Sound source data for aircraft noise calculations – state of the art and future challenges

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Summary
All aircraft noise calculation programs need a data base on aircraft sound emission. The time-step program FLULA2 used in Switzerland requires directivity information not available in the Noise-Power-Distance tables (NPD) used in many programs. Thus, an independent data base has been established for a great number of aircraft types on the basis of measurements in the close vicinity of airports. This measurement procedure has proven to yield accurate and reliable departure (initial climb) and final approach directivities. However, changes in flight configuration, i.e., airplane configuration plus flight parameters such as power setting, taking place during different stages of flight are modelled so far with relatively rudimentary overall sound level differences. In this paper a brief review of the state of the art of aircraft noise measurements and analysis is given for two- or three-dimensional sound source data. On the basis of typical results, advantages and limitations of the existing acquisition process for sound source data used in Switzerland are discussed and requirements for measurement procedures for next generation aircraft sound source models are identified. Based on these considerations a concept to derive spectral three-dimensional sound directivity patterns in dependence of flight configuration is presented.

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1. Introduction
All aircraft noise calculation programs need a data base on aircraft sound emission. To date, different approaches with various levels of sophistication to calculate aircraft noise exist [1]. Aircraft noise models, source description, corresponding source data and methods to obtain the data are inseparable from each other. This paper briefly reviews available state-of-the-art source descriptions, data acquisition and data bases world-wide. Thereafter the sound source model of FLULA2 developed at Empa, the Swiss Federal Laboratories for Materials Science and Technology, is discussed. Advantages and limitations of the existing approach and requirements for next generation sound source models are identified, and a concept to derive spectral three-dimensional (3D) sound directivity patterns in dependence of flight configuration, i.e., airplane configuration plus flight parameters such as power setting [2], is presented.

2. Sound source description and data acquisition – international
Generally, models may be classified as immission and emission models [1], the former directly producing the sound level at the receiver (e.g., INM [3]), and the latter separately describing sound source and propagation (e.g., AAM [4]). Emission models may be further classified as (i) purely empirical descriptions of sound emission, (ii) completely analytical descriptions based on physical models, and (iii) semi-empirical descriptions, the latter being a compromise between (i) and (ii) [5]. Currently available sound source or immission data bases include:

- Noise-Power-Distance tables (NPD) for INM [3]: Immission data (integral $L_{AE}$ and $L_{AS\text{max}}$; also in EPNdB) for whole flights, in dependence of power setting and distance. No information regarding sound directivity. Data base derived from certification measurements.
- Aircraft Noise and Performance (ANP) data base for ECAC Doc.29 [6] and ICAO Doc 9911 [2]: Public subset of with same acoustic information as NPD tables.
• German AzB [7]: Octave band information with cosine function sound directivities [5] and level differences for aircraft classes. Data base of 1996 with revisions of 1999, derived from measurements on several German airports.

• Swiss aircraft noise calculation data base (SANC-DB) [8]: Performance, acoustic parameters ($L_{A\text{max}}$, $L_{AE}$, emission spectrum) and simple directivity for several power settings. Data derived from certification measurements (small aircraft, helicopters) and from FLULA2 (large aircraft, helicopters).

Besides, there are various programs which use more detailed sound source modelling and data, such as SIMUL (semi-empirical model based on partial sound sources, currently available for the A319/A320 only [5]) or AAM [4] (3D spectral sound directivity). However, these data sets are not publicly available. In Switzerland, FLULA2 uses sound source data determined under real air traffic, as described in the following section.

3. Sound source description, data acquisition and application in Switzerland

Empa has a tradition of several decades in aircraft noise calculations and sound source data measurements, with 10 measurement campaigns over the last 20 years. The most important campaigns were those conducted in 1991 and 1996 at Zurich airport under real air traffic conditions, with data acquisition of the most frequent large aircraft types operating in Switzerland.

Details on the state-of-the-art sound source data acquisition at Empa may be found in [9]. Sections 3.1 to 3.4 give the basic principles.

3.1. FLULA2 and sound source model

The basics of the time-step program FLULA2 are described in [10, 11]. In short, FLULA2 considers (i) the sound source data of individual aircraft (see below), (ii) the statistics of movements per aircraft type, air route and period of day, (iii) the flight geometries determined from radar data or idealized flight paths (single flight simulation), and (iv) the topography.

The sound source model of FLULA2 was established in the early 1980’s when computational power was very limited. It yields the A-weighted sound level in dependence of the distance ($r$) and the longitudinal sound source angle $\theta$, described by a cosine power series.

$$L_A(r, \theta) = \sum_{i=0}^{7} A_i(r) \cos^i(\theta), \quad (1)$$

with the coefficients $A_i$ being functions of the radius $r$:

$$A_i(r) = H_{i4} 20 \log \left( \frac{r}{r_0} \right) + H_{i2} + H_{i3} \left( \frac{r}{r_0} \right)^2 + H_{i4} \left( \frac{r}{r_0} \right)^4,$$

with $r_0 = 1$ m. Equations (1) and (2) are valid for distances up to 4’500 m. For larger distances, the equations diverge, and the source description is modified (details see [11]). The $A_i$ coefficients characterize the shape of the directivity at a given distance $r$, while the $H_{ik}$ describe the dependency of $A_i$ on the distance $r$. The 32 $H_{ik}$ coefficients thus describe the sound immission level at receiver locations of a specific aircraft for all directions and distances, assuming rotational symmetry in the axis of flight, i.e., two-dimensional (2D) directionality.

3.2. Measurements

Sound is recorded simultaneously at different microphones placed at the side and at the extension of the centre line of the runway, in close vicinity of the airport. Aircraft position is recorded with a precision tracking system. The acoustic and position recordings are synchronised by the radio clock signal of the DCF77 transmitter in Germany. Recorded data is processed in the laboratory.

3.3. Data Processing

Data processing is done in four steps. Firstly, measured spectra (1/3 octave bands from 25 Hz to 5’000 Hz, time steps of 50 ms) related to specific aircraft positions are selected (details see [9]). For each of these spectra, the geometry of sound radiation is defined by the distance $r$ between source and receiver, and by the longitudinal and transversal angles of radiation.

Secondly, the 1/3 octave band spectra are normalized to standard atmospheric conditions ($T = 15^\circ$C, r.h. = 70%, P = 1013.2 hPa) and transformed to seven reference distances from 30 to 6’000 m: The recorded spectra are calculated back to the source using the atmospheric absorption during measurements and transformed to the reference distances using the atmospheric absorption of the standard conditions. The atmospheric absorption is calculated according to ISO 9613-1 [12]. The spectra are then converted to A-weighted sound levels.

Thirdly, the mathematical model is fitted to the normalised A-weighted sound levels as illustrated in Figure 1. The $A_i$ coefficients are determined for the seven reference distances using equation (1) (Figure 1a). From these, the $H_{ik}$ coefficients are calculated using equation (2) (Figure 1b).
The fit algorithm (least square) leads to small systematic errors, yielding values close to the arithmetic mean of the input data. Therefore, in a last step the differences between the energetic mean of the measured and simulated exposure levels are determined and used to scale the preliminary model coefficients. The final coefficients adequately reproduce the measured sound exposure levels.

3.5. Application—strengths and limitations
FLULA2 is one of currently three programs approved by the Federal Office of the Environment (FOEN) for aircraft noise calculations in Switzerland [8]. Currently, its three main applications are:

- **Military and helicopter airfields**: Noise mapping using idealized flight paths (no radar data available) for purposes such as noise exposure registers or environmental impact assessment.
- **Airports—past time scenarios**: Yearly noise mapping for Zurich and Geneva airports to monitor the sound level development. In the calculations, all available radar data are used [15] (more than 140'000 and 240'000 trajectories for Geneva and Zurich, respectively).
- **Airports—prognoses or scenario studies**: These calculations are based on idealized flight paths. Future scenarios for Zurich airport are currently being politically evaluated in Switzerland, based on results of such calculations (so called “SIL process of coordination” [16]).

FLULA2 is well suited for investigations of complex air traffic scenarios as those described above: The sound source data represent the aircraft fleet operating in Switzerland in great detail (many aircraft types) and with well-known accuracy and reliability. Further, the air operations (number of movements, allocation of movements to air routes, trajectories) are accounted for in great detail [15]. For such scenarios, FLULA2 yields reliable results, with uncertainties of $L_{Aeq}$ values relevant for Swiss legislation [17] of 0.6 dB (day) to 1.0 dB (night) for past-time scenarios, and about the double for prognoses [18]. Also, the $L_{Aeq}$ calculated with FLULA2 agree well with monitoring measurements [15, 18].

However, FLULA2 and the underlying sound source data have certain shortcomings, such as:

1. **Sound emission and propagation modelling** should be clearly separated, as for example proposed in ISO 9613-2 [19].
2. **Sound emission and propagation should be modelled frequency dependent**, preferably in 1/3 octave bands, not as A-weighted sound levels.
3. The current sound source data describe the initial climb (maximum and flex power) and final approach. Changes in flight configuration are accounted for relatively coarsely (cutback, touch down) with sound level differences $\Delta L_A$, neglecting possible changes in directivity characteristics and spectrum. Changes in flight configurations other than cutback and touch down are not accounted for.
The above shortcomings in principle apply to most available “conventional” models, i.e., models primarily designed to investigate the acoustics of complex scenarios such as yearly air traffic [5]. For these conventional purposes, FLULA2 yields sufficiently reliable and accurate results, as discussed above. For future requirements, however, these shortcomings may become important, as discussed in the next section.

4. Future requirements

Besides the conventional task of aircraft noise calculations (complex pastime or future scenarios), the acoustic investigation and/or optimization of single flights or noise abatement operational procedures become an increasingly important issue. For such tasks the conventional models only feature a limited applicability. They can only grossly estimate the acoustic effects of noise abatement flight procedures, because the latter do not only affect flight tracks and profiles (which may easily be accounted for by current models), but in particular also flight configuration, i.e., aeroplane configuration (slats, flaps, landing gear) plus flight parameters such as power setting [2], which are far more difficult to model acoustically. Accounting for the latter effects is an important requirement for future models. Possible modelling approaches are outlined in literature (e.g., [20]). An enhanced model should particularly improve the sound source description, which currently bears most current shortcomings identified above.

5. Concept to develop and acquire future sound source model and data

Responding to the requirement of future aircraft noise calculation models, Empa established a concept to develop a new program, denoted sonAIR, which is currently under evaluation for funding. Its centrepiece is to develop a sound emission model for different aircraft/engine types and flight configurations, as well as to establish an underlying data base representing the aircraft fleet operating in Switzerland. Well-established parts of FLULA2, such as the single flight simulation, are to be adopted by the new program. The sound emission model development and data acquisition are closely related to each other. The measured acoustic data will determine the level of sophistication of the model, while the possibilities of sound emission modelling will give the level of detail of the acoustical analysis.

5.1. Measurements

Measurements are planned in the close vicinity of the airport for three weeks with 6–8 microphones, and in the far field for two months with 5 additional microphones. Measurements are to be done on Zurich airport, as this allows detecting the major part of aircraft operating in Switzerland. In principle the measurements will follow the procedures of Empa described above, but will be more demanding due to increased requirements for sound emission models. In the close vicinity (initial climb: “near field” in Figure 2), they will have to cover a maximum possible amount of longitudinal and transversal emission angles to establish reliable 3D sound directivity patterns. Far field measurements of approaches should cover distances from the airport of ~16 km or even more, if clean configuration is to be recorded. For departures, as shown exemplarily in Figure 2, they should cover distances of ~20 km to record continuous climb after cutback (“far field 1”) and clean configuration (final climb: “far field 2”). Far field measurements bear the problem that aircraft noise levels are low, so that the signal-to-noise ratio becomes progressively small. Therefore only $L_{\text{max}}$ and their spectra will probably be measurable, potentially preventing the establishment of sound directivities in the far field (too small variation in sound emission angles). Furthermore, while approaches are well bundled on the glideslope allowing for precise positioning of the microphones, departures scatter strongly, so that the limited number of microphones will only grasp a relatively small fraction of departures, necessitating the long measurement period of 2 months. Separate establishment of engine and airframe sound sources is desirable and will be investigated. However, this is a very difficult task for measurements on real air traffic, without flights under pre-defined flight configurations.

5.2. Data processing

Data processing in principle follows the established procedures, but will yield spectral 3D sound directivity patterns, following the adapted methodology described in [13, 14].

5.3. Flight configuration data

The measured data will be brought in closer relation to flight configuration than it had been possible in previous measurement campaigns. For that purpose, cockpit data as presented in Figure 2 will be analysed which will be available for aircraft of the Swiss International Airlines Company.
For aircraft of other companies, for which no cockpit data is available, engine power setting (N1 in Figure 2) will be determined from spectral analysis of the sound recordings.

5.4. Sound emission model

Given the critical points identified in section 3.5 and considering the possibilities and limitations of measurements, the aim is to determine a semi-empirical model yielding spectral (1/3 octave bands) 3D sound directivity patterns for different flight configurations (aeroplane configuration plus flight parameters, cf. Figure 2). The model will be established as follows:

1. Close vicinity of airport: The sound directivity is reliably determinable [13, 14].
2. Far field: The sound directivity is difficult to establish (section 5.1). As a fall-back option, spectral sound level differences for different flight configurations are identified from far field measurements of $L_{\text{max}}$ and their spectra.
3. Analysis of the dependency of the acoustical data on flight configuration using cockpit data.
4. Definition of continuous functions for sound emission in dependence of flight configuration. Knowledge and quantitative approaches from literature are to be considered (e.g., [21]), and parameters are to be scaled with the measurements.
5. If possible, separate engine and airframe sound source models are to be established. As separating these sources is a challenging task (section 5.1), combined source descriptions for distinct flight conditions is a fall-back option.

In the model development, also results and experiences of international research programs on noise abatement procedures are to be considered, such as NIROS (e.g., [22]) and SOURDINE II [23], or the currently running project MODAL by the German Aerospace Center.

The data base of the final model is to be extended to aircraft types which were not measured, using approaches already applied at Empa.

5.5. Program implementation

The new sound emission model is to be implemented as a software tool. The sound propagation model will be taken from the existing model sonRAIL which was developed at Empa for railway noise calculations [24] (thus the name “sonAIR”). For that purpose, the propagation model has to be adapted for specific aircraft noise requirements. The program sonAIR will separately account for sound emission and propagation.

6. Conclusions and outlook

In this paper, the current status of aircraft sound source descriptions, data bases and measurements is given, with special focus on FLULA2 of Empa. Based on experiences, requirements for future sound source models are identified and a concept is outlined on how to establish a next-generation aircraft noise calculation program. A proposal for the development of such a program, called sonAIR, is currently being under evaluation for funding. If funding is granted, the realization of the concept will start in autumn 2012.
References


