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Lateral directivity of aircraft noise

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A three-dimensional model was developed to characterise the directional sound emission of different aircraft. The model is based on spherical harmonics and defines the directional spectral sound pressure level at a reference distance. The parameters of the model are derived from acoustic measurements on real aircraft traffic. With the help of this model different physical effects on sound propagation and sound impact are analysed. Variations with respect to rotational symmetric sound emission are outlined and compared to the engine installation corrections proposed in the revised Doc29 3rd edition. In addition the influence of the ground effect on A-weighted sound levels is analysed for different receiver heights and ground impedances.

1 Introduction

Aircraft noise is still a severe problem in the vicinity of major airports, in spite of the significant progress achieved in the reduction of noise emitted by modern turbofan engines. Due to the large ground area affected, aircraft noise is mainly assessed by means of noise calculations programs. In order to carry out reliable calculations both the sound source and the sound propagation have to be modelled accurately. Aside from the sound power of an individual aircraft the spectral content and the directivity of the sound source is of utmost importance.

In the absence of valid data most current aircraft noise simulation programs do not account for the spatial directivity of the sound source or they rely on simplified methods to account for the spatial directivity of aircraft noise. Under the term *lateral attenuation* different physical effects are often combined and corrected for. A new formalism was proposed in SAE-AIR-5662 [1], which explicitly considers engine installation effects to account for the non-uniform lateral emission of sound. This methodology has also been adapted in the revised Doc29 3rd edition [2]. Two different lateral directivities are assumed, namely for aircraft with engines mounted beneath the wings and those with engines mounted at the fuselage.

In order to improve the description of the three-dimensional directivity of the sound source, a new model was developed at Empa [3]. This source model defines the spectral sound level at a reference distance on a sphere by means of spherical harmonics. Based on acoustic measurements taken from real aircraft traffic the sound directivity of six fixed-wing aircraft was established. In this paper the outline of the model is presented and first results are given. More details may be found in [3,4].

2 Three-dimensional sound source model

Spherical harmonics $Y^m_i(\theta,\varphi)$ are functions defined on the sphere, representing a complete orthogonal system. Any quantity defined on a sphere can be modeled as a sum of these functions. This general method is employed to describe the directivity of the sound source. The co-ordinate system used to define the angular quantities is given in Figure 1. According to these definitions the sound emission in the direction specified by the two angles θ and φ is given by equation (1).

$$L_k(\theta,\varphi) = \sum_{i=0}^{n} \sum_{m=-i}^{i} A^m_{k,i} \cdot Y^m_i(\theta,\varphi) \qquad (1)$$

$L_k(\theta,\varphi)$ is the sound pressure level in the one-third octave band k at the reference distance r_{ref} = 305 meters in the direction (θ,φ) relative to the reference system of the aircraft, $Y^m_i(\theta,\varphi)$ are the spherical harmonics, $A^m_{k,i}$ are the coefficients describing the sound source and n is the order of the spherical harmonics used. For this analysis spherical harmonics up to the order n = 7 were used. The coefficients were established by means of a least square fit to measured data, normalised to the fixed reference distance r_{ref} = 305 m (1000 ft) [3].

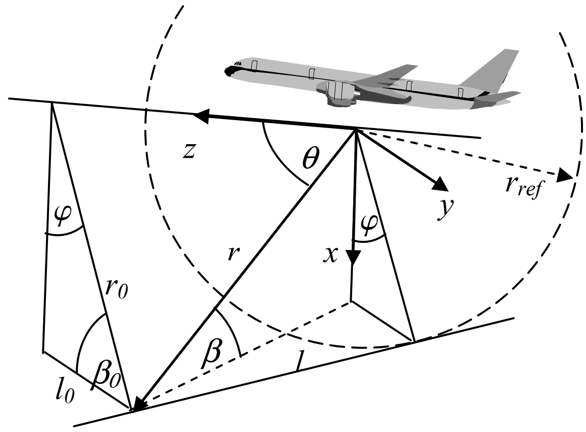


Fig.1 Schematic representation of the co-ordinate system.

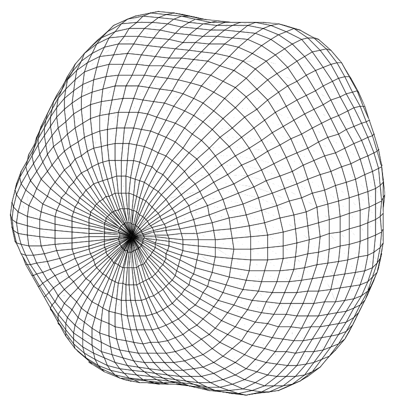


Fig.2 Graphical representation of the A-weighted sound level defined by the three-dimensional source model.

A graphical representation of the resulting A-weighted sound level at the reference distance is given in Figure 2. In this representation the three-dimensional surface, i.e. the distance between the surface and the center is a measure of the sound level at r_{ref} = 305 m in the corresponding direction. A cross-section of this model is given in Figure 3 together with measured data used to derive the coefficients of the model. For practical reasons only A-weighted levels are shown, although the analysis was actually performed consequently in 1/3 octave bands. Three-dimensional characteristics were established for the six aircraft given in Table 1.

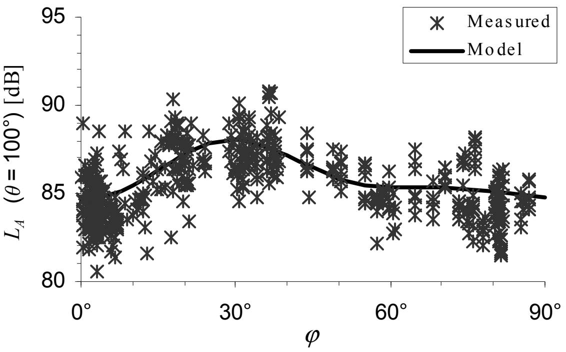


Fig. 3: A-weighted sound level given by the three-dimensional model for a polar angle $\varphi = 100°$ and measured data normalised to $r_{ref} = 305$ meters, related to the polar angle interval $90° \le \theta \le 110°$.

Aircraft	***N***
Airbus A310-300	7
Airbus A320	22
McDonnell Douglas MD-11	19
McDonnell Douglas MD-83	10
BAe Avro RJ-100	33
Saab 2000	20

Table 1 Summary of aircraft types analysed.
Legend: Aircraft - Aircraft type. N - Numbers of flyovers.

The uncertainty of the resulting directivity model is predominated by the uncertainty of the fit of the model to the measured data and the uncertainty of the measured data itself. The uncertainty of the fit is estimated by the dispersion of the measured data used to derive the parameters of the three-dimensional model and divided by the square root of the number of independently measured flights *N* (see Table 1). The resulting standard uncertainty of the three-dimensional source model is estimated by the following relation:

$$u_{3d} = \sqrt{\left(\frac{SD}{\sqrt{N}}\right)^2 + u_m^{\ 2}} \qquad (2)$$

SD : Standard deviation of the measured A-weighted sound levels used to derive the three-dimensional source model within a solid angle of 10° x 10° .

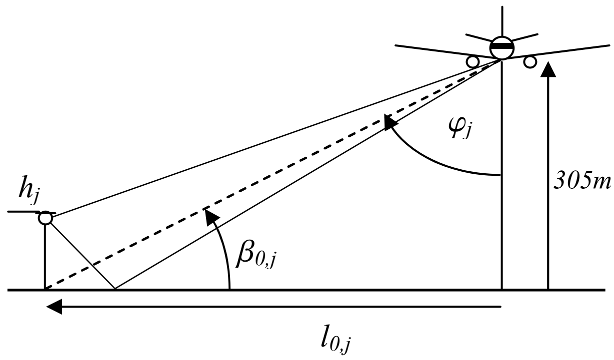
N : Number of events, i.e. number of independent flights measured contributing to the corresponding direction (see Table 1).

u_m : Standard uncertainty of the measurements, estimated as 0.5 dB.

The typical standard uncertainty of the three-dimensional source model determined with this method is in the range 1.1 dB … 1.8 dB.

3 Results

The effect of the lateral directivity of the sound source was analysed by calculating the sound immission at different immission points and compared to the corresponding sound levels, calculated with the rotationally symmetric model of Flula2 for the same aircraft type, based on the same acoustical measurements [5, 6]. In order to facilitate the analysis and interpretation of the results a simple design was used. The A-weighted sound level was calculated for a straight level flight at constant speed and constant height $H = 305\ m$ at immission points located in a line perpendicular to the flight path (see Figure 4). Calculations were performed for two different receiver heights and for soft and for hard ground. The difference *dLAE* between the sound exposure levels calculated with these two models is given in Figure 5 as a function of the azimuth angle φ and compared with the engine installation correction proposed in the revised Doc 29 [2].



.Fig.4: Geometric layout of the simulation for the immission point j

4 Discussion

The deviations *dLAE* between the sound levels calculated with the three-dimensional model with respect to the levels calculated with the rotational symmetric model originate from two different effects:

a.) differences in sound level due to non-uniform lateral sound radiation of the source,

b.) differences caused by different methods used to account for sound attenuation effects at small incidence angles, i.e. at azimuth angles near 90 degrees.

At lateral angles $\varphi \le 70°$ the sound incidence angles β are large for the relevant segment of the flight path; thus effects caused by ground effects are less important. The differences observed between the calculations with the two models are mainly a consequence of the lateral directivity of the three-dimensional source model.

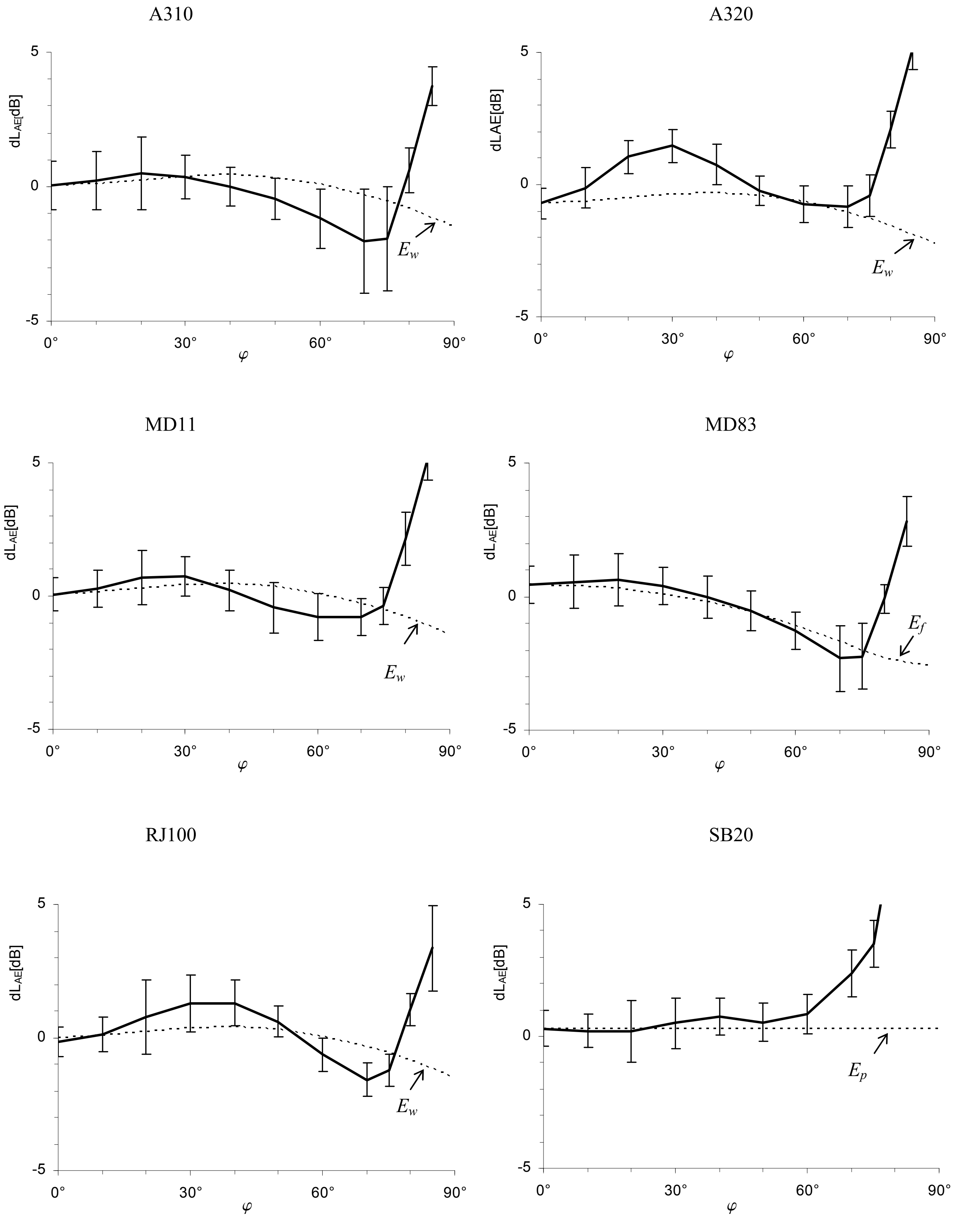


Fig. 5: Lateral sound directivity for different aircraft. Solid line: Difference dL_{AE} between the A-weighted sound immission levels calculated with the three-dimensional model and with the rotationally symmetric model. Dashed line: Engine installation correction proposed in Doc 29 3rd edition: E_f, E_w, E_p for fuselage-mounted engines, wing-mounted engines and for propeller driven aircraft respectively. Error bars show the standard uncertainty of the calculated immission levels.

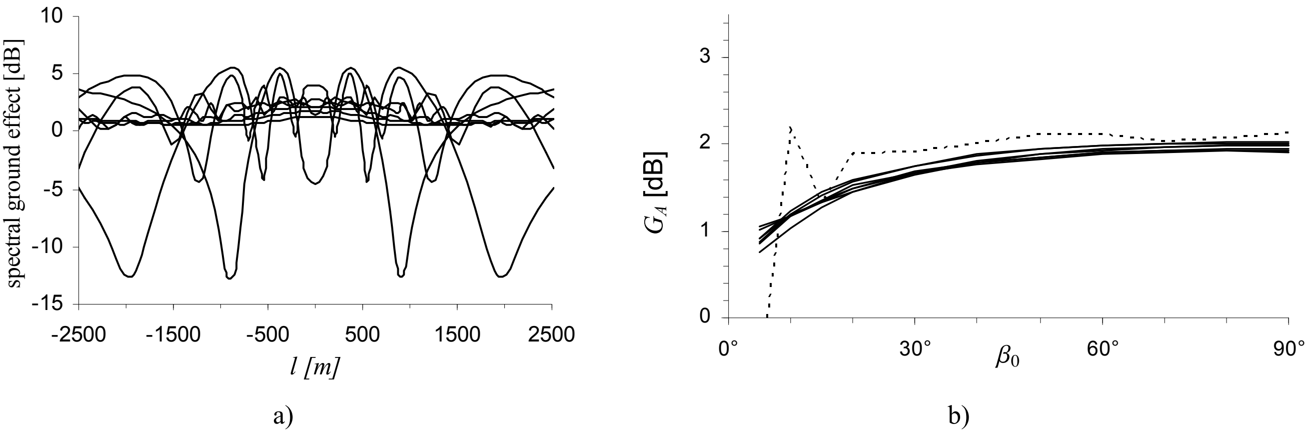


Fig.6: Spectral ground effect (a) and overall impact of the A-weighted ground effect G_A (b). The spectral ground effect calculated for different 1/3 octave bands is shown as a function of the horizontal distance l for one single flyover at H = 305 m, the overall impact G_A is evaluated as a function of the sound incidence angle β_0 for different aircraft types. Solid lines: turbofan aircraft, dotted line: propeller driven aircraft (Saab 2000).

For the MD-83 the directivity found in our analysis corresponds well with the engine installation correction proposed in Doc 29 3rd edition for aircraft with fuselage-mounted engines [2]. For this aircraft a clear reduction of the sound power radiated in the horizontal plane with respect to the sound power measured below the aircraft is observed. In contrast to these findings the lateral directivity given by our models differs considerably from the engine installation correction proposed by Doc29 for aircraft with wing-mounted engines. Our analysis with the three-dimensional model revealed that the lateral directivity may differ substantially even for aircraft with almost identical engine configuration. The lateral directivities established for the Airbus types A310 and A320, both equipped with two wing-mounted engines, differ significantly. While the directivity observed for the Airbus A310 coincides to a large extent with the directivity reported for aircraft with fuselage-mounted engines, the directivity established for the Airbus A320 shows a pronounced maximum at an azimuth angle φ = 30°. Until now no clear explanation for this large excess of the lateral sound level has been found. Additional investigations are still in progress in order to establish the directivities for other aircraft types equipped with wing-mounted engines.

Large differences between the sound exposure levels calculated with the two models arise at azimuth angles above 70°. Differences *dLAE* up to 9 decibels are observed. This discrepancy arises mainly due to the different methods applied to account for sound attenuation at small incidence angles. The empirical formula used in Flula2 implies an additional attenuation up to 10 decibels for sound incidence angles β below 15° [6]. On the other hand a spectral ground interference model is implemented in the three dimensional model [3]. The sound level at the receiver is calculated by the coherent addition of the sound wave propagating directly from the source to the receiver and the wave reflected from the ground [7, 8]. While the spectral ground effect oscillates considerably according to the varying geometry during a single flyover, the overall effect on the A-weighted sound exposure level, i.e. the difference between the exposure level with and without ground effect remains nearly constant and varies only slightly for different flight geometries (see Fig. 6). Our results show that for turbofan powered aircraft the overall impact of the ground effect $G_A(l_0,\beta_0)$ on A-weighted sound exposure levels depends only smoothly on the source-receiver geometry. A more irregular behaviour of the ground effect arises for the propeller driven Saab 2000. This is probably caused by the pronounced tonal components contained in the spectra of this aircraft.

Our findings show that the variation of the resulting sound exposure level due to effects caused by the spectral ground effect G_A is of the order of 1-2 decibels. This is only a small part of the total variation of the lateral attenuation predicted with the well established empirical formulas in many programs [1]. Other effects, in particular meteorological effects contribute much more to the total lateral attenuation. Therefore sophisticated and time consuming methods to evaluate the spectral ground effect do not contribute much to the accuracy and reliability of aircraft noise simulation programs designed to predict A-weighted sound levels. Future efforts to improve the overall performance of sound immission models should be focused on meteorological effects rather than on spectral ground effect. At least for turbofan powered aircraft the overall impact of the ground effect on A-weighted sound levels could be modelled for a given ground impedance by a simple formula as a function of the sound incidence angle β_0 and the horizontal distance l_0 between the flight track and the receiver. In order to establish this relation, additional simulations should be performed exploring all relevant geometries between sound source and receiver. Investigations on this subject are currently in progress at Empa.

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