise-generating mechanisms—at least between engine noise and aerodynamic noise. This model type always requires a time step-based flightpath description, whereas the best practice models usually are based on a flightpath description by longer segments. Finally, the selected application examples are presented for both model categories. This covers the range from noise zoning over what-if studies for noise mitigation measures or definition of noise abatement flight procedures up to the modeling of noise reduction measures at the source. Finally, the application of scientific models in the aircraft design phase is explained.

Keywords Aircraft noise · Aircraft noise modeling

List of symbols

Quantities

BPR	Bypass ratio
c	Speed of sound (m/s)
d_n	Atmospheric absorption coefficient for frequency band n (dB/m)
E	Normalized noise exposure
EPNL	Effective perceived noise level (dB)
f	Frequency (Hz)
f_{AWR}	Exposure–response relationship for aircraft noise-induced awakenings
F	Energy fraction
FNI	Frankfurter Nacht index
FTI	Frankfurter Tages index
H_{rel}	Relative humidity (%)
l	Length of flightpath segment (m)
L	Sound level (dB)

This paper is part of a Special Issue on Aircraft Noise Generation and Assessment.

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L_{AX}	Sound exposure level (synonym for $L_{p,\mathrm{AE}}$) (dB)
$L_{\max}$	Maximum sound level (dB)
$\overline{L}_{\max}$	Average maximum sound level
$L_{N\%}$	N% percentile level
L_{den}	Day–evening–night sound level (dB
L_{E}	Single event sound level (dB)
L_{eq}	Equivalent continuous sound level (dB)
$L_{p,\mathrm{AE}}$	A-weighted single event sound pressure level (dB)
$L_{p,\mathrm{A,eq}}$	A-weighted equivalent continuous sound pressure level (dB)
L_{r}	Rating level (dB)
L_{thr}	Threshold level (dB)
$L_{W,n}$	Sound power level of frequency band n (dB)
N	Number of noise events
N_{thr}	Number of noise events above a threshold level
N_{AWR}	Number of aircraft noise-induced awakenings
NAT	Number above threshold
P	Engine power parameter
PNL	Perceived noise level (dB)
PNLT	Tone-corrected perceived noise level (dB)
s	Distance between source and observer (m)
SEL	Sound exposure level (synonym for $L_{p,\mathrm{AE}}$) (dB)
t	Time (s)
t_0	Normalizing time (s)
t_{10}	10 dB down time (s)
t_{e}	Effective duration (s)
t_{ret}	Retarded time (s)
T	Temperature (°C)
T_{c}	Characterization time (s)
T_i	Partial time (of rating time) (s)
T_{r}	Rating time (s)
V	Aircraft speed (m/s)
Z	Level correction accounting for engine power changes (dB)
ZFI	Zürcher Fluglärm index
α, β	Elevation angles
Δ_{atm}	Level correction for atmospheric attenuation (dB)
Δ_{div}	Level correction for geometrical spreading (dB)
Δ_{grnd}	Level correction for overground attenuation (dB)
θ	Longitudinal emission angle
φ	Lateral emission angle

Subscripts

A	Frequency weighting A
PN	Perceived noise
E	Exposure
eff	Effective
eq	Equivalent
k	Flightpath segment number
n	Frequency band number
p	Pressure
r	Rating (level or time)
S	Time weighting SLOW
thr	Threshold
W	Sound power

Superscripts

in	Indoor value
obs	Value at observer position
src	Related to the sound source

Abbreviations

ANP	Aircraft Noise and Performance Database
ANoPP	Aircraft Noise Prediction Program
AzB	German aircraft noise calculation procedure
Doc.29	ECAC Standard method for aircraft noise calculation
FLULA2	Swiss aircraft noise calculation procedure
ICAO	International Civil Aviation Organization
INM	Integrated Noise Model
NPD	Noise–power–distance data
PANAM	Parametric Aircraft Noise Analysis Module
SAE	Society of Automotive Engineers
sonAIR	Swiss aircraft noise calculation procedure

1 Introduction

This contribution of the CEAS special edition *Aircraft Noise Generation and Assessment* focuses on the simulation of the aircraft noise immission, i.e., noise levels as received at selected ground-based observers. This requires first the modeling of the overall sound emission characteristics of the (moving) aircraft. The second step is the modeling of the sound propagation process through the atmosphere, taking into account different physical damping mechanisms.

The overall aircraft noise emission is comprised of all its relevant noise components, i.e., the sum of all major individual noise contributors like engine components, structures of the airframe, landing gear, and high-lift devices. Noise immission can only be predicted accurately, if the movement of the aircraft along its flightpath is modeled correctly—including the variations of all parameters defining the noise emission as well as the changing geometry between aircraft and observer and the local variation of atmospheric properties. The actual flight operation of the aircraft has to be accounted for via dedicated flight simulation or corresponding data input, e.g., flight data recorder information. Consequently, a noise assessment can only be realized if all noise sources can be accounted for, as they become relevant along a flightpath.

This part of the special edition consists of several sections. In Sect. 2, it is explained how aircraft noise immission can be described and assessed, introducing the most common noise descriptors. The fundamental concepts of aircraft noise modeling are described in Sect. 3. They are independent of the particular modeling strategy or noise model type. Moreover, this section includes a classification of noise models according to their characteristics and main areas of application. Section 4 describes the modeling of sound propagation effects—covering the standard mechanisms each model is required to account for as well as effects needing more sophisticated modeling approaches. Whereas different types of noise models account for propagation effects in a similar way they differ in source modeling. Section 5 deals with this topic, treating two main model categories: best practice models and scientific models. Exemplary applications are presented in Sect. 6. Finally, the contribution is completed by a brief summary and conclusion section.

2 Description and assessment of aircraft noise immission

2.1 Fundamental requirements

In this section, the fundamental requirements and definitions necessary to describe aircraft noise are introduced. Noise can be defined as “unwanted sound”. Consequently, a quantity used to describe noise—a noise descriptor or a noise index—must be based on physical measurable properties of sound. However, rating a sound to be unwanted or not is a much more complicated process, because it depends not only on its physical characteristics but mainly on the subjective judgement by individuals or groups of individuals.

Since noise descriptors are essential for noise legislation, land use planning and the development of noise mitigation measures, they should fulfill at least a set of fundamental requirements. These are defined by the ECAC Document 29 [23] in Vol.1 as:

> *“A practical noise index must be simple, practical, unambiguous, and capable of accurate measurement (using conventional, standard instrumentation). It must also be suitable for estimation by calculation from underlying source variables and robust – not over-sensitive to small changes in input variables.”*

Aircraft noise is intermittently, i.e., it can be described by a series of particular noise events. Consequently, any aircraft noise descriptor should be based on the measurable parameters describing any single noise event. These parameters are introduced in the following section.

The value of an aircraft noise descriptor depends on the observer location and the air traffic scenario (i.e., the spatial and temporal distribution of aircraft movements, the airport structure, the local terrain and the weather situation). Such local descriptor values are usually compared with limiting or critical values. An exceedance of such noise limits gives rise to legal or planning actions (e.g., construction bans, sound insulation measures or noise mitigation action plans). Noise descriptors are usually depicted by noise contours (i.e., isolines of constant descriptor values) which represent the boundaries of noise protection zones. However, some descriptors provide a representative value for the whole airport scenario (e.g., the number of people highly annoyed by aircraft noise). Such descriptors are by now commonly denoted as noise indices (see Sect. 2.5).

2.2 Parameters describing a single noise event

If an aircraft passes an observer, the sound level L recorded at this location is a function of time t, as shown schematically in Fig. 1. The level time history $L(t)$ can be characterized by two parameters: the maximum sound level $L_{\max}$ and a noise duration. For aircraft noise, the level L is usually expressed as an A-weighted sound pressure level L_{pAS}, measured with time weighting “SLOW” [19], or as a perceived noise level (PNL) or L_{PN} (which is denoted as PNLT in case that it includes a tone correction) [29].

There are two common definitions for the noise duration, the so-called *10 dB down time* t_{10}, where $L(t)$ is at most 10 dB below the maximum level $L_{\max}$ and the effective duration t_{eff} which is defined by the equation

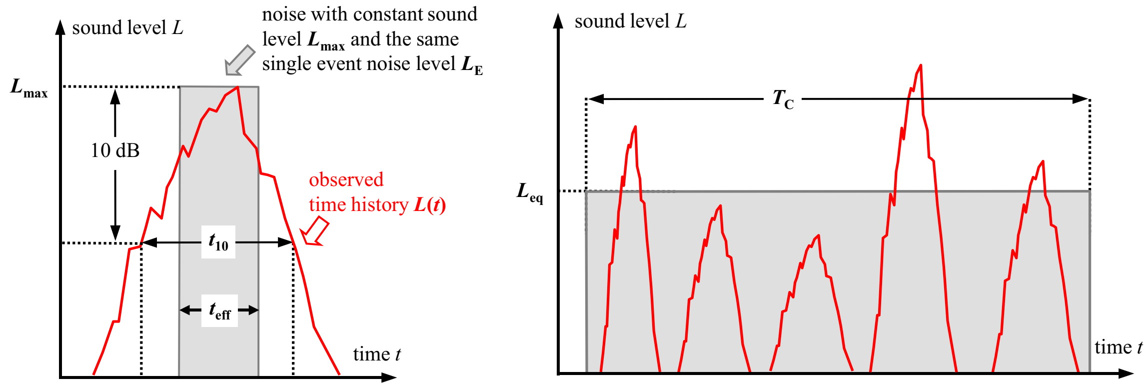
$$\int_{t_1}^{t_2} 10^{L(t)/10}\mathrm{d}t = t_{\mathrm{eff}} \times 10^{L_{\max}/10}. \tag{1}$$

The interval $[t_1, t_2]$ should cover the time during which the noise can be identified (i.e., the time where it exceeds the background noise level). It should at least cover the interval over t_{10} because otherwise the noise event may be contaminated by background noise.

According to the German standard DIN 45643 [19], the approximate relationship $t_{\mathrm{eff}} \approx t_{10}/2$ can be used. Building the logarithm of Eq. (1) yields

$$L_{\mathrm{E}} = 10 \times \log\left(\frac{1}{t_0} \times \int_{t_1}^{t_2} 10^{L(t)/10}\mathrm{d}t\right) = L_{\max} + 10 \times \lg\left(\frac{t_{\mathrm{eff}}}{t_0}\right). \tag{2}$$

This level is designated as single event sound level. For a normalizing time t_0 of 1 s, the A-weighted single event sound pressure level $L_{p,\mathrm{AE}}$ is often called sound exposure level SEL



(a) Sound-level time history **(b)** Series of noise events

Fig. 1 **a** The characteristic parameters of a single noise event. **b** A series of noise events during a characteristic time T_c resulting in an equivalent continuous sound level L_{eq}

Table 1 Examples for rating levels L_r used in practice (from DIN 45643 [19])

Rating level L_r	Characterization time T_c	Partial time T_i (h)	Adjustment Δ_i (dB)	Rating time T_r (h)
L_{den}	All calendar days within one year	6–18 18–22 22–6	0 5 10	24
$L_{A,eq,night}$	All nights in the six busiest months of the year	22–6	0	8
$L_{A,eq,day}^{Weekend}$	All weekend days in the three busiest months of the year	6–22	0	16

The L_{den} is the day–evening–night sound level defined by the EU Environmental directive [15]. The definition of the $L_{A,eq,night}$ corresponds to the German Aircraft Noise Act from 2007 [20]

or L_{AX}. For a tone-corrected perceived noise level PNLT and a normalizing time t_0 of 10 s, the result is called effective perceived noise level EPNL, which is the metric used for aircraft noise type certification according to ICAO Annex 16 [29].

It should be noticed that single event sound levels are integrated quantities and hence not "hearable": a particular L_E value can result either from a short noise with high maximum level or from a longer noise event with a lower maximum level. On the other hand, the perception "loud/quiet" is related to the magnitude of the actual sound level L—notably to the maximum sound level.

2.3 Exposure-based descriptors (equivalent continuous sound levels)

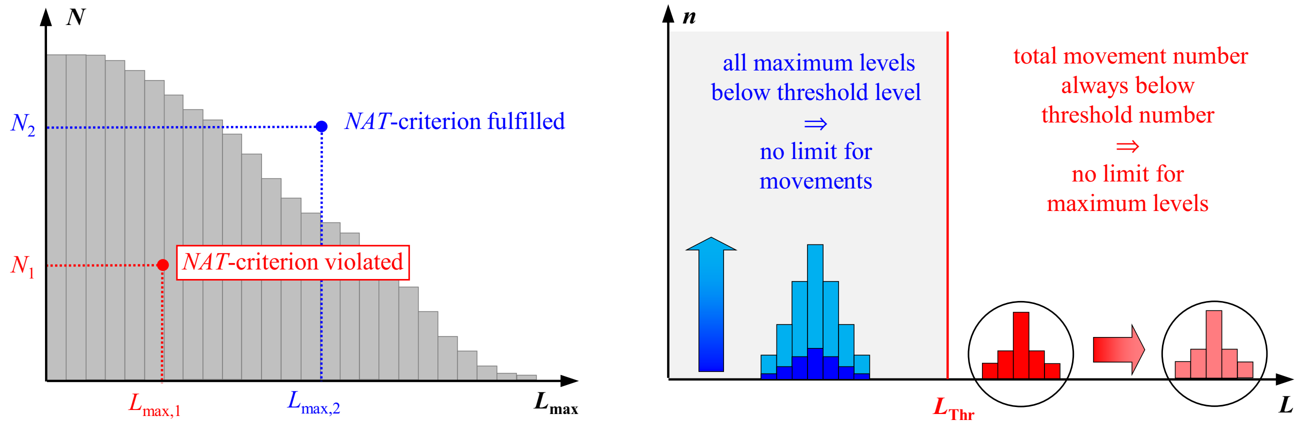
Long-term impact of aircraft noise is usually estimated in terms of *equivalent continuous sound level* L_{eq} which is defined for a series of N noise events $L_{E,i}$, as depicted in Fig. 1b, occurring during a *characterization time* T_c and with a normalizing time t_0 as

$$L_{eq} = 10 \times \log \left(\frac{t_0}{T_c} \times \sum_{i=1}^{N} 10^{L_{E,i}/10} \right). \tag{3}$$

The equivalent sound level is a measure for the total sound energy impinging at the observer location—consequently it is often denoted as *energy equivalent sound level*. However, Eq. (3) is finally a generic one. It is the basis for so-called rating levels

$$L_{r,T_r} = 10 \times \log \left(\frac{1}{T_r} \times \sum_{i=1}^{n} T_i \times 10^{(L_{eq,i}+\Delta_i)/10} \right) \text{ with } T_r = \sum_{i=1}^{n} T_i \ . \tag{4}$$

The rating time T_r is a recurring time interval within the characterization time period T_c, for which the rating level L_r is to be determined. It is subdivided into partial times T_i in which the characteristics of the sound rating (e.g., emission conditions or level adjustments Δ_i) remain the same. Table 1 shows examples for rating levels. In principle, rating levels expand the energy concept by a weighting that is realized by level adjustments. These may account for noise-sensitive time periods as well as for specific emission characteristics



(a) NAT and cumulative frequency distribution N

(b) Negative properties of a NAT criterion

Fig. 2 **a** A cumulative frequency and the relationship between cumulative frequency and number above threshold criteria. **b** The negative properties of a $\mathrm{NAT}_{N_{\mathrm{thr}} \times L_{\mathrm{thr}}}$ criterion. As long as all maximum levels are lower than the threshold level L_{thr} the total number of movements can be increased arbitrarily without violating the criterion (blue distributions). In contrast, there is no limit for the maximum levels as long as the total number of movements is lower than the threshold value N_{thr} (red distributions)

(e.g., tonal or impulsive noise). However, Eq. (4) is only one of different ways to define a rating level. It can also be expressed as weighted equivalent sound levels using weighting factors for the number of operations within the different partial times [23].

Rating levels are typically designed to show a good correlation to annoyance, i.e., the psychological reactions on noise. Moreover, different kinds of rating levels show a good correlation among each other [32]. Consequently, they are worldwide in use as the basis for noise legislation. As rating levels are based on single event noise levels, they are not "hearable" as well.

2.4 Descriptors based on maximum sound levels

2.4.1 Parameters describing a maximum level distribution

Some physiological human reactions to noise—especially the awakening from sleep—are closely related to the maximum sound level of a noise event rather than to its energy, i.e., on the single event level [4]. In the past, the use of maximum level-based noise descriptors was not very common, but since the turn of the millennium they were introduced more and more in land use planning and noise legislation. One reason was the increasing number of studies related to the effects of aircraft noise on sleep.

Basis for the estimation of a maximum level-related descriptor is a local maximum sound level distribution. Characteristic parameters for such a distribution are the average maximum sound level $\overline{L_{\max}}$ and the percentile levels $L_{N\%}$. A percentile level $L_{N\%}$ is the maximum level which is exceeded for $N\%$ of the observed aircraft noise events (e.g., the median level L_{50}). The average maximum sound level is usually estimated by energetic averaging according to

$$\overline{L_{\max,L_{\mathrm{thr}}}} = 10 \times \log\left(\frac{1}{N_{\mathrm{thr}}} \times \sum_{i=1}^{N_{\mathrm{thr}}} 10^{L_{\max,i}/10}\right). \tag{5}$$

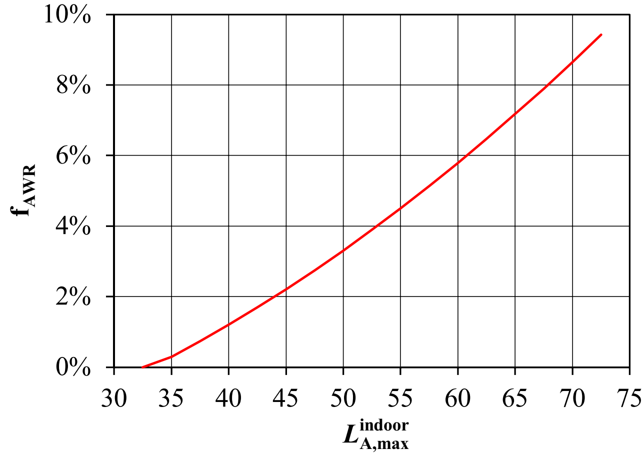
The summation is performed over all N_{thr} noise events with $L_{\max,i} \geqq L_{\mathrm{thr}}$. The introduction of a *threshold level* L_{thr} avoids that a high number of noise events with low maximum levels (which have no relevance to the noise situation) decreases the mean level. The threshold should be chosen suitably with respect to the special application of the average sound level (e.g., as the background noise level L_{95}).

It should be noticed that the average maximum sound level as well as the percentile levels depend only on the shape of the level distribution. A scaling of the distribution by multiplication with an arbitrary factor has no effect on these parameters. Consequently, they should not be used as a standalone metric but only in addition to other descriptors (see next section).

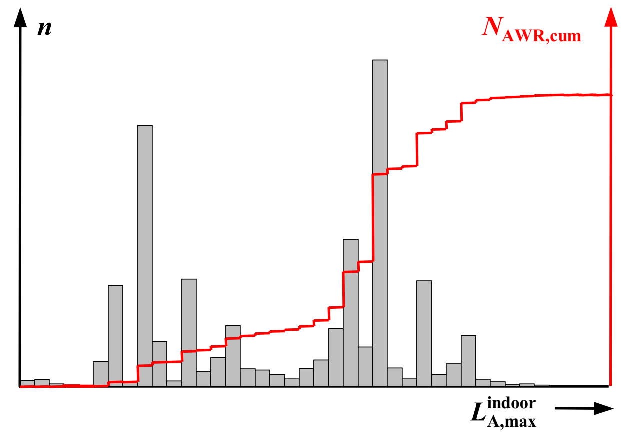
2.4.2 Number above threshold criteria

A common maximum level-based descriptor is the number above threshold $\mathrm{NAT}_{L_{\mathrm{thr}}}$. This is the number of aircraft noise events with maximum levels exceeding a threshold level L_{thr}. The local NAT values can be taken directly from the local maximum sound level distribution as

$$\mathrm{NAT}_{L_{\mathrm{thr}}} = \sum_{i=1}^{N} u\left(L_{\max}, L_{\mathrm{thr}}\right) \text{ with } u\left(L_{\max}, L_{\mathrm{thr}}\right) = \begin{cases} 1 & \text{if } L_{\max} > L_{\mathrm{thr}} \\ 0 & \text{if } L_{\max} \leq L_{\mathrm{thr}} \end{cases}. \tag{6}$$



(a) Exposure-response relationship for awakenings



(b) Level distribution and cumulated awakenings

Fig. 3 **a** The relationship between the percentage of aircraft noise-induced awakenings and A-weighted maximum sound level indoors according to Eq. (8). **b** The shape of the cumulated number of awakenings resulting from a distribution of A-weighted maximum sound level indoors

The number above threshold $\mathrm{NAT}_{L_{\mathrm{thr}}}$ can be compared with a limiting number N_{thr}. Such a "NAT criterion" is usually denoted as $\mathrm{NAT}_{N_{\mathrm{thr}} \times L_{\mathrm{thr}}}$ (e.g., $\mathrm{NAT}_{6\times 55\,\mathrm{dB}}$). It is represented by a single point in the cumulative frequency diagram for maximum sound levels: the criterion is violated (i.e., the observer is located inside the contour $\mathrm{NAT}_{N_{\mathrm{thr}} \times L_{\mathrm{thr}}}$) if this single point falls below the cumulative frequency function (see Fig. 2a).

The disadvantage of any NAT criterion is the fact, that it only provides an information whether it is violated or not—but not to what extent. If $\mathrm{NAT}_{6\times 55\,\mathrm{dB}}$ is violated, this may be due to 7 events with maximum levels of 56 dB as well as due to 100 events with maximum levels of 80 dB. In the opposite, the criterion is independent of the number of noise events if all levels are below the threshold L_{thr} and independent of the magnitude of the levels if the number of events is lower than N_{thr}, as depicted in Fig. 2b. Obviously, the information on the shape of the cumulative frequency function is lost. This is in opposite to the behavior of the average maximum sound level discussed in the preceding section. This suggests a combination of both metrics. A comprehensive discussion of the (dis)advantages of NAT criteria can be found in [5].

Nevertheless, $\mathrm{NAT}_{6\times L_{\mathrm{T}}}$ criteria were introduced to define the night protection zones in the German Act on Protection against Aircraft Noise during its revision in 2007 [20]. However, the resulting NAT contours are only used in combination with contours of an equivalent sound level $L_{\mathrm{A,eq,night}}$ according to Table 1.

2.4.3 Aircraft noise-induced awakenings

A very stable descriptor based on maximum sound levels was developed within the DLR project "Quiet Air Traffic" [4]—the number N_{AWR} of aircraft noise-induced awakenings at a particular observer location. It can be estimated from the local distribution $n\left(L_{\mathrm{A,max}}^{\mathrm{in}}\right)$ of the A-weighted maximum sound level indoors as

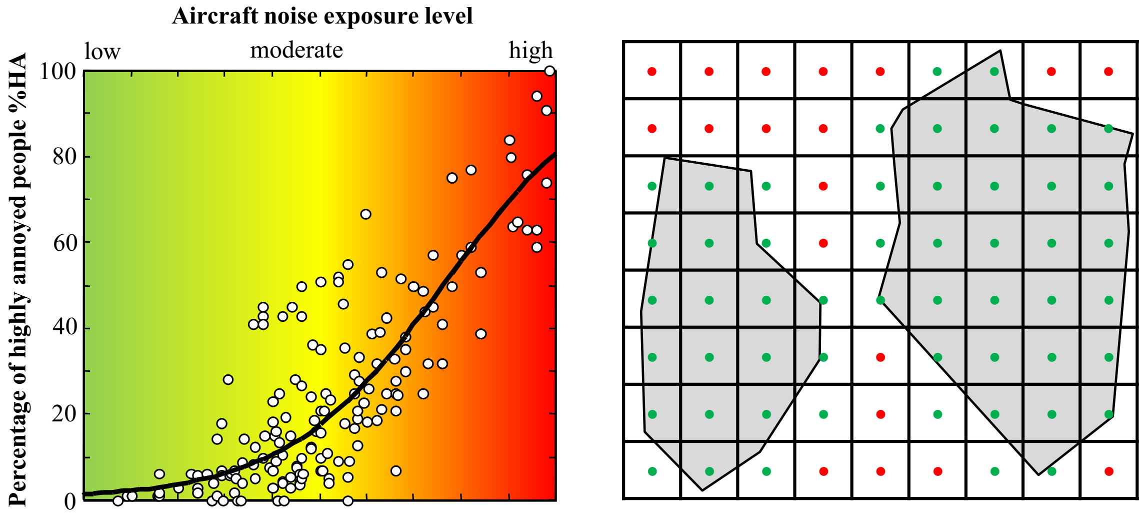
$$N_{\mathrm{AWR}} = \sum_{i=1}^{N_{\mathrm{C}}} \mathrm{f}_{\mathrm{AWR}} \times n\left(L_{\mathrm{A,max},i}^{\mathrm{in}}\right). \tag{7}$$

The summation is performed over all level classes N_{C} of the discrete frequency distribution, as depicted in Fig. 3. The function $\mathrm{f}_{\mathrm{AWR}}$ is defined as

$$f_{\mathrm{AWR}} = \begin{cases} 1.894 \times 10^{-5} \times \left(L_{\mathrm{A,max}}^{\mathrm{in}}\right)^2 + 4.00810^{-4} \times L_{\mathrm{A,max}}^{\mathrm{in}} - 3.4343 \times 10^{-2} & \text{if } L_{\mathrm{A,max}}^{\mathrm{in}} > L_{\mathrm{A,thr}} \\ 0 & \text{if } L_{\mathrm{A,max}}^{\mathrm{in}} \le L_{\mathrm{A,thr}} \end{cases} \tag{8}$$

with a limiting level $L_{\mathrm{A,thr}}$ of 32.7 dB.

The N_{AWR} descriptor fulfills all requirements for a noise descriptor mentioned in Sect. 2.1. Moreover, it represents a special kind of an exposure–response relationship which is the basis for a kind of descriptors called noise indices (see the following section). A first practical use was its integration in a concept for the protection against adverse effects of nocturnal aircraft noise at Leipzig/Halle airport in Germany



(a) Example of an exposure-response relationship

(b) Calculation grid for noise index

Fig. 4 **a** An exposure–response relationship, i.e., a function relating a physical quantity (noise exposure) to a noise effect on humans (annoyance) [23]. **b** The concept of a noise index calculation. The grid splits the airport environment into parcels. The gray polygons represent residential areas. Noise exposure has to be calculated at least at the centers of inhabited parcels (green dots)

in 2005 [6]. Later, it was included in the ZFI index used at Zürich airport [48] as well as in the FNI index developed for Frankfurt airport [25].

2.5 Noise effect-related descriptors (noise indices)

Figure 4a shows a graph of a typical relationship between aircraft noise exposure and percentage of highly annoyed people [23]. It is based on data from several social survey studies carried out in different countries. Each point of this diagram represents the response of a sample of individuals to the particular noise level. The curve is fitted by means of a logistic regression.

Such an exposure–response relationship maps the physical quantity sound to the perception of noise. There are several types of exposure–response relationships. Generally, annoyance is related to equivalent sound levels like L_{den} or L_{eq}, whereas physiological reactions (like awakenings, see previous section) are related to maximum sound levels.

In the past, noise exposure in the vicinity of an airport was usually estimated by calculation of noise contours. Changes of the noise situation were analyzed in terms of contour area change and/or a visual comparison of the contour shapes. More recently, the availability of geographic information systems (GIS) and digitized census data allowed the estimation of the number of residents living inside of a contour. The obvious step of introducing exposure–response relationships in practical assessment schemes was performed during the last decade by the introduction of noise indices, i.e., descriptors which characterize the noise situation in the vicinity of an airport by a single number, usually representing residents in the airport vicinity.

At Zürich airport, the Zürcher Fluglärm index ZFI was introduced in 2006 [48]. It is a combined day/night index describing the sum of the number HA of people highly annoyed during daytime and the number HSD of people highly sleep disturbed during the night. Separate indices for night and day were introduced at Frankfurt airport [25]. The day index (Frankfurter Tag index FTI) is based on a local exposure–response relationship between $L_{\mathrm{A,eq,day}}$ and percentage of highly annoyed people. The night index (Frankfurter Nacht index FNI) is based on the percentage of aircraft noise-induced awakenings.

The estimation of a noise index is a straightforward procedure as depicted in Fig. 4b. It is based on a subdivision of the aircraft environment in (quadratic) parcels with a side length of approximately 100 m. The number of residents living inside of such a parcel must be known, e.g., from census data. The suitable noise metric is calculated at the center of each parcel (or at least of each inhabited parcel). It is assumed to be constant over the whole parcel area. The contribution of each parcel to the index is the product of the number of residents and the percentage of annoyed or awakened people from the corresponding exposure–response relationship. Summing up all parcel contributions yields the total index. The problem is to define the area for which the index has to be estimated. Common approaches are characteristic noise contours or the borders of residential areas.

3 Aircraft noise modeling

3.1 Aircraft noise models and their classification

One of the fundamental requirements in an aircraft noise descriptor is its computability. This is evident, because an overall measurability is usually not given (e.g., for forecasted air traffic scenarios). The computation of noise descriptors is performed by software which implements a particular aircraft noise calculation/prediction model. Such a model is a combination of a calculation algorithm (sometimes called the noise engine) and a corresponding database. The calculation algorithm describes the generation, emission and propagation of the sound. The database provides all the information needed by the noise engine.

The fields of application for noise models cover a wide range. The underlying air traffic scenarios may be past/present or future ones, including existing and/or future aircraft. The studies can be of comparative nature or dealing with the estimation of the absolute impact. Moreover, they may be used to model noise abatement flight procedures or noise reductions at the source (both measures specified by ICAO's Guidance on the Balanced Approach to Aircraft Noise Management [30]). More detailed application examples can be found in Sect. 6. Depending on the specific application, the type of algorithm covers a range from simple empirical models up to sophisticated approaches that try to reflect the underlying physics as exact as possible. Each type of algorithm will come with different requirements with respect to the database (see Sect. 3.3). The available models are often classified by their main field of application into best practice or scientific models as described in [8].

Best practice models are used for practical purposes like the estimation of noise protection zones or noise mitigation and land use planning. These models are primarily designed to estimate the noise resulting from complex air traffic scenarios rather than to describe the noise produced by individual aircraft operations. The prediction results of best practice models usually have a direct impact on expensive countermeasures, e.g., payment of sound insulation or compensation. Hence, the results of these models should be reliable and proved by measurements. As a consequence, the models are subject to standardization and can therefore adequately be applied in the context of legislative issues. Any best practice model has to be built upon a database suitable to describe the noise and performance characteristic of any aircraft currently in service. This may be realized by grouping schemes (like the German AzB [21]) or definition of the noise significant types and corresponding substitution rules (like the combination of ECAC Doc.28 and the underlying ANP database [22]). It should be noticed that all actual best practice models describe the aircraft as an integrated sound source or effectively a simple point source, i.e., they do not account for differences in particular sound generation mechanisms (e.g., aerodynamic or engine noise) as well as for the fact that any aircraft is a spatial distribution of different noise sources.

Describing the noise generation by relevant source mechanisms under all operating conditions is typical for scientific models. The term scientific is intentionally selected to highlight the major field of application of these kind of tools. Scientific models are usually of multi-source type, i.e., they describe individual source mechanisms. Engine noise is at least split into jet and fan components, while airframe noise is at least split into the noise produced by the landing gears and by the high-lift devices, respectively. The sound emission of the individual sources is described by dedicated source models. These can either be semi-empirical or fully analytical, but they try to include physical approaches which can be expressed by equations that allow a processing by computer algorithms other than simple interpolations. Since these algorithms usually need a set of input parameters to describe system physical features, all scientific models are parametric models.

The development of scientific models usually requires a huge amount of experimental and/or computational input data. Extensive research and large databases are essential to derive a particular noise source model. The particular noise source mechanisms have to be well-understood by theory, measurement and computation. Therefore, these kind of models are usually found in research and scientific environments or at aircraft manufacturers where the models are subject to constant development and modification. This is in direct contrast to the best practice models, where the calculation algorithms are defined and documented to ensure reliable and reproducible results as required for legislative application.

The amount of relevant parameters depends on the specific model. Semi-parametric models are based on a set of measured data (spectra, directivities) for reference conditions. These data are corrected for non-reference situations with respect to the most important physical mechanisms that influence the noise generation. The corrections are usually based on a limited set of (mostly operational) parameters like Mach number, engine exhaust velocity and gear/flap settings, each of them usually within a particular range.

The DLR multi-source model SIMUL [8] is of semi-parametric type. The concept of SIMUL is a separation based on the way the source mechanisms are influenced by the aircraft speed. The generation of jet noise is influenced by the relative jet velocity, whereas the other engine noise sources (rotating machinery and combustion) are assumed to be speed independent. Airframe noise (which is divided into the noise produced by high-lift devices, landing gears and spoilers) is depending on flight speed only and vanishes—in

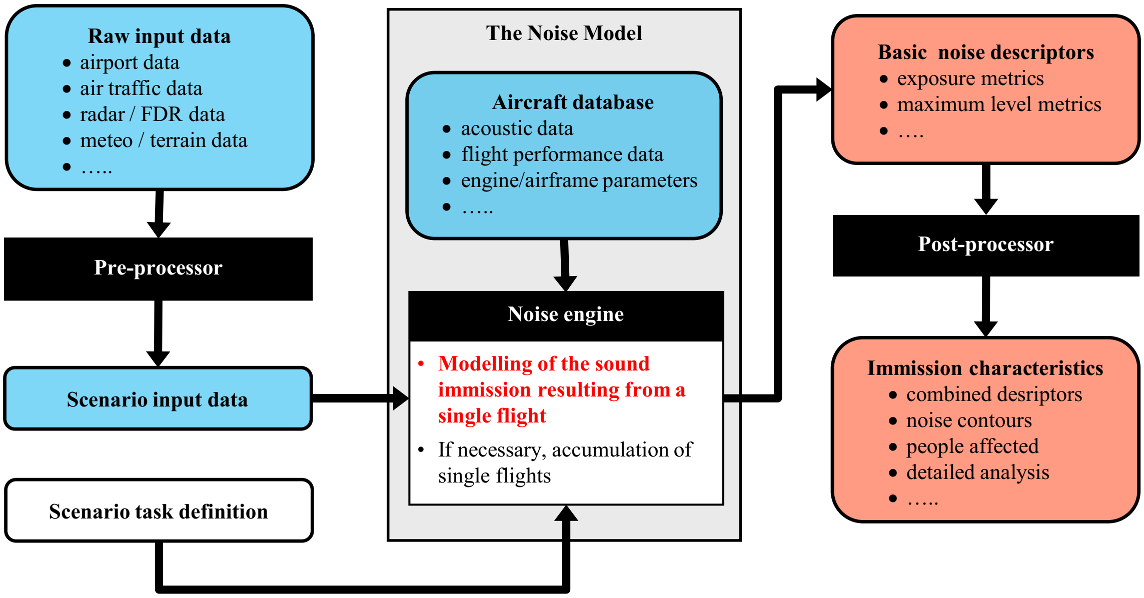


Fig. 5 Fundamental elements and workflows for an aircraft noise scenario. Not all interdependencies are shown. The task definition determines e.g., the choice of the noise model as well as steps of the post-processing. The modeling of the single event noise (highlighted in red color) is depicted in Fig. 6

contrast to engine noise—in the static case. The engine source model reference data of SIMUL are derived from measurements and manufacturers' information. The airframe noise model was developed by DLR.

Another semi-parametric model is the multi-source model sonAIR developed by Empa in Switzerland [57]. The particular source models for engine- and airframe-noise components were derived by a statistical approach from extensive measurements performed at Swiss airports.

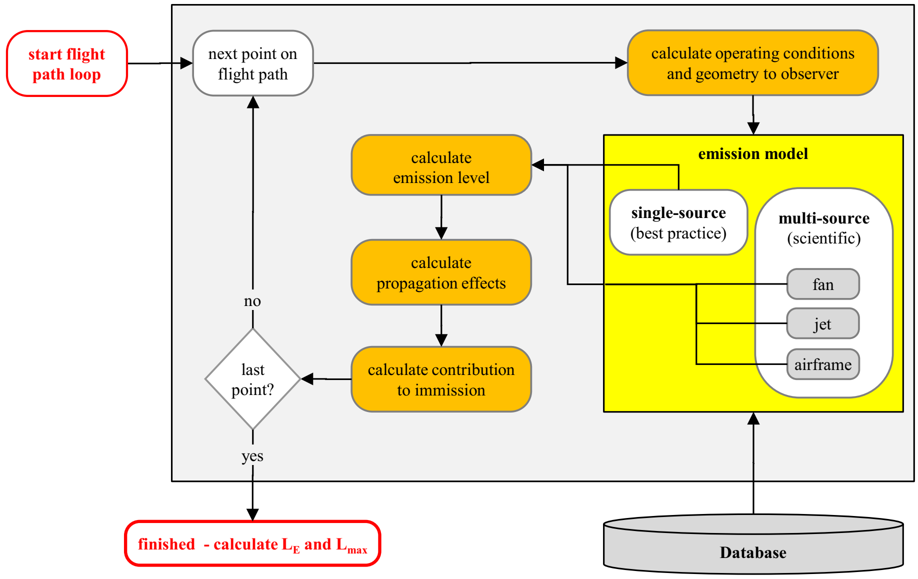
Fully parametric scientific models include all relevant operational and constructional parameters that influence the noise generation (e.g., engine internal pressures and temperatures as well as parameters describing the geometry of fan, gear, flaps or slats). It is obvious that the models have to be parametric with respect to the operational conditions to simulate aircraft noise along any flight trajectory, e.g., to study the effects of the deployment of high-lift elements and landing gear during an approach. Moreover, another important application of the scientific tools is the assessment of novel and unconventional technology and aircraft designs. This special application requires that a particular model has to be parametric not only with respect to the current operating conditions but also with respect to geometrical details of the vehicle and the engine. Established fully parametric tools can be found at large research institutions such as DLR (*PANAM* [7]), NASA (*ANoPP 2* [54]) and ONERA (*Carmen* [40]). Moreover, some universities also run their own code development applying available and non-proprietary noise source models, e.g., Delft Technical University, RWTH Aachen or University Roma Tre.

In contrast to the best practice models, the application of scientific tools is focused on a detailed assessment of single noise events. Due to the significantly increased complexity and input data requirement, the application is usually limited to few aircraft and engine types. Hence, complex air traffic scenarios cannot be handled by such models. However, detailed single flight simulations with scientific model can be used to improve best practice tools. Due to parametric and componential characteristic of the scientific tools, they are typically used for comparative studies, e.g., analysis of different propulsion technologies or future vs. actual aircraft concepts.

3.2 The overall workflow

Any aircraft noise study is defined by a combination of input data and instructions called a scenario. Its complexity can reach from a single flight modeling up to the treatment of a comprehensive air traffic situation. A scenario is described by a set of input data in a format suitable for processing by the selected noise model (e.g., a set of XML files). Furthermore, any scenario includes a task definition which tells the noise engine what actions have to be performed to the input

Fig. 6 Modeling of the noise produced by a single noise event for a given observer location



data. The scenario data have at least to describe the airport geometry (e.g., runways location, terrain and weather data), the shape of the flight track(s), as well as the air traffic (i.e., a list of the aircraft operating within a defined reference time period on the particular flight tracks). Scenario input data for comprehensive air traffic situations are are usually derived by means of a pre-processor from raw data sources (e.g., radar data or data from aircraft simulators or flight data recorders). If only single flights are modeled, only very generic and simplified scenario data is required, e.g., flight-path and observer arrangement.

Figure 5 shows an overview of the modeling workflow. The first step is the processing or generation of the required input data. If required, the input data will be calculated at this point. If the flight path is to be generated, its horizontal shape is defined by the corresponding flight track from the scenario data and its vertical shape is derived from the performance data of the noise model. If aircraft or engine design and performance are required as inputs, data from external simulation tools or experimental data can be processed for the noise prediction at this point. Before initiating the noise engine, all required input data has to be available and processed (usually into specific file formats). The second step is the assignment of the sound emission characteristics along the flightpath, based on the acoustic information from the model or database. The fundamental step is the calculation of the noise immission produced by the single flight at the selected observer, which is depicted in detail in Fig. 6. This step has to be repeated for each combination of flight operation (defined by the scenario data) and observer location (defined by the task definition). It should be noticed that this scheme is independent of the calculation algorithm as well as of the complexity of the air traffic scenario (e.g., single flight or based on an annual air traffic).

The calculation of the noise immission produced by a single flight event at an observer location is a straightforward process. It is depicted in Fig. 6. The flight path, which is represented by a series of discrete points, is processed step by step. The location of an individual point and the spatial orientation of the aircraft define the distance as well as the emission angles with respect to the observer. The actual performance parameters (engine power setting, aircraft speed and aerodynamic configuration) determine the sound emission characteristic, usually expressed in terms of a spectral sound power level. Finally, the aircraft speed defines the emission times and hence the level time history at the observer. Each level of this time history is estimated by means of a sound propagation calculation. A numerical integration of this time history yields the single event sound level, whereas the maximum sound level is estimated via simple level comparison.

This whole process is in principle identical for any type of noise model. However, the emission as well as the propagation modeling depends on the specific model type. Whereas the propagation modeling is in most cases limited to standard effects (see Sect. 4.1), the emission modeling can cover different levels of detail. Best practice models usually describe the aircraft by a single sound source. They set up on acoustic databases containing emission-level data of different degrees of detail (see Sect. 5.1). Scientific models account usually for different source mechanisms, at least jet, fan and airframe noise. The straightforward approach is to describe these particular sound sources in the best practice way. However, sophisticated models use a parametric approach. They require geometrical input data of the high-lift system and the landing gear design to calculate the airframe noise based on analytical or semi-empirical models. Construction parameters of the engine (e.g., diameter,

<table>
<tr><th rowspan="2">MTOM</th><th colspan="3">Number of engines</th></tr>
<tr><th>2</th><th>3</th><th>4</th></tr>
<tr><td>≤ 50 t</td><td colspan="3">S5.1</td></tr>
<tr><td>≤ 120 t</td><td colspan="3">BPR > 3 → S5.2
BPR ≤ 3 → S5.3</td></tr>
<tr><td>≤ 300 t</td><td rowspan="3">S6.1</td><td colspan="2">A340 → S6.3
other → S6.2</td></tr>
<tr><td>≤ 500 t</td><td colspan="2">A340 → S6.3
other → S7</td></tr>
<tr><td>> 500 t</td><td>Ø</td><td>S8</td></tr>
</table>

(a) AzB (aircraft categories S5.1 to S8)

<table>
<tr><th rowspan="2">MTOM</th><th colspan="3">Number of engines</th></tr>
<tr><th>2</th><th>3</th><th>4</th></tr>
<tr><td>≤ 50 t</td><td colspan="3">29</td></tr>
<tr><td>≤ 120 t</td><td colspan="3">17
9</td></tr>
<tr><td>≤ 300 t</td><td rowspan="3">14</td><td colspan="2">1
8</td></tr>
<tr><td>≤ 500 t</td><td colspan="2">1
8</td></tr>
<tr><td>> 500 t</td><td>Ø</td><td>2</td></tr>
</table>

(b) ANP database (airframe/engine combinations)

Fig. 7 Structure of aircraft noise databases for commercial jet aircraft certified according to chapter 3/4 ICAO Annex 16. **a** The category structure of the German AzB. The A340 was assigned to a separate group because of the poor performance of the early versions − 200/− 300. **b** The corresponding airframe/engine combinations contained in the ANP database V2.1. *BPR* is the engine bypass ratio and *MTOM* is the maximum takeoff mass

number of fan blades and stator vanes) as well as thermodynamic parameters describing the engine behavior are used to model the sound produced by the propulsion system (see Sect. 5.2). These data are extracted from dedicated engine performance decks for the prevailing operating conditions. It is obvious, that such models result in great demands on the underlying database.

3.3 The role of databases

Databases of different complexities and input details are required depending on the selected calculation algorithms. The model-specific aircraft noise database is of fundamental importance, because it is closely related to the noise model complexity as well as to the possible fields of application of the model. Generally, the database structure can be defined for particular aircraft types or for aircraft groups. The process of aircraft grouping (and the related process of aircraft substitution) is comprehensively described in Volume 1 of ECAC Doc.29 [23], including a discussion of the underlying principles of acoustic equivalence and noise significance.

As an example, Fig. 7 shows a comparison of the structures of the AzB database and the international Aircraft Noise and Performance Database (ANP) [22]. AzB data are categorized according to maximum takeoff mass, number of engines and engine bypass ratio. All commercial jet aircraft with noise certificate according to chapter 3/4 of ICAO Annex 16 [29] can be grouped into eight categories. In contrast, the ANP contains 89 airframe/engine combinations for the chapter 3/4 aircraft. However, these cover not all aircraft currently in service—combinations not included in the ANP are substituted by comparable ANP combinations. The AzB uses a grouped database because the model is specially designed for future scenarios and a simple database structure facilitates the required air traffic forecast for the required planning interval of 10 years. In contrast, the ANP database is more suitable for calculation of past scenarios where the air traffic can be described much more exactly.

Moreover, the structure of the model (see Sect. 3.1) and database must match, because they influence each other: the model type defines requirements on the database, whereas the amount of available data limits the model structure—it can only be as detailed as the available data allow. This is of special importance for the acoustic data. They must be very detailed for scientific multi-source models, reaching from semi-empiric acoustical data for each partial sound source up to constructional parameters describing particular components of engine and airframe. Single-source models used for practical purposes require less detailed, but very reliable acoustic information. Moreover, they must cover all aircraft in service, what usually reduces the database complexity due to the availability of source data.

Flight performance data describe the vertical shape of an aircraft trajectory, including information on position, speed and engine power setting. Such flight profiles can be two different types. The first are the so-called fixed point profiles. They are defined for a flight without any turns under fixed conditions (aircraft mass, meteorology, operational procedure). Fixed point profiles can be processed by any aircraft noise model. The more flexible approach is procedural profiles. They model the flightpath by a series of commands like:

> *(1) Maintain takeoff power and climb at constant speed to 1500 ft, (2) accelerate to flap retraction speed, (3) reduce power to climb power and (4) accelerate to 250 knots.*

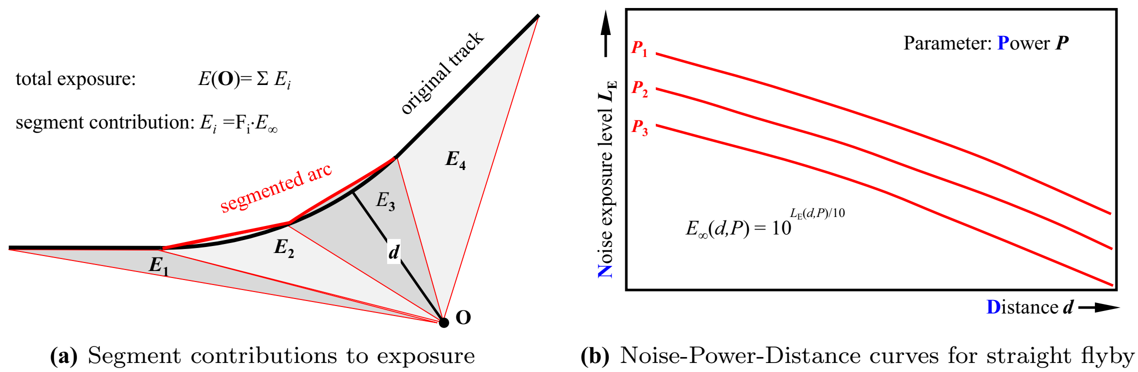


Fig. 8 Principle of a segmentation model based on noise–power–distance (NPD) data. **a** The segmentation of an arc segment of the flight track. Each segment contributes to the total exposure at the observer O. The contribution E_i is estimated by multiplication of the exposure E_∞ from a horizontal flyover with the energy fraction F_i. E_∞ can be derived from the NPD data (**b**)

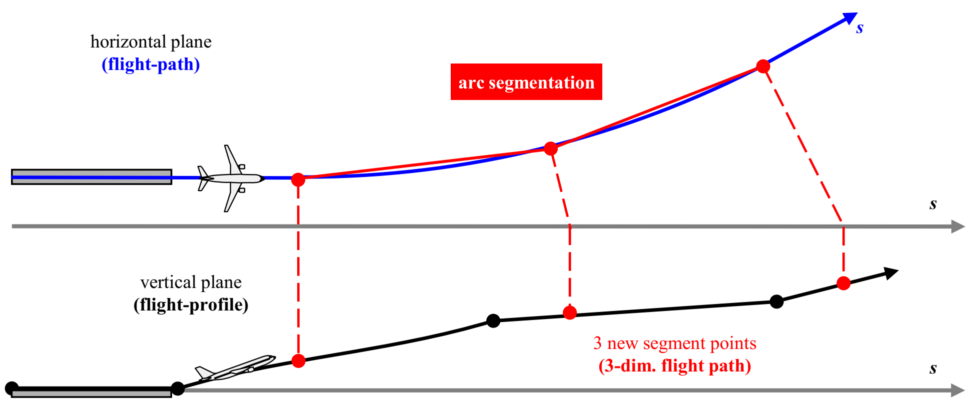


Fig. 9 Combination of a segmented flight track with a flight profile to a three-dimensional flight path. Speed and power setting along the flightpath are derived from the flight profile

The disadvantage of this approach is that it needs a model for aerodynamic performance calculations (like that described in ECAC Doc.29) as well as an underlying database (like the ANP) to a generate a flight profile from the procedural steps. The advantage is that this profile accounts for the effect of meteorology, aircraft mass and turns as well as airport altitude. This means that the same procedural profile can be used to generate a set of fixed point profiles for different boundary conditions.

3.4 Flight path definition

Basis of any aircraft noise calculation is a flight path that is in practice represented by a series of discrete points forming a three-dimensional series of adjacent segments. A flight path is always a combination of a flight track defined in the ground plane and and an altitude shape defined by a flight profile (see previous section). The standard description of a flight track is a series of straight segments and arcs [23]. If radar or flight recorder data are used, the path consists only of straight segments.

The early noise models calculated the sound level at the observer based on the distance of closest approach. These DCA models are outdated—the current models for practical applications are segmentation models. The segmentation concept is depicted in Fig. 8a in two dimensions: each arc segment of a flight track is replaced by suitably chosen linear segments so that the resulting track is built up only by straight segments. Each of these segments contributes to the total sound exposure E at the observer location. However, Fig. 8a shows only the first step of the segmentation process, i.e., the flight track segmentation. The second step is the combination of the segmented track with the flight profile as depicted by Fig. 9. These two steps are fundamental and identical for all segmentation models. Additional segmentation steps have to be applied if speed and/or acoustic emission change significantly along the flightpath. These segmentation steps depend on the particular model [33].

The calculation of the segment contributions E_i depends on the model algorithm. The integrated noise model (INM) [26] and its successor, the Aviation Environmental Design Tool (AEDT) [58], as well as ECAC Doc.29 [23] use noise–power–distance (NPD) data. Each NPD set includes curves of sound exposure level or maximum sound level vs. propagation distance for different power settings and a reference aircraft speed. These curves represent levels produced

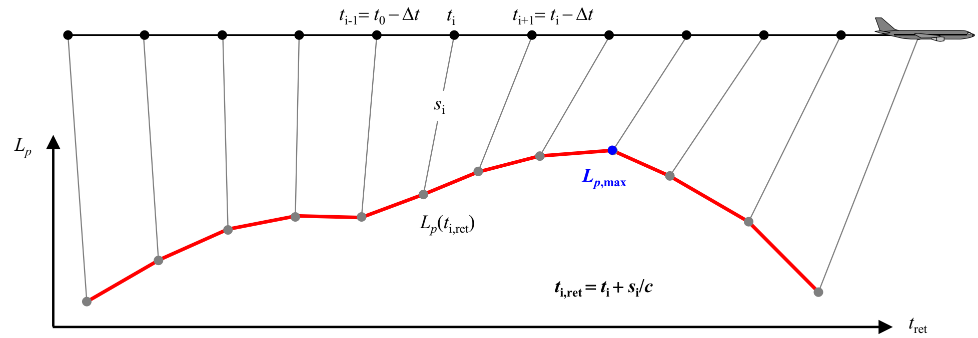


Fig. 10 Principle of a time step model: sound levels at observer are calculated for the retarded time t_{ret}

by a horizontal flyover of infinite length in an altitude d. Multiplication of the exposure E_∞ from the NPD data with the so-called energy fraction F_i yields the contribution E_i of a finite length segment to the total exposure. Under the assumption that the directional characteristic of the aircraft is of dipole type, F_i is an analytical function of the parameters describing the geometry between aircraft and observer and the NPD curve reference speed.

Although the NPD concept is quite elegant due to its analytical nature, it is from a physical perspective unsatisfactory, because it combines the effects of emission and propagation. Moreover, the dipole approach is quite accurate for propeller aircraft and modern jet aircraft, but it fails for aircraft with a pronounced longitudinal directivity (such as military or older jet aircraft).

A more flexible approach is used by the German AzB [21], where source and propagation modeling are separated. The source is described by spectral sound power exposure levels and a description of the longitudinal spectral directivity by a Fourier series. Moreover, the AzB introduces an additional observer related segmentation step called the sub-segment method: a flight path segment has to be split up into sub-segments, if the distance from the segment center to the observer is less than ten times the segment length. After this final segmentation step, the segment is replaced by a point source at the segment center.

An alternative concept is the time step models which follow a straightforward approach: the flight path is described by a series of points which are passed by the aircraft in constant time intervals Δt. Based on the actual sound emission characteristics at each point, a sound propagation calculation to the observer is performed, including the effects of time retarding due to the finite speed of sound c. This yields a sound level vs. time history similar to Fig. 1a—calculated for the retarded time t_{ret}, i.e., see Fig. 10. As for a real measurement, exposure and maximum level metrics can be derived from this time history.

Time step modeling is the standard approach for models designed for scientific applications (see Sect. 5.1). However, the Swiss models FLULA2 [37] and sonAIR [57] are examples of time step models that are used for practical applications. A very special approach used by FLULA2 is a combined description of source and propagation (see Sect. 5).

4 Sound propagation modeling

Sound propagation in the atmosphere is a rather complex topic. Different mechanisms—from the molecular level up to the meteorological mesoscale—have an influence on the passing of a sound wave through the atmosphere. These mechanisms can be subdivided into effects caused by the atmosphere and effects related to the ground properties. Atmospheric effects are

- sound absorption by the air,
- refraction effects resulting from gradients in sound velocity and
- scattering of sound waves by turbulence in the atmosphere.

Ground effects are

- reflection, diffraction and shielding effects due to obstacles and buildings
- corresponding effects due to the shape of topography
- changes in the sound propagation path due to terrain elevation and
- effects of ground surface properties on overground sound propagation.

Moreover the effects of ground and atmosphere cannot be treated separately, since on the meteorological micro- and mesocales, the earth surface influences the structure of the atmosphere (e.g., temperature inversions which are a result of the radiation balance).

The fundamental physical laws of acoustics and meteorology are well-known, and analytical, as well as numerical models for sound propagation are available. Nevertheless, we are currently far away from a comprehensive and satisfying treatment of sound propagation in the atmosphere for the

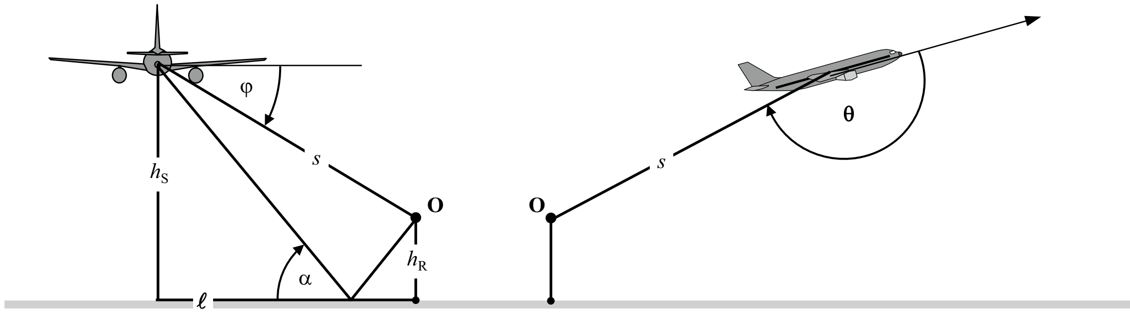


Fig. 11 Geometry between aircraft and observer including the distances and angles needed for the source description as well as the progagation modeling

purpose of aircraft noise modeling. It is simply a problem of the amount of input data needed and of the computer power necessary to run the calculations within an acceptable time frame.

4.1 Modeling the standard effects

The spectral sound pressure level at an observer location **O** (see Fig. 11) can be calculated from the sound power level $L_{W,n}^{\mathrm{src}}$ at the source as

$$L_{p,n}^{\mathrm{obs}} = L_{W,n}^{\mathrm{src}} + \Delta_{\mathrm{div}} + \Delta_{\mathrm{atm},n} + \Delta_{\mathrm{grnd},n} + \sum_i \Delta_{\mathrm{misc},n}^{i} \ \mathrm{dB}. \tag{9}$$

Analogous, the spectral contribution from a flightpath segment k to the sound exposure level at the observer is calculated from on the spectral sound power exposure level $L_{WE,n,k}$,$^{\mathrm{src}}$ at the source according to

$$L_{pE,n,k}^{\mathrm{obs}} = L_{WE,n,k}^{\mathrm{src}} + \Delta_{\mathrm{div}} + \Delta_{\mathrm{atm},n} + \Delta_{\mathrm{grnd},n} + \sum_i \Delta_{\mathrm{misc},n}^{i} \ \mathrm{dB}. \tag{10}$$

The index n is the identifier for a particular frequency band and the correction terms Δ_x describe propagation effects. The first three correction terms are standard corrections and common to all propagation models. They are described in the following subsections. The corrections Δ_{misc} are for non-standard effects. These are discussed in Sect. 4.2.

The estimation of a maximum sound level is quite simple. The first step is to combine the band levels at the observer into the appropriate (weighted) overall sound level. For A-weighting this has to be done according to

$$L_{p_{\mathrm{AE},k}}^{\mathrm{obs}} = 10 \times \lg \sum_i 10^{\left(L_{pE,i,k}^{\mathrm{obs}} + A_i\right)/10} \ \mathrm{dB}. \tag{11}$$

with the appropriate A-weighting factors A_i for the frequency band i. After processing these steps for each combination of emission point and observer location, the maximum level can be estimated very simply.

The calculation of the contribution of a flight to the A-weighted exposure level $L_{p\mathrm{AE}}^{\mathrm{obs}}$ at the observer is depending on the model structure. Segmentation models sum up the particular exposure contributions $L_{p\mathrm{AE},k}$ of all flightpath segments k according to

$$L_{p_{\mathrm{AE}}}^{\mathrm{obs}} = 10 \times \lg \sum_k 10^{L_{p\mathrm{AE},k}^{\mathrm{obs}}/10} \ \mathrm{dB}. \tag{12}$$

For NPD-based models, the contribution $L_{p\mathrm{AE},k}^{\mathrm{obs}}$ is provided by the energy fraction algorithm described in Sect. 3.4. Other models have to sum up first the spectral contributions from each flightpath segment k according to

$$L_{p\mathrm{AE},k}^{\mathrm{obs}} = 10 \times \lg \sum_i 10^{\left(L_{pE,i,k}^{\mathrm{obs}} + A_i\right)/10} \ \mathrm{dB}. \tag{13}$$

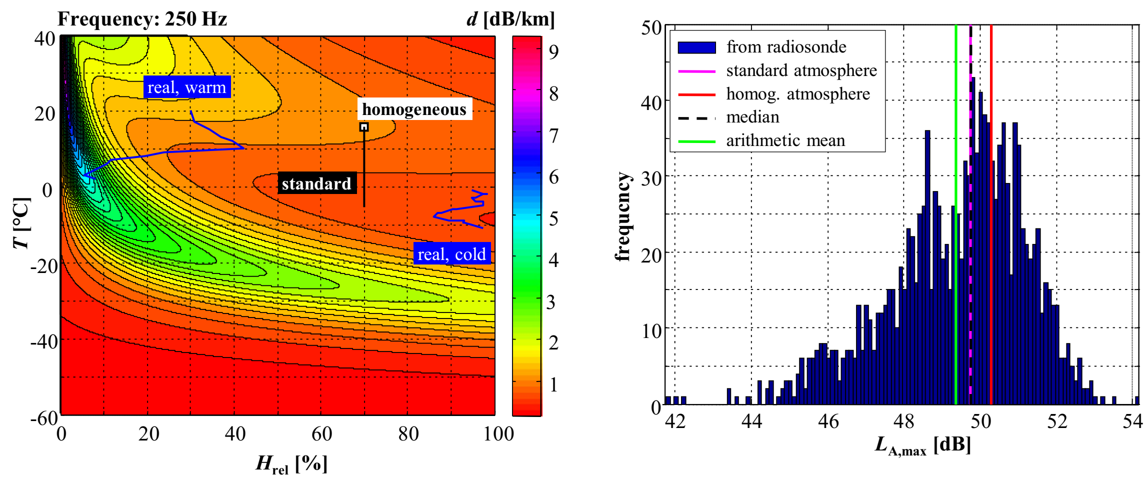
If time step models are used, the A-weighted exposure is estimated based on the level vs. retarded time history (see Fig. 10) at the observer according to

$$L_{p\mathrm{AE}}^{\mathrm{obs}} = 10 \times \lg \left[\frac{1}{t_0} \sum_{i=2}^{N} \left(t_{\mathrm{ret},i} - t_{\mathrm{ret},i-1}\right) \times \frac{10^{L_{p,\mathrm{A}}^{\mathrm{obs}}(t_{\mathrm{ret},i})/10} + 10^{L_{p,\mathrm{A}}^{\mathrm{obs}}(t_{\mathrm{ret},i-1})/10}}{2} \right] \mathrm{dB}. \tag{14}$$

It should be noticed, that the Eqs. (9)–(14) are for single-source noise models only. As far as multi-source models are considered, a suitable additional logarithmic summation over all source components is necessary.

4.1.1 Geometrical spreading correction Δ_{div}

The geometrical spreading correction is based on the assumption that the sound is propagated as a spherical



(a) Atmospheric attenuation rates for 250 Hz

(b) Variation of maximum sound levels

Fig. 12 **a** ISO 9613-1 absorption coefficient for a frequency of 250 Hz as function of temperature T and relative humidity H_{rel}. Included are T–H_{rel} shapes up to 3 km altitude for homogeneous and standard atmosphere and for two examples from radiosonde measurements. **b** Variation of maximum sound levels on the ground for a sound source in 10 km altitude for real atmospheric conditions (based on radiosonde data for 1 year)

wave. It is not depending on frequency and results in a level decrease of 6 dB per doubling of propagation distance s. The correction is calculated as

$$\Delta_{\text{div}}(s) = 10 \times \lg\left(4\pi \times \frac{s^2}{s_0^2}\right) \text{dB} \tag{15}$$

with a reference distance s_0 of 1 m. It may be noticed that Eq. (9) is sometimes based on the sound pressure level for a certain reference distance (that may also differ from 1 m). In this case, the factor 4π must be omitted.

4.1.2 Atmospheric attenuation correction $\Delta_{\text{atm},n}$

In the context of environmental noise calculation, atmospheric attenuation means the effect of dissipating the energy of a sound wave by effects of heat conduction and viscosity as well as by energy transfer to a molecular level (i.e., excitation of rotational and vibrational modes of the oxygen, nitrogen and water molecules in the air). The atmospheric attenuation is usually quantified by absorption coefficients d_n in dB per distance unit and the atmospheric attenuation correction is calculated as

$$\Delta_{\text{atm},n}(s) = -d_n(T, H_{\text{rel}}, p) \times \frac{s}{s_0} \text{ dB.} \tag{16}$$

The coefficients d_n are a function of frequency, temperature T, relative humidity H_{rel} and—to a small extent—of the ambient pressure p. It can be calculated using the formulas provided by ISO 9613-1 [35] or SAE ARP5534 [50] (the latter standard replaces SAE ARP866A [49], which is still referenced in some noise models).

Figure 12a shows the result of an example calculation based upon ISO 9613-1 for a frequency of 250 Hz. Attenuation rates are shown in dB/km as a function of temperature and relative humidity for standard atmospheric pressure. Obviously, the attenuation rate will vary with height, since atmospheric conditions vary as well. The two blue lines in Fig. 12a show typical combinations of temperature and humidity measured during radiosonde starts up to an altitude of 3 km at a cold and a warm day, respectively [11].

Nevertheless, most aircraft noise models use fixed attenuation rates for standardized atmospheric conditions usually 15 °C and 70% relative humidity or averaged attenuation rates for a reference atmosphere. This assumption of a homogeneous atmosphere (which is represented by the white square in Fig. 12a is in fact wrong. More realistic would be to assume at least an atmosphere with a constant temperature gradient such as the International Standard Atmosphere [34] which is indicated by the black line in Fig. 12a. However, this assumption would require a calculation algorithm accounting for a stratified atmosphere, i.e., something that would increase computation time. So the choice of a homogeneous atmosphere has practical reasons.

The question is, how large are the errors that are introduced using this assumption. An impression on that can be taken from Fig. 12b [11]. It shows the variation of maximum A-weighted sound levels on the ground resulting from a sound source with a typical jet aircraft spectrum located 10 km above ground. The atmospheric attenuation was calculated based on a stratified atmosphere with layers of

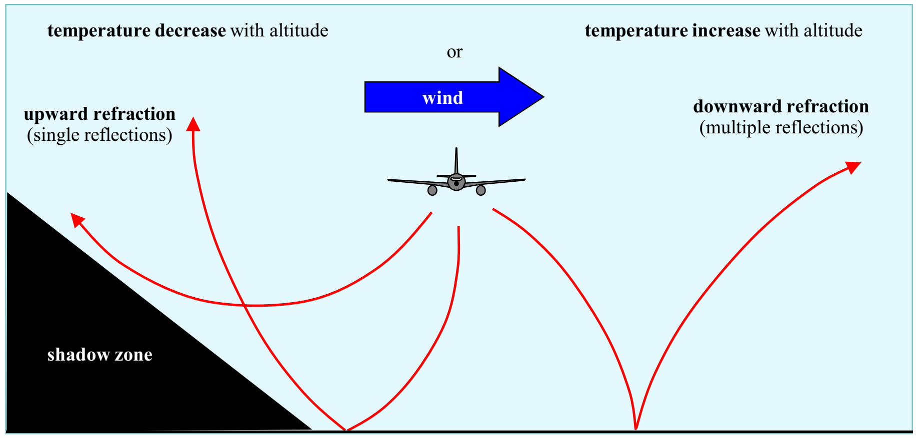


Fig. 13 Effect of temperature gradients and/or wind on sound propagation

100 m thickness, where the attenuation rates were assumed to be constant (computation according to ISO 9613-1). Any effects of temperature gradients on ray bending were neglected (i.e., propagation perpendicular to the layers). The properties of the atmosphere were taken from radiosonde data provided from a German observatory collected for one year with 4 radiosonde launches per day (at 06:00, 12:00, 18:00 and 00:00 local time) [10]. Additionally, the ground levels were computed using a homogenous atmosphere with 15 °C and 70% relative humidity and a standard atmosphere with 15 °C on the ground and 70% relative humidity over the whole atmosphere.

The resulting level distribution on the ground shows a range of about 10 dB with the median level identical to the level for the standard atmosphere. The mean value is about one half of a decibel below, the level for the homogeneous atmosphere about one half of a decibel above the median level. This indicates that even under the adverse conditions of long propagation the assumption of a homogeneous atmosphere provides reasonable results (at least for typical Mid-European conditions). For source altitudes typical for aircraft noise calculations, the distribution becomes narrower: for a propagation distance of 2 km the range of the resulting distribution is reduced to about 4 dB. The corresponding standard deviation decreases from 1.8 to 0.8 dB.

4.1.3 Overground attenuation

The term overground attenuation (sometimes denoted as ground excess attenuation) describes the effects of several physical phenomena occurring when sound waves are travelling under shallow angles close to the ground surface, i.e., mainly absorption by the ground itself as well as cumulative effects of meteorology [3]. A generic formulation for this correction is

$$\Delta_{\mathrm{grnd},n}(s) = F_s(s) \times F_\alpha(\alpha)\ \mathrm{dB} \tag{17}$$

where F_s and F_α are functions describing the dependency of the correction from propagation distance s and elevation angle α between aircraft and observer.

The German AzB defines a frequency-dependent approach based on octave bands according to

$$F_{s,n}^{\mathrm{AzB}}(s) = \frac{G_n \times \frac{s}{s_0}}{\sqrt{1 + \frac{s^2}{s_0^2}}}\ \mathrm{dB}\ \text{and}\ F_\alpha^{\mathrm{AzB}}(\alpha) = \begin{cases} 1 - \frac{\sin\alpha}{\sin 15^\circ} & \text{if } 0^\circ \le \alpha \le 15^\circ \\ 0 & \text{if } \alpha < 0^\circ \\ 0 & \text{if } \alpha > 15^\circ \end{cases} \tag{18}$$

with a reference distance s_0 of 700 m and an asymptotic level decrease G_n for ground-to-ground propagation.

ECAC Doc.29 uses the algorithm specified in SAE AIR5662 [51]. This standard defines a frequency-independent overground attenuation as:

$$F_s^{\mathrm{SAE}}(\ell) = \begin{cases} 1 - 1.137 - 0.0229\alpha + 9.72 \times \exp(-0.142 \times 10^{-3} \times \ell) & \text{if } \ell \le 914\ \mathrm{m} \\ 10.86 & \text{if } \ell > 914\ \mathrm{m} \end{cases}\ \mathrm{dB} \tag{19}$$

and

$$F_\alpha^{\mathrm{SAE}}(\alpha) = \begin{cases} 1 - 1.137 - 0.0229\beta + 9.72 \times \exp(-0.142\beta) & \text{if } \beta \le 50^\circ \\ 0 & \text{if } \beta > 50^\circ \end{cases}.$$

The difference between both models is the definition of the geometry parameters: AzB is based on the propagation distance s, whereas the SAE algorithm is based on the lateral distance ℓ between aircraft and observer. Moreover, the SAE standard does not account for the receiver height h_R – i.e., $\beta = \alpha(0)$. The models are insofar comparable, as they produce an asymptotic ground-to-ground attenuation in the order of 10 dB.

4.2 Other propagation effects

4.2.1 Temperature gradients and wind

Temperature gradients in the atmosphere result in gradients in sound velocity. The effect of such gradients as well as of wind is that the direction of sound propagation is no longer constant i.e., the sound rays become curved (in case of a constant gradient in sound speed they build circular arcs). Depending on the wind direction and the sign of the temperature gradient the sound rays are bent up- or downwards as shown in Fig. 13.

This has different consequences: in case of upward refraction ("temperature lapse" condition or upwind situation), the sound rays are reflected only once and a shadow zone is formed where no direct sound ray is incident. However, sound energy is transferred into this zone by mechanisms like scattering (see below). Downward refraction usually occurs in case of temperature inversions (e.g., in the night) or downwind situations. This is an unfavorable situation, since sound energy may be transported over long distances due to multiple reflections or over obstacles like screens. These refraction effects can be very pronounced if the source is close to the ground—leading to sound level amplifications of about 5 dB for downward refraction and level decreases of up to 20 dB for upward refraction.

With increasing altitude of the sound source, the effects of refraction decrease very fast for typical meteorological situations [10]. This implies that for the calculation of aircraft noise, the effects of refraction are more or less bound to the direct runway vicinity. For larger distances along the flightpath (i.e., with increasing distance between aircraft and ground), the influence of temperature and wind on aircraft performance (climb gradient and engine performance) and the related acoustic effects dominate the influence of refraction.

Modeling techniques to account for refraction effects are well-known—from ray tracing up to approaches based on Euler equations [12]. The disadvantage of these model is that they are very time-consuming and that they need detailed information on the structure of the atmosphere in the whole airport environment over a long time period—which are usually not available in sufficient detail to apply such techniques. However, there are some approaches to deal with the problem, e.g., by approximations derived from such reference models [28] or by pre-calculation of meteorological effects using reference models and building lookup tables for defined atmospheric states that can be used by conventional best practice models [18].

4.2.2 The effects of atmospheric turbulence

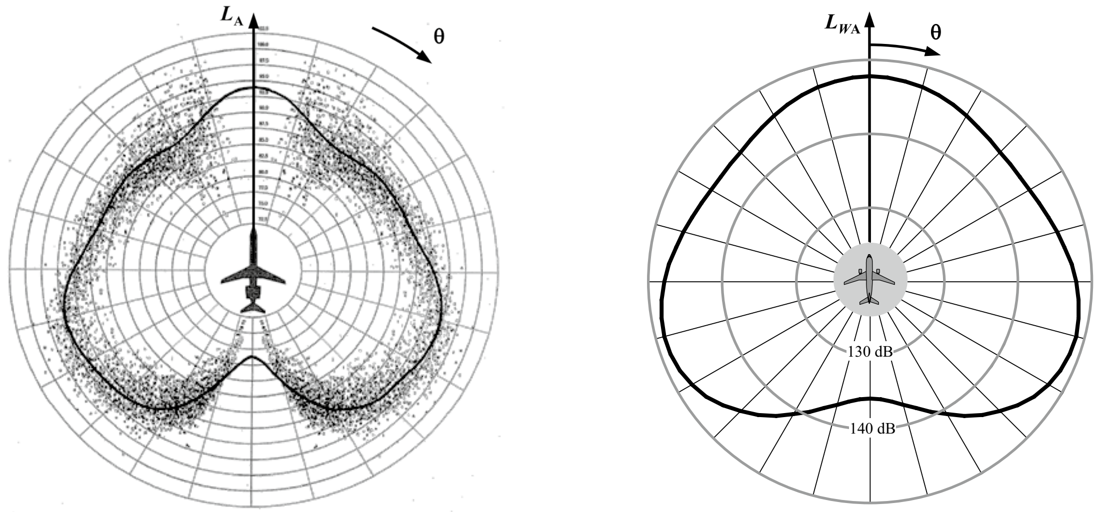
The atmosphere is not a homogeneous medium. Turbulence is always present—especially in the vicinity of the earth's surface—and sound is scattered by turbulence. This yields adverse effects: on the one hand it is an additional attenuation effect, on the other hand it can direct sound energy into areas which would be shielded normally. This shielding effect may be due to obstacles or terrain shape as well as due to shadow zones created by upwind situations or under temperature lapse conditions. Turbulent scattering of sound is the reason why the excess attenuation due to shadow zones is limited to about 20 dB.

Taking into account the effects of atmospheric turbulence within an aircraft noise calculation is an unrealistic undertaking, since it would require knowledge on the structure of the inhomogeneous atmosphere in the whole airport environment. Sophisticated models like [12] usually account for turbulence only by setting a limiting value of about 20 dB for the attenuation in shadow zones.

4.2.3 The effect of topography

Digital terrain models, which have been available for several years, offer the possibility to include the effects of topography into aircraft noise calculations. However, the current best practice procedures account only for one effect of topography, that is elevation: when the propagation distance is calculated, the altitude is estimated with respect to the elevation of the receiver rather than with respect to the airport altitude. In most cases, no account is taken for effects like shielding or reflections due to the shape of terrain. Overground attenuation is calculated for a default soft ground, i.e., surface impedance changes are neglected.

However, there is sometimes a need to account for these effects, e.g., in mountainous regions. Special cases in Europe are some Norwegian airports located near the sea and surrounded by mountains. Here effects of reflections and shielding as well as of rapidly changing ground impedance will affect noise propagation significantly. Some computer programs currently in use account for these effects. These programs use slightly different modeling techniques, reaching from a simple line-of-sight-blocking (as implemented in INM [13] or NORTIM [43]) up to complex models like



(a) FLULA2: departure MD-80, 305m distance

(b) AzB: departure aircraft category S5.2

Fig. 14 **a** The combined emission/propagation model used by FLULA2. Shown is the A-weighted sound level L_A resulting from the departure of a MD-80 aircraft in 305 m [37]. **b** The emission directivity used by AzB for the departure of an aircraft of category S5.2 (e.g., A320) in terms of A-weighted sound power level L_WA

sonAIR [56]. Some of these models additionally include and process surface impedance information.

4.2.4 Effects of obstacles and building

Obstacles and buildings result in effects such as shielding (barrier effects) and (multiple) reflections. Algorithms to account for them are available and already in practical use for the calculation of traffic, railroad and industrial noise. However, obstacles and buildings are generally ignored as far as aircraft noise is calculated. This is primarily due to practical reasons:

- Aircraft noise covers large areas. It would require a significant amount of effort to describe all buildings and obstacles in such a large region (although the information is available).
- Calculation time will increase significantly.
- Calculation grids for aircraft noise have mesh widths of typically 100 m. This is larger than the dimensions of typical houses or obstacles. It is not the intention of aircraft noise calculation to deal with small objects.

Taking into account these aspects it is doubtful, whether it would make sense to include these effects generally within an aircraft noise calculation model, e.g., by adapting the propagation algorithms from the rail and road noise prediction models. However, the influence of buildings can be significant in the vicinity of heliports or if ground operations (APU, run-ups) need to be modeled.

5 Source modeling

5.1 Best practice source models

5.1.1 Models combining source and propagation

Some aircraft noise models are not based on a strict separation of source and propagation modeling. For NPD-based models like INM or ECAC Doc.29, the effects of geometrical spreading as well as of atmospheric absorption are already included in the NPD data (see Sect. 3.4). Changes of atmospheric conditions that affects the atmospheric absorption can be taken into account only by re-calculation of the NPD curves. This is done by a set of corresponding reference spectra [26, 58].

Another approach that combines the source levels with geometrical spreading and atmospheric absorption is that used by FLULA2 [37]. The A-weighted maximum sound levels at the observer is described by the formula

$$L_A(s,\theta) = \sum_{i=0}^{7} \left(H_{i1} \times 20 \times \lg(s) + H_{i2} + H_{i3} \times s + H_{i4} \times s^2 \right) \times \cos^i \theta \text{ dB}. \tag{20}$$

The 32 coefficients H_{ij} are derived from measurements. It should be noted, that this approach is more or less a mathematical one. Furthermore, such a coefficient set is required for each flight condition. An examplary FLULA2 emission directivity is compared to an AzB emission directivity in Fig. 14.

5.1.2 Explicit source models

The general description of the noise emitted by an aircraft operating with the speed V and the engine power P is a spectral sound power level $L_{W,n}(\theta, \varphi, V, P)$ (see Eq. (9)). It is obvious, that this quantity depends on additional parameters, like ambient conditions and aerodynamic configuration, but best practice models usually account only for speed and engine power setting. The power parameter is usually the engine thrust F, the corrected rotorspeed N_1 or the engine pressure ratio EPR. A different approach is used by the German AzB by definition of a level correction Z that maps changes in power setting to changes in sound power level.

In most practical cases, the dependency of the longitudinal angle θ and the lateral angle φ (see Fig. 11) is separated and realized by separate corrections and the sound power according to

$$L_{W,n}(\theta, \varphi, P) = L_{W,n,0}(P) + \Delta_{\theta,n} + \Delta_{\varphi,n} \text{ dB} \tag{21}$$

or—in case of a level correction—as

$$L_{W,n}(\theta, \varphi, P) = L_{W,n,0} + \Delta_{\theta,\mathrm{n}} + \Delta_{\varphi,n} + Z(P) \text{ dB}.$$

A dependency of the sound power level on the aircraft speed V is usually neglected for conventional models. However, velocity has an effect on spectral sound power exposure level $L_{WE,n,k}$ produced by a flight path segment numbered k, which is the basis for the sound exposure calculation at the observer according to Eq. (10). For a segment length l_k and an average velocity V_k along this segment, this quantity can be expressed (similar to the AzB formulation) as

$$\begin{aligned} L_{WE,n,k}(\theta, \varphi, P, V) = {} & L_{W,n,0} + \Delta_V(V_k) + \Delta_l(l_k) \\ & + \Delta_{\theta,n} + \Delta_{\varphi,n} + Z(P) \text{ dB} \end{aligned} \tag{22}$$

with

$$\Delta_V(V_k) = -10 \times \lg\left(\frac{V_k}{V_0}\right) \text{ and } \Delta_l(l_k) = -10 \times \lg\left(\frac{l_k}{l_0}\right).$$

The reference speed V_0 is 1 m/s and the reference length l_0 is 1 m. The sum of L_W and Δ_V is called the length-related sound power exposure level. It describes the sound exposure emitted from a segment of 1 m length. Δ_l corrects this exposure level to the segment length. An identical velocity correction Δ_V has to be applied for NPD data—with V_0 replaced by the reference speed V_{ref} of the NPD curves.

5.2 Scientific source models

5.2.1 Fundamental characteristics

As pointed out in Sect. 3.1, the key characteristic of scientific tools is a componential source model: the sound emitted by the aircraft is simulated as the sum of its relevant noise sources. This approach ensures, that the contribution of the particular noise sources are adequately taken into account as they become relevant along a flight trajectory: any variation of power setting and configuration as well as varying operating conditions will directly change the sound emission. This is essential if, e.g., noise abatement flight procedures have to be developed or analyzed.

The spectral sound power level of a particular source component can usually not be expressed in a straightforward formula like Eq. (21). Naturally, it depends on the longitudinal and lateral emission angles θ and φ. But due to the parametric nature of scientific models, each source mechanism depends on a set of geometrical input parameters as well as a set of parameters describing the actual operating condition. The total number of parameters needed depends on the complexity of the particular source model. They can account for different effects like Doppler frequency shift, shielding effects of the airframe or sound absorption by acoustic liners. Moreover, a moving source effect (convective amplification) depending on aircraft Mach number and longitudinal emission angle may be included. Depending on the particular model and the field of application, the contributions of the particular source components may be summed up at the source to a total sound power level or at the observer location from the resulting componential sound pressure levels.

Scientific models may be of semi-empirical, analytical or some hybrid type. For most source mechanisms, fully analytical models are not readily available: either the source mechanism cannot be described analytically or—more often—the required input data is not sufficiently available. Therefore, most models published in the common literature are semi-empirical which is a good compromise between representation of the physical effects and input data requirements. However, for some of these models, input data are confidential. Ongoing research activities therefore aim at fully analytical models with reasonable input data requirements to avoid the dependence on empirical data (e.g., [41]). If no explicit analytical or semi-empirical source model is available, one has to fall back to simple adjustments which are applied to an available model for a comparable aircraft configuration.

It is obvious, that the applicability of any scientific model based upon empirical data is limited by the extent of the underlying data base. Extrapolation should be avoided—or at least be performed very carefully—to ensure an adequate reliability of the modeling results. If, e.g., novel technology is evaluated with available models, it has to be decided from case to case whether a model can still be applied or has to be replaced.

5.2.2 Engine noise emission modeling

The most commonly used parametric noise source models for conventional turbofan engines are Heidmann's model for fan noise and Stone's model for jet noise. The original formulations [27, 52] are meanwhile amended by derivatives [36, 53] that account for recent developments in the engine design. For example, there are modifications to Heidmann's model to account for higher bypass ratio engines and modifications to Stone's original model to account for inverse velocity profiles (i.e., the situation when flight velocities are greater than the jet exhaust velocities). With a source model for fan and jet noise contribution, the most dominating noise sources of current turbofan designs can be simulated. For other less dominant sources such as turbine or combustion chamber, strongly simplified models can be found in the literature, e.g., ESDU approach.[1] Furthermore, it can be expected that all engine manufacturers develop and operate their own and in-house prediction models.

Fan noise is usually suppressed by acoustic lining—liners are installed on all current engines. Both broadband and tonal contribution of the fan noise are affected. Since the installation of special lining material in the engine inlet and exhaust ducts can significantly decrease the fan noise, this should be accounted for by parametric source models. Usually, the effect of liners is modeled using lookup tables derived from external data or by specific algorithms like a DLR semi-empirical liner model [42].

Furthermore, the fan noise can be reduced to some extent by structural shielding of the emission by airframe or wings. Simple approaches to model shielding effects for conventional aircraft are already included in best practice models (e.g., the engine installation correction described by SAE AIR5662 [51]). Yet, improved shielding is a very promising concept of engine fan noise reduction for unconventional and novel low-noise aircraft concepts. Structural elements can be used to obstruct direct noise radiation toward the ground. To assess these effects, either external data from measurements can be processed [55] or simulation algorithms can be applied [7]. Such algorithms can range from simplified concepts adopted from noise barrier models [39] over ray-tracing concepts [38] up to various high-fidelity numerical approaches. Since high-fidelity approaches with extensive computational requirements are far from a direct application, they are commonly used to create lookup tables with shielding factors for fast predictions.

5.2.3 Airframe noise emission modeling

Multiple parametric approaches toward a fast and simple modeling of airframe noise can be found at various research groups (e.g., the flap side edge and tailing edge noise models described in [44, 46], respectively). However, the most commonly applied airframe noise source models were developed by Fink [24]. Their low input data requirement and simplicity allow to quickly set up an airframe noise prediction code. The models have been derived from a database ranging from small glider aircraft to large, long-range transport aircraft. Consequently, these models can be applied to a large variety of aircraft, but only with a limited accuracy. This is in direct contrast to more sophisticated models that are derived for an individual aircraft type or an aircraft family, hence providing a much higher accuracy. Such models can be found at large research organizations, e.g., NASA and DLR, but also at aircraft manufacturers with in-house and confidential models, e.g., Boeing and Airbus. Most recent models that are still under investigation will not only sum up the individual components of the airframe but also consider interaction effects, e.g., the noise generation due to interaction of the gear wake with a deployed high-lift system at the trailing edge.

6 Fields of application and suitable model types

6.1 Support of land use planning and noise legislation

Land use planning and noise legislation is the most important field of application of best practice models. Because these tasks are defined for airport scenarios rather than single flights, they require databases that allow to model any aircraft in service. This requirement cannot be fulfilled by scientific models.

In practice, two different types of scenarios are investigated, past and future ones. For a bygone air traffic, information on at least aircraft type and departure/approach track is available for each individual flight operation. Most commercial airports provide radar track information as well. Conventional models with a high aircraft-type resolution (like INM [26], AEDT [58] or Doc.29 [23]) are the optimal choice for past scenarios. Future scenarios are based on air traffic forecasts. These are usually elaborated for aircraft categories (usually mass classes or mission lengths). A suitable grouping like that used by the German AzB [21] facilitates such tasks. Moreover, the exact routings are not known and the tool used must be capable of modeling standard backbone tracks and a corresponding lateral spreading.

[1] Various noise source models are published and available on http://www.esdu.com.

6.2 Modeling of noise mitigation measures

The modeling of noise mitigation measures is in most cases a comparative task ("what-if study"). As for the legal applications described in the previous section, these studies are in most cases scenario based and hence require the use of best practice models. Typical tasks are dealing with the effects of changed fleet mix (e.g., due to the phase out of older aircraft), of changed traffic amount or of changed departure or approach routes (e.g., due to construction of a new runway).

A special case is scenarios dealing with the introduction of new flight procedures or noise mitigation measures at the source (e.g., due to acoustic retrofit of particular aircraft types). For such tasks, scientific models can be helpful as pre-processing tools. Detailed information of the available vehicles within the scientific tools can be used to improve scenario simulation with the best practice tools.

6.3 Development of noise abatement flight procedures

Noise abatement flight procedures (NAPs) are one measure recommended by the ICAO's Balanced Approach [30]. Two different tasks have to be distinguished here—the procedure development and the modeling of the effects of the introduction of this procedure in a complex air traffic situation. Moreover, the type of operation (i.e., departure or approach) is of importance. Obviously, the database or noise model to be selected must be structured into individual aircraft types.

To define a NAP, the influence of the varying operating conditions on the individual noise sources has to be accounted for. Along a departure, the dominating noise source is the engine—the impact of the airframe noise is negligible. Best practice models like INM/AEDT or Doc.29 are tools that provide an adequate accuracy for the calculation of departure noise—and moreover they support flight performance calculations for a great set of different aircraft. Scientific models are more accurate, however, they cover only a limited set of aircraft. Consequently, they are more practical for the procedure design then for modeling of its implementation.

Though the best practice models can do the job of simulating conventional and existing aircraft departure procedures, they are no longer applicable to investigate individual approach procedures. An orchestra of various noise sources has to be accounted for and the dominating noise source is significantly changing during the procedure, according to the changes of the aerodynamic configuration. Especially, airframe noise can become the dominating noise source along a substantial part of the approach flight path and consequently the model used must be capable to account explicitly for airframe noise. Therefore, scientific models have to be applied when noise abatement approach procedures have to be developed.

However—as for departure NAPs—the use of scientific models is limited and implementation into complex scenarios require best practice tools. A workaround is the use of scientific models as a pre-processing tool to derive suitable corrections as an input for best practice tools.

It should be noticed that the effect of noise abatement flight procedures is strongly depending on the population density in the vicinity of the flight tracks. Ideally, NAPs should be defined based an a track-type combination. However, this is not realized in practice—airlines often use standardized procedures, independent of airport or track. Moreover, optimized approach procedures are often not realizable due to interference with air traffic control requirements.

6.4 Modeling of noise reduction at the source

The most effective and hence most preferable measure addressed by ICAO's Balanced Approach is the noise reduction at the source. It offers an overall noise reduction potential, whereas noise abatement flight procedures mainly redistribute the noise in the airport environment.

Although best current practice models do not separate the aircraft noise into individual contributions, the effect of noise reduction measures at the source can be assessed in a simplified way by subtracting a constant level from the overall aircraft noise emission. Obviously, this is only valid for noise reduction measures that equally affect the sum of all noise sources and furthermore remain constant during flight. However, this approach is broad international practice—especially for studies dealing with aircraft phase out or replacement.

Scientific models are much more flexible because they account for the change of dominant noise generation mechanisms along a flight path. This is of importance as some noise reduction measures (e.g., suppression of individual tones) will come into effect only for specific engine power settings or aerodynamic configurations. Altogether, scientific models provide a much more detailed and realistic possibility to assess the effects of noise reduction measures at the source than best practice tools.

The fact that the instantaneous noise source ranking changes along a flight path implies that the effect of reduction measure can be optimized by suitable definition of flight procedures. Earlier papers on aircraft noise optimization (e.g., [1]) investigated the effects of noise reduction measures at the source under fixed operating conditions—including all relevant mechanisms and interactions but ignoring the influence of the flightpath on sound emission as well as on the geometry between aircraft and observer (and hence on propagation effects).

6.5 Low-noise aircraft design

More recently, a process chain for automated low-noise aircraft design synthesis has been established at TU Braunschweig and DLR [7]. All required input parameters for the noise prediction are generated within this fully automated workflow. Ultimately, an individual flight trajectory is simulated for the aircraft under consideration to finally predict the noise immission levels. The simulation is performed according to the scenario task definition by the user, i.e., selection of a runway with corresponding observer locations along the flightpath. The noise calculation is directly incorporated into the aircraft design synthesis, hence enabling aircraft design optimization and flight trajectory adaption. Furthermore, external tools and/or experimental data can be processed to include more sophisticated results in the simulation process. This workflow has successfully been applied toward novel aircraft configurations with emphasis on fan noise shielding [7].

NASA has published many aircraft design concepts and ideas based on a similar simulation process [14, 54]. The NASA approach combines simulation methods of multiple fidelity and can process external experimental data. If simulation tools or noise source models of various fidelity levels are combined, special attention has to be paid to the compatibility. Therefore, knowledge of the inherent uncertainties behind each simulation result is required but is generally not known or available. NASA and DLR have started to investigate into the simulation uncertainties of their in-house scientific noise prediction processes [9, 54].

The so-called Silent Aircraft Initiative by MIT and Cambridge is another example of a full assessment of low-noise aircraft design under consideration of changed flight performance [17]. Also, high-fidelity simulation results have been integrated and processed toward a comprehensive noise assessment. Here, the focus of the noise analysis lies on the evaluation in direct proximity to the airport. Large-scale assessment of the noise situation along the entire approach and departure flights has not been in the scope of the work.

Many other activities are still in early stages of development and are not considered here. Often, the research is limited to certain aspects of the problem, e.g., modifications to the aircraft source geometry only, without consideration of the actual flight performance. In this paper, only simulation processes that simultaneously account for aircraft design, engine design, and flight simulation have been considered.

Within the EU project COSMA, the first steps toward an annoyance-based optimization of aircraft and flightpath are documented [31]. The aircraft and flight procedures were modified to yield the least annoying spectral shapes of the perceived noise on the ground. The perception influenced design (PID) by NASA [45] goes one step further and computes audible signals for novel aircraft concepts moving along individual flight tracks. Based on these signals, listening tests can be conducted to assess the annoyance associated with each simulated flyover event. Based on this annoyance evaluation, the least annoying concepts can be identified and selected for further investigation. Inspired by NASA's PID work, similar research has been conducted at RWTH Aachen [47] and in a joint effort by TU Delft, NLR, and DLR [2].

Ultimately, it can be concluded that many researchers launched low-noise aircraft designs activities in the recent years but have not published about their methods and results yet. Therefore, it is expected to see many more aircraft concepts and ideas toward low-noise aviation in the future, e.g., results from the joint projects Impact DrivEn Assessment of Low-noise aircraft configurations (IDEAL) of Switzerland's Empa and DLR or the Aircraft Noise Simulation Workgroup (ANSWr) by NASA, ONERA, and DLR.

Based on available research results in the field, some simple recipes toward low-noise aircraft design can be derived. These instructions are readily applicable to conventional transport aircraft with today's turbofan engines of high bypass ratios, i.e., the fan is a relevant or even the dominating noise source along approach and departure.

- Componential modifications to certain individual noise sources should always be applied if available (e.g., installation of a mesh fairing to reduce flap side edge noise emission). However, the focus has to lie on the dominating noise sources along a simulated approach or departure flight path.
- In addition to any source modification to reduce the fan emission, the fan noise radiation can significantly be reduced by structural noise shielding. New aircraft designs promise increased shielding for more integrated engine installation concepts. It has to be noticed, that both the forward and the rearward radiated fan noise have to be accounted for.
- Noise generation due to interaction of various structural elements of the aircraft can dominate the noise radiation [16]. Prominent examples are the interaction of the gear wake with the high-lift system or the jet impingement on deployed high-lift components. These interaction noise sources should be avoided by not arranging certain aircraft elements downstream of other elements but rather consider some lateral offset.
- The final recipe toward a low-noise aircraft is the early incorporation of acoustical advantageous flight performance in the aircraft design process. It can be demonstrated, that no optimal low-noise aircraft design can be identified if the focus is limited to only the geometry of the aircraft. It is essential to consider the aircraft in flight

to finally assess the ground noise immission. If it turns out that certain flight characteristics are very promising from a noise point of view, they should be incorporated already in the conceptual aircraft design.

7 Summary and conclusion

Aircraft noise calculation models were originally introduced as essential supporting tools for noise legislation and land use planning. However, their field of application has been broadly extended within the last decades. The major reason is the enormous increase of computer performance which nowadays allow the implementation of sophisticated physical models of sound generation and propagation (which have been partly developed in the primeval times of aircraft noise modeling). ICAO's Balanced Approach to Aircraft Noise Management is a good example for the increased demands on aircraft noise modeling.

Before aircraft noise can be reduced, it must be quantified and assessed. This is done by so-called noise descriptors. Principles of noise assessment are explained in Sect. 2—reaching from the fundamental measurable quantities (maximum sound levels, single event levels) over common noise descriptors like equivalent continuous sound levels up to the novel family of noise indices which include exposure–response relationships to account for human reactions.

The third section deals with general concepts of aircraft noise modeling. First, it presents a noise model classification into best practice noise models and models which are used for scientific purposes. The next subsections describe the typical workflow for noise modeling tasks, introducing the concepts of scenarios, the noise engine as the basic processing unit and the different types of databases. The special role of these databases is discussed afterwards and it is pointed out that the model type determines the structure of the underlying database and vice versa. The final part of the second section describes the two different approaches of flight path description (segmentation and time step structure) which are closely related to the noise model type as well.

From a descriptive point of view, any kind of noise modeling can be split up into two steps: the description of the sound emission by the source (usually in terms of spectral sound power level) and the modeling of the sound propagation through the atmosphere up to an observer location. Section 4 deals with the modeling of propagation effects, which can be split up into standard effects (geometrical spreading, atmospheric absorption and overground attenuation) and other effects which are of relevance for the propagation of aircraft noise only under specific conditions. These effects (like temperature gradients, wind, turbulence, topography and obstacles or buildings) can be neglected in most practical cases. The fundamental equations of aircraft noise modeling are introduced in this section.

Section 5 describes the source modeling for best practice as well as for scientific models. The first model type is based on the assumption of a single-source model which is realized by two common approaches. The first one is a description which combines emission and propagation. Examples are INM/AEDT and the ECAC Doc.29 compliant models with their pre-calculated noise–power–distance data and the Swiss FLULA2 model, which uses a mathematical model based on a series expansion in distance and radiation angle. Other models like the German AzB and the Swiss sonAIR model are based on a separation between emission propagation. Although this is the more physical approach, NPD models are the most common ones worldwide.

The characteristic of a scientific model is the splitting of the total sound emission into particular source mechanisms, which are related to airframe and engine noise. These multi-source models use a parametric description of the noise emission mechanisms—partly semi-empirical, partly fully analytical—and are always based on a time step flight path description. Obviously, this model type is more flexible than a best practice model. However, basic data for scientific models are rare and comprehensive data sets are available only for a small set of aircraft. Consequently, the field of application is limited to tasks dealing with single flights. Complex air traffic scenarios are the domain of best practice models and this situation will not change in the foreseeable future.

The final section of this contribution to the CEAS special edition deals with the different fields of application of noise modeling and the choice of suitable models. It can be summarized as follows:

- Land use planning or noise legislation requires the modeling of complex air traffic scenarios, i.e., each aircraft participating to the traffic must be modeled. This can be achieved only by best practice models.
- The modeling of noise mitigation measures is in most cases scenario based and hence a domain of best practice models as well. However, scientific model can provide support for such tasks.
- The development of noise abatement departure procedures can be handled by best practice models, too. This is not the case as far as approach procedures are addressed: the dominant noise sources change along the flight path and consequently airframe and engine noise must be taken into account separately. This can only be achieved by scientific models. However—since they are limited to a small set of aircraft—they may be used to improve the best practice models with respect to this task.
- Noise reduction at the source—the most effective measure proposed by the ICAO's Balanced Approach—can

be handled by best practice models only in a simplified manner (i.e., by adding of level corrections to the total emission). Scientific models are more flexible and hence the optimal choice for such tasks—with the known limitations.
- The design of low-noise aircraft concepts is a very new area of aircraft noise research. Its treatment is completely limited to scientific models.

The importance of the last item will increase in future, although the design-to-noise is a very challenging task. Developing new noise source models will enable a simulation of more advanced vehicle concepts. Beside that, the integration of advanced analytical approaches as well as of high-fidelity computation results into fast prediction codes will reduce the limiting applicability of empirical data for the modeling. In addition, most recent developments such as an integrated low-noise aircraft design process or perception influence design are discussed. Hence, it can be expected that an ongoing development of the scientific modeling tools will open up additional fields of application.

It should be noted that in the long term the best practice models will benefit from the development of scientific models. Ultimately, information on particular sound sources mechanisms may be integrated into these models. Initial approaches are documented by the Swiss Empa laboratories [57]. What still remains is the lack of basic acoustic input data for both model categories. This is insofar frustrating for the community of noise modelers as a big part of these data is in principle available, but aircraft and engine manufacturers hesitate to provide them.

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