sonAIR – data acquisition for a next generation aircraft noise simulation model

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ABSTRACT
The acoustic optimization of flight procedures requires sophisticated models that account for flight configuration parameters as they can have a major influence on the resulting sound exposure. For these purposes a new aircraft noise simulation model, denoted sonAIR, is being developed. Its semi-empirical emission model shall deliver a detailed spectral description of the sound source to account for configuration changes. The aircraft shall be modelled by separate sound sources for engine noise and airframe noise, each featuring different spectra and directivity patterns and possibly being assigned to different locations. As sufficiently detailed sound source data is not available, extensive measurements under real air traffic are planned. In this paper an overview on the sonAIR project is given and the measurement layout is presented. The latter comprises the optimal placement of the microphones in terms of longitudinal and azimuthal emission angles as well as directional uncertainty.
Keywords: Aircraft noise, Simulation model, Sound source data base

1. INTRODUCTION
Aircraft noise is a significant environmental problem around airports, causing considerable noise costs. According to a study considering five European airports (Heathrow, Gatwick, Stansted, Schiphol and Maastricht), the resulting yearly airport-specific noise costs add up from 1.3 to 179.5 million euros [1]. The guidance on the Balance Approach of the International Civil Aviation Organization (ICAO) addresses the noise problem by four principal elements [2]. One possibility is to acoustically optimize flight procedures on the basis of model calculations that account for flight configuration parameters, as the latter sensitively influence the sound exposure.

However, currently available aircraft noise models are of limited use for such requirements as the influence of flight configuration parameters is neglected [3]. Other calculation models with more detailed source descriptions such as SIMUL (semi-empirical model based on partial sound sources) [4] or AAM [5] are not public and/or comprehend only source data for a small number of aircraft types.

Therefore, a research project was started at the beginning of 2013 at the authors’ institution, Empa, to develop a new aircraft noise calculation model named sonAIR. The main tasks are to develop a
sound emission model, to acquire sound source data and to implement a sound propagation model. As the sound emission model and the sound source data are inseparable from each other, a measurement campaign is currently being planned. This paper shortly introduces the concept of sonAIR and discusses the data requirements for the development of three-dimensional (3D) sound directivity patterns. The focus is on the prediction of the emission angle coverage and directional uncertainty.

2. OVERVIEW

2.1 Objectives

A time-step program for aircraft noise calculations will be developed, in which sound source and propagation are strictly separated. In contrast to the simulation model FLULA2 [6], previously developed at Empa for the acoustic investigation of complex scenarios such as yearly air traffic, the new program focuses on single flight events to investigate and optimize noise abatement procedures by using either generic data, e.g. from a full flight simulator, or cockpit data from real flights.

The aircraft as a sound source will be described by physical laws and empiric data to scale with flight parameters such as power setting or speed and aeroplane configuration (slats, flaps, landing gear). To gain a sufficient database for different aircraft and engine types, extensive measurements under real air traffic at Zurich airport will be done.

A highly sophisticated sound propagation model, available at the authors’ institution, is adapted to the special characteristics of aircraft noise calculations. The sound emission and propagation model are combined in a geographical information system. This interface will allow for the preparation of projects, perform the execution of calculation tasks and yield helpful tools for the analysis and presentation of results. Besides single flight events, the algorithms and program structure will also allow calculating complex scenarios such as yearly air traffic. While the emission model causes higher effort in preparing the input data, it has no relevant effect on calculation time. In contrast, the efficiency of propagation model is crucial.

2.2 Sound Emission Model

A semi-empirical sound emission model will be developed by combining data measured under real air traffic with generalized physical laws establishing the relation between flight configuration and sound emission, including information on the frequency spectrum and directivity. Thereby, also results and experiences of the MODAL research program of the German Aerospace Center will be considered. In the close vicinity of the airport, 3D sound directivity patterns will be established, which represent the stationary flight conditions of initial climb and final approach. The principles of data processing and the development of directivity patterns are described by Krebs [7] and Schäffer [3]. In larger distances to the airport, it is not possible to cover a wide range of polar angles. Possibly, sound directivities cannot be established. However, measurements are still of interest to determine the sound emission for different flight conditions. Therefore, five mobile measurement stations will be used at approximately twelve different locations in distances up to 25 km from the airport. If directivity cannot be determined at far-away locations, spectral sound level differences will be used as a fall-back option to account for changes in flight configuration.

Cockpit data will be used to determine the flight configuration of the measured aircraft events. They are available for the Swiss aircraft fleet, namely for the Airbus A320 family, the A330-300, the A340-300 and the Avro RJ100. The cockpit data covers all necessary information in high time-resolution, such as flight path, orientation in space, true airspeed, rotary speeds of the engines as well as the position of flaps, slats and gears. For airplanes of other airlines, where cockpit data is not available, the ground speed and the bank angle can be derived from the flight path. Additionally the low compressor speed (N1) will be estimated by spectral evaluation of the acoustical data as an indicator for power setting. This method is expected to work accurately in close vicinity of the airport. In larger distances with highly attenuated signals, the evaluation of N1 will be more challenging.

2.3 Sound Propagation Model

For the calculation of sound propagation, an existing model named sonX will be used. sonX was engineered in the years 2007 to 2009 within the sonRAIL project, in which a new railway noise calculation program was developed\(^4\). Since 2009 the sonX propagation core has been optimized from

\(^4\) http://www.empa.ch/sonrail/
an acoustic point of view as well as in terms of performance [8]. Additionally the range of application has been extended to road traffic and shooting noise [9].

The propagation model of sonX applies to point sources. Direct sound is calculated on the basis of vertical terrain sections from source to receiver including buildings and other barriers. The calculation is conducted in two steps. In a first step, a calculation under the assumption of a homogenous atmosphere is performed. Thereby geometrical divergence, dissipation according to ISO 9613-1 [10], barrier and ground effects as well as foliage attenuation according to ISO 9613-2 [11] are taken into account. Barrier effects can either be calculated according to the approach of Maekawa [12] as implemented in ISO 9613-2 or according to a solution presented by Pierce [13]. For the calculation of ground effects, an analytical solution for spherical waves is used, which has been extended for uneven terrain and varying surface properties. In a second step the meteorological effects on sound propagation are determined, namely, the influence of local temperature and humidity on dissipation and consequences of vertical gradients of wind and temperature on shielding effects. The latter is done using a ray tracing algorithm, which derives the sound path from source to receiver including possible barrier edges for a given profile of the effective speed of sound (Figure 1). As an additional effect the evolution of acoustical shadow zones can be derived, applying an approach by Hofmann et al. [14].

Figure 1 – Ray tracing algorithm to derive the sound path from source S to receiver R.

Reflections at buildings and walls are taken into account according to Heutschi [15]. The model distinguishes between coherent, specular reflections and scattering. Diffuse reflections from forest edges and cliffs are represented by two separate models published in [16] and [17], respectively.

The sound propagation modelling is performed in one-third-octave bands. For aircraft noise a frequency range from 20 Hz to 5 kHz will be applied.

2.4 Simulation Tool

According to the time-step concept, a single flight is represented by source positions that follow the aircraft trajectory with a given time step, typically of one second. At each position the angle-dependent sound emission is calculated with the momentary power setting, aeroplane configuration and orientation. At a given receiver location the contributions from each source position are summed up in chronological order. From the resulting level-time histories, acoustical quantities such as equivalent continuous sound pressure level or maximum sound pressure level can be derived.

The resulting simulation tool shall be used for the detailed analysis of single flights, as well as for the calculation of complex scenarios, processing several 10'000 flights to produce noise maps of large areas of several tens of square kilometres. In the latter case the computing time is a major issue, which will be reduced by two measures.

Firstly, a distinction of the propagation situation will be introduced. If sound propagates close to the ground, the model according to Section 2.3 will be used. For large aircraft heights, in contrast, the situation is much simpler because no shielding effects occur and the laborious processing of terrain profiles can be omitted. Furthermore, the influence of temperature and humidity on the dissipation is the only relevant meteorological effect. In addition, direct sound dominates and reflections can be neglected. Therefore a simplified approach will be applied, accounting only for geometrical divergence, dissipation and a standardized ground effect. As a criterion for the distinction of complex and simplified situations, the angle of sight relative to the line of horizon will be used.

Secondly, the (detailed) sound propagation calculations will be done prior to the actual aircraft noise calculations and the resulting attenuations will be stored in a look-up database. For that purpose the airspace will be subdivided into basic volumes of rectangular shape. A sound propagation calculation will be performed for each of the eight corners of those cells that are actually flown through by aircraft. During the simulation of single flights the relevant attenuations are derived by interpolating at the actual source position from the values of cell corners according to the database.
To avoid inconsistencies at the transition from the simplified to the sophisticated model, dissipations per meter will be pre-calculated with sonX for given meteorological conditions and stored in a look-up table for different layers of the atmosphere. During the single flight simulation, attenuations will either be accessed from the database or, in the simple case, directly calculated using the latter dissipation values.

3. MEASUREMENT CONCEPT

3.1 General

Measurements are to be done at Zurich airport under real air traffic, which allows collecting the dominant commercial aircraft types operating on Swiss airports. Due to different runway lengths, operational concepts and destinations at Zurich airport, a large variety of flight parameters can be gathered for the development of the semi-empiric sound source model. Independent measurement will be done in small as well as in large distances from the airport.

In close vicinity of the airport, data for 3D directivity patterns are collected (Section 2.2) by placing six to eight microphones next to the runways (Figure 2). The angles covered depend on the microphone position as well as on the take-off point that varies up to 500 m for the same aircraft type and up to 1500 m between different aircraft types, mainly because of different take-off weights and thrust levels. Therefore the microphones are located not only at the end of the runways, but also alongside the runways to catch early take-offs. During daytime, most of the data can be collected on runway 28 (departures to the west, Figure 2) and on runway 14 (approaches from the north, not shown). Due to the German restrictions during early daytime hours (6 to 7 a.m.), some aircraft types are approaching from the south only (runway 34). Besides, heavy aircraft types such as the A330 or A380 normally take off to the south from runway 16. Because these types are acoustically relevant, measurements are planned on runway 16/34 too. To cover a wide range of polar angles and hence cumulate enough data for the 3D directivity patterns, the locations of the microphones have been optimized (Section 3.2).

For larger distances, approximately twelve microphone locations up to 25 km from the airport are planned, which are to cover different flight configurations. Departures will be measured along the nominal flight track to the west of runway 28 and to the east from runway 16. Approaches will only be measured on runway 34, as sufficient data for all aircraft types are available there.

Flight paths are determined in close vicinity of the airport (time and position) by an optical tracking system, which is developed by the partner company SciTracks®. In large distances from the airport the requirements in terms of the accuracy of the flight path localization are lower and radar data should be sufficiently accurate (Section 3.3). These systems are needed particularly for the aircraft of airlines where no cockpit data are available. For validation of tracking data derived from different sources, a mobile multilateration system is planned to be used in cooperation with skyguide®.

Figure 2 – Measurement layout on runways 28 and 16 / 34

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3.2 Prediction of Angle Variety for 3D Directivities

To establish reliable 3D directivity patterns, a wide range of polar angles has to be covered. The microphone positions have been optimized accordingly, using a Matlab program predicting the coverage of the polar angles. As the take-off positions are very variable (Section 3.1), flight paths derived from radar data of different aircraft types and with an early and a late take-off point per type were used as input data for the prediction tool. For each discrete source position \(n\) of the selected flight path the relative vector \(r_{g\text{,mic}}\) to a microphone location was determined described in aircraft-carried normal earth coordinates (index \(g\)) as defined in DIN9300-1 [18]. As all data were given in Swiss coordinates CH1903, the \(x_g\)-axis is oriented to true north.

\[
L_{g\text{,mic}}(n) = \begin{bmatrix}
x_{\text{mic}} - x_{\text{path}}(n) \\
y_{\text{mic}} - y_{\text{path}}(n) \\
z_{\text{mic}} - z_{\text{path}}(n)
\end{bmatrix}
\]

\[
L_{k\text{,mic}}(n) = L_{g\text{,mic}}(n)
\]

With Eq. (2) the vector \(r_{g\text{,mic}}\) is transformed into the Cartesian flight-path axis system (index \(k\), cf. Figure 3) to determine the polar angles from each source position to the microphone. As information of the inclination angle is usually unavailable, the influence on aircraft orientation was neglected but will be subject to future investigations. The transformation matrix into the flight-path axis system was done according to Brockhaus [19].

![Figure 3 – Flight-path axis system with longitudinal and lateral polar angles \(\theta\) and \(\varphi\)](image)

Finally the polar angles \(\theta\) and \(\varphi\) for each discrete point of the flight path are determined by the law of cosines with the vector \(r_{k\text{,mic}}\) (Eq. 2) respectively the vector \(r_{k\text{,mic},yz}\) and the unit vectors \(x_k\) and \(z_k\) as shown in Figure 3.

\[
\theta = \arccos \left( \frac{r_{k\text{,mic}} \cdot x_k}{|r_{k\text{,mic}}| \cdot |x_k|} \right) = \arccos \left( \frac{x_{k\text{,mic}}}{\sqrt{x_{k\text{,mic}}^2 + y_{k\text{,mic}}^2 + z_{k\text{,mic}}^2}^{0.5}} \right),
\]

\[
\varphi = \arccos \left( \frac{r_{k\text{,mic},yz} \cdot z_k}{|r_{k\text{,mic},yz}| \cdot |z_k|} \right) = \arccos \left( \frac{z_{k\text{,mic}}}{\sqrt{x_{k\text{,mic}}^2 + y_{k\text{,mic}}^2 + z_{k\text{,mic}}^2}^{0.5}} \right)
\]

In the calculations, the part of the flyover from shortly after take-off up to 1500 ft height above runway is considered. This flight segment represents an almost stationary flight with constant speed and power setting. The aerodynamic noise of the gears, which are retracting in this phase, may be neglected due to the dominance of the engines. A height of 30 ft or a climb angle of 10° is proposed as criterion to start the evaluation, while the cutback at 1,500 ft is the criterion to end the measurement.
Figure 4 exemplarily shows results of the prediction tool, namely, the resulting polar angles for given flight paths, plotted in flight-path axes with normalized vectors on a one side of the half sphere that represents the bottom side of the aircraft. (Only one side is plotted, as the sound directivity will be modelled symmetrically along the longitudinal axis, $x_k$). For a flight path with a short lift off, almost all microphones showed a good coverage in $\theta$ (Figure 4) because of their location in front of the lift off point. While the data will be limited for angles of $\theta$ between $15^\circ$ and $170^\circ$, however, these angles are negligible with respect to their sound contribution. Further, even if the angle coverage of a single flyover is insufficient, the variation of the flight paths of a statistical adequate number of events will fill this gap, as shown in Figure 4 (right). Within the marked surfaces for two exemplary microphone positions, good data coverage can be predicted.

For the optimization of the microphone positions shown in Figure 2, all eight microphones of a given setup were calculated. The positions have been optimized for different flight paths of different aircraft types on each runway covered by the measurements. In addition the final layout of Figure 2 also depends on various other conditions such as safety restrictions at the airport, inaccessibility of some areas and acoustically disadvantageous locations with reflections or high background noise.

### 3.3 Directional Uncertainty

Reliable 3D directivity patterns require a precise determination of the aircraft position, which affects the accuracy of the polar angles. Their standard uncertainties, $u_\theta$ and $u_\phi$ (68% confidence interval) may be estimated by the law of propagation of uncertainty [20], based on the uncertainties of the horizontal and vertical aircraft position, by applying Eqs. (5) and (6) to Eqs. (3) and (4).

\[
\begin{align*}
 u_\theta^2 &= \left( \frac{\partial \theta}{\partial x_k} u_{x_k} \right)^2 + \left( \frac{\partial \theta}{\partial y_k} u_{y_k} \right)^2 + \left( \frac{\partial \theta}{\partial z_k} u_{z_k} \right)^2 \\
 u_\phi^2 &= \left( \frac{\partial \phi}{\partial x_k} u_{x_k} \right)^2 + \left( \frac{\partial \phi}{\partial y_k} u_{y_k} \right)^2 + \left( \frac{\partial \phi}{\partial z_k} u_{z_k} \right)^2
\end{align*}
\]

Where $x_k$ is the longitudinal axis, $y_k$ the lateral axis and $z_k$ the vertical axis of the flight-path axis system (Figure 3). The quantities of $u_\theta$ and $u_\phi$ were quantified for radar data which has a lateral tolerance of 230 m and a vertical tolerance of 46 m [21]. This estimation yields an upper limit for $u_\theta$ and $u_\phi$, as other positioning systems such as cockpit data are more accurate. Assuming a rectangular distribution within the tolerance limits, the conversion from tolerances $t$ to standard uncertainties $u_t$ can calculated as [21]:

\[
 u_t = \frac{t}{\sqrt{3}}
\]
The uncertainties of the polar angles are of particular interest in close vicinity to the airport, as they will be used for the sound directivity patterns (Section 2.2). Unfortunately, due to the small distances between microphones and sound source, the relative uncertainties in aircraft position turn out to be increased [21]. For the estimation of a maximum uncertainty in sound emission angles, microphones at a distance of 1 km to the touch down point are investigated, which are gradually shifted sidewise by a distance \( s \) from 0 to 300 m. With the flight path of an approach of usually 3° for all aircraft types, the resulting minimum distance between source and microphone is quite small. The geometry of the scenario is shown in Figure 5 (top left). Similar considerations apply for a microphone located at a distance of 5 km (Figure 5, top right).

In Figure 5 (middle left) the resulting uncertainty \( u_\theta \) for small distances to the runway is shown. It reaches a maximum of 2.5° when the aircraft is directly above the microphone \( (s=0) \). The uncertainty \( u_\phi \) (Figure 5, middle left) mounts above 6° for decreasing height of the aircraft. This prominent curvature for small \( s \) is due to high sensitivity of the lateral angle \( \phi \) for low heights. By shifting the microphone sidewise in steps of 100 m, the maximum uncertainties of \( u_\theta \) and \( u_\phi \) decrease rapidly. For \( u_\phi \) the trend of the curvature even changes, it declines for low heights. Thus, the uncertainties of the polar angles for radar data are acceptable, particularly for microphones with a sidewise distance above 100 m. In general a microphone position directly under the flight path has the highest uncertainties for both polar angles, while sidewise positioned microphones feature lower uncertainties. However, major problems of radar data in small distances to the airport are the imprecise timestamp and insufficient coverage. For a microphone located in 5 km distance to the runway (Figure 5, right), the uncertainty for both polar angles is below 0.6°, again decreasing with increasing lateral distance. Hence, for distances greater than 5 km, radar data is sufficiently accurate. This also applies for time synchronization.

To achieve higher accuracy in short distances to the airport, three other positioning systems are available within the project (cf. Section 3.1). The uncertainties of the optical tracking system and the mobile multilateration system are under development and therefore verified uncertainties are currently not available. For cockpit data, a horizontal uncertainty (68% confidence interval) of 1.5 m and a vertical uncertainty of 2.5 m can be achieved according to the GPS Performance Standard of the U.S. Government [22]. A first estimate with a lateral and vertical uncertainty of 10 m was done by the presented method, indicating that all three systems have lower uncertainty. The situation in a distance of 1 km already showed uncertainties of \( u_\theta \) below 0.2° and \( u_\phi \) below 0.5°, which is of sufficient accuracy. For the distance up to 5 km the uncertainties are negligible (< 0.05°). Applying the above estimation of the uncertainties of GPS yields maximum values of 0.03° for \( u_\theta \) and 0.15° for \( u_\phi \).

![Figure 5](image-url)

Figure 5 – Directional uncertainty for radar data in a distance of 1 km (left) and 5 km (right) before touch down. The microphone position was shifted sidewise from 0 to 100, 200 and 300 m. Top: Glide path; Middle: Uncertainty \( u_\theta \); Bottom: Uncertainty \( u_\phi \). (Note the different scales of the standard uncertainties for 1 km.)
4. CONCLUSIONS

In this paper the concept for a next generation aircraft noise model, sonAIR, is presented. The model accounts for flight configuration parameters and hence fulfils the requirements to acoustically optimize flight procedures. For the development of such a model, the sound emission model in function of the flight configuration and the underlying sound source database are crucial. Extensive measurements are therefore planned in close vicinity and far away from the airport of Zurich. A particular focus is set on the development of reliable 3D sound directivity patterns. The latter requires optimized microphone positioning for large polar angle coverage. The prediction of the polar angle coverage of a certain measurement layout is of great help to optimize the measurement setup. Furthermore, the determination of polar angles itself must be reliable. Their uncertainties were therefore estimated exemplarily for a typical approach. The results showed that radar data is sufficiently accurate for measurement positions far away from the airport (uncertainties of 0.6°), while other systems are required in close vicinity of the airport.

Using a hybrid, case sensitive propagation model in combination with an attenuation database, it is possible to achieve a simulation tool with high flexibility and accuracy without increasing the computational demand. A major advantage of the attenuation database is that once established for an airport, it can be reused for numerous calculations. Further steps in the project sonAIR will be the evaluation of the sound source data in combination with the tracking data, the development of the sound emission model and the integration into the simulation tool.

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REFERENCES


