An experimental evaluation of a new approach to aircraft noise modelling

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Common engineering models for aircraft noise, such as INM, yield noise levels by interpolation of Noise Power Distance (NPD) tables. In the European project Imagine (2004 - 2006), a different approach was proposed: the source is characterized by an emission spectrum and the received noise spectrum is calculated by subtracting the propagation attenuation spectrum from this emission spectrum. This is the usual approach for noise mapping of most noise sources. The aircraft emission spectrum is a function of (downward) emission direction, so each aircraft is represented by a hemisphere of emission spectra. This has been described by Bütikofer in Acta Acustica 93 (2007). As hemisphere emission data are not yet available for all aircraft types, a 'reverse engineering' scheme was developed within Imagine to derive first order estimates of hemispheres from NPD tables. To gain experience with this approach, we have performed an experiment near Amsterdam airport. Various types of data were collected for a set of aircraft departures, including noise data at twelve positions and flight data. The Imagine approach was used to calculate noise contours, and noise spectra at the twelve positions. The differences between measured and calculated spectra may be used as a basis for improving the first order estimates of the hemispheres.

1 Introduction

Aircraft noise around Amsterdam airport is continuously monitored at various locations, up to distances of several tens of kilometers (see Fig. 1). The recorded levels are displayed on the internet, as a service to the people living around the airport.

For the purpose of noise regulation, noise contours around the airport are determined by calculation, taking into account all flights to and from the airport. The calculations are performed with a noise model that is similar to the Integrated Noise Model (INM). Both models are based on Noise Power Distance (NPD) tables, which give the noise level as a function of distance for various aircraft power settings. Actual noise levels are derived by interpolation of the tables.

In the European project Imagine (2004 – 2006) a new approach for calculating aircraft noise was proposed [1]. This approach is based on the relation

immision level =

emission level – propagation attenuation, (1)

which is the basis of common prediction models for other types of noise, such as traffic noise and industrial noise. The levels in Eq. (1) depend on frequency, so we are dealing with spectra rather than broadband levels.

In the case of aircraft noise, the emission spectrum is a complex function of (downward) emission direction. Consequently, the sound emission of an aircraft is represented by a hemisphere of emission spectra.

As hemisphere emission data are not yet available for most types of aircraft, a 'reverse engineering' scheme was developed in Imagine to derive first order estimates of hemispheres from NPD tables [2,3]. To gain experience with this new approach, we have performed an experiment near Amsterdam airport.

The experiment is described in Sec. 2. Section 3 describes model calculations based on the reverse engineering method. The propagation attenuation in Eq. (1) was calculated with a propagation model that is described in Secs. 3 and 4. In Sec. 5 we describe how we deal with the effect of aircraft thrust variations on sound emission. In Sec. 6 we describe an approach for improving the 'reverse engineering' emission hemispheres, based on the measurement results.
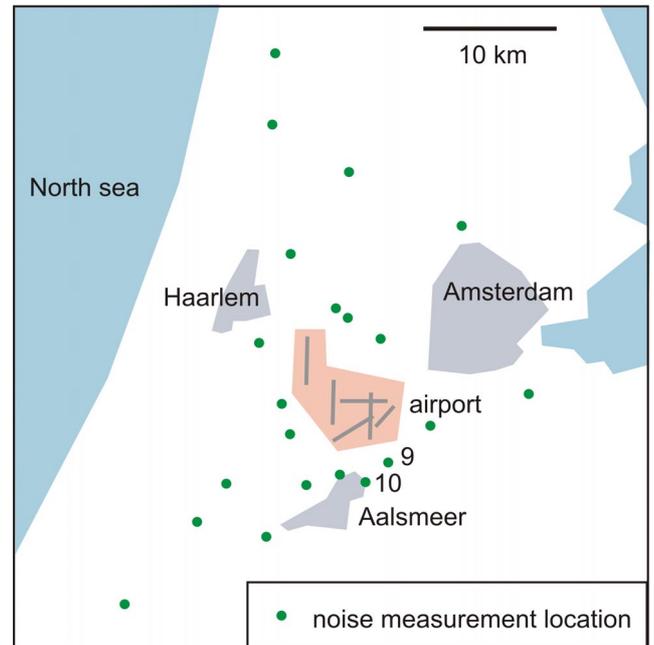

Fig. 1. Noise measurement locations around Amsterdam airport (red area). The six runways of the airport are shown as gray lines.

2 Description of the experiment

The experiment was performed in the region between the village of Aalsmeer and the airport, on a cloudy day between 12:30 pm and 4:30 pm. Various types of data were collected for all airplanes taking off in the direction of Aalsmeer:

- noise data at twelve locations,

- flight data,

- meteorological data.

The total data set comprised 103 flights. The twelve locations are numbered as 1 – 5, 9, 10, 25, 47 – 50. Locations 9 and 10 are stationary measurement locations near Aalsmeer (these locations are indicated in Fig. 1). At the other locations we used mobile or temporary measurement setups (these locations are indicated in Fig. 3 below).

Figure 2 shows the maximum take-off weights of the 103 airplanes, and also the A-weighted sound exposure levels (SEL) as derived from the measurements at location 5.

Figure 3 shows a map of the area with the measurement locations indicated (location 25 is outside the map; locations 47 – 50 are near the end of the runway). Also included in Fig. 3 are the 50 and 60 dB noise contours of the contribution of the 103 airplanes to the day-evening-night level (L_{den}), calculated with the model described in Sec. 3. This contribution is equal to $10\log(12/24\ 10^{L/10})$, where L is the equivalent sound level over the measurement period of about 4 hours.

At locations 1 – 5 we recorded complete sound signals of all flights, at two heights: 0 and 5 m. The microphone at height zero was mounted on a hard wooden plate of 1.2 m x 1.2 m. In this paper we present results only for the microphone at height zero. The sound signals were converted to sound spectra as a function of time.
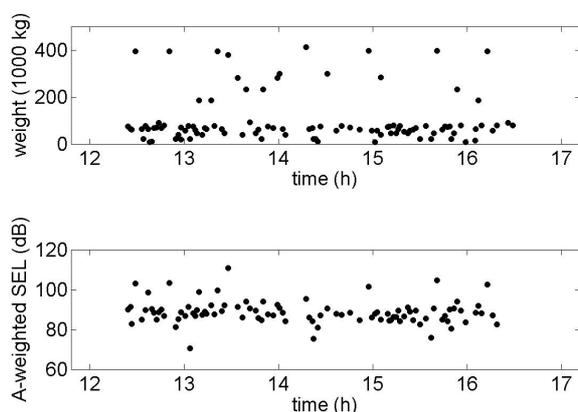

Fig. 2. Maximum take-off weight (top) and A-weighted SEL measured at location 5 (bottom) as a function of time, for all 103 recorded flights.
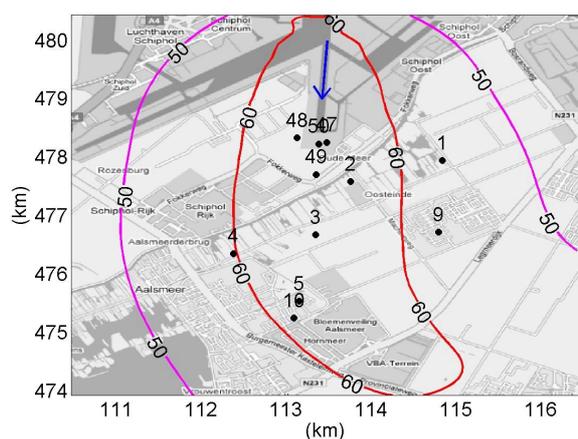

Fig. 3. Noise contours of the day-evening-night level L_{den}, summed over all 103 flights. The blue arrow represents the direction of take off from the runway.
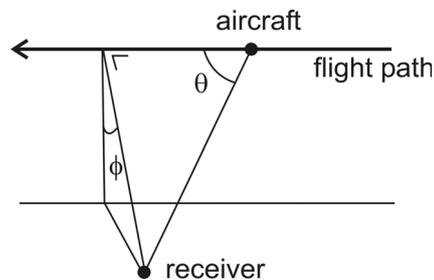

Fig. 4. Diagram showing emission angles θ and ϕ.

3   Model calculations

The model employed in this study is based on Eq. (1). The emission spectrum as a function of downward emission direction is represented as a hemisphere, or rather a set of eight hemispheres, one for each of the eight octave bands 63 – 8000 Hz.

The emission direction is represented by two angles (see Fig. 4):

- angle θ between the flight path and the line from the aircraft to the receiver,
- angle ϕ between the line from the aircraft to the receiver and the downward vertical through the aircraft, measured in the vertical plane normal to the flight path.

The emission spectrum is expressed as the sum of three terms:

- a spectral term that is a function of the frequency band,
- a longitudinal directivity term that is a function of angle θ,
- a lateral directivity term that is a function of angle ϕ.

The reverse engineering scheme [2,3] consists basically of two steps. First the above three terms are determined based on general characteristics of the aircraft, which can be found in Refs. [3,4]. A classification is used with 13 spectral classes, 6 longitudinal directivity classes, and 3 lateral directivity classes. Next a constant is added to the emission spectrum such that the average difference between calculated values of SEL and values of SEL from NPD tables given in Ref. [3] becomes zero.

The propagation attenuation in Eq. (1) is written as

propagation attenuation = geometrical attenuation +

atmospheric attenuation + excess attenuation, (2)

where geometrical attenuation represents spherical spreading of sound waves, atmospheric attenuation represents damping of sound waves by molecular processes in air, and the excess attenuation represents effects of atmospheric refraction and ground reflection. We prefer to work with a quantity that is *minus* the excess attenuation, which will be referred to as *relative sound level*.

In this study the relative sound level was approximated by 6 dB for the microphones mounted on a hard plate. In Sec. 4 we support this approximation by numerical

calculations, and present an improvement of this approximation to be used in future versions of the model.

The noise contours shown in Fig. 3 were calculated with the model described above, including corrections for aircraft thrust variations with height (see Sec. 5). Figure 5 shows a snapshot of an animation of one of the flights, with the sound field on the ground calculated with the model. Figure 6 shows an example of a comparison between a measured spectrum and a calculated spectrum at location 5. The agreement is good in this case. In general we found deviations up to 5 dB, and occasionally up to 10 dB.
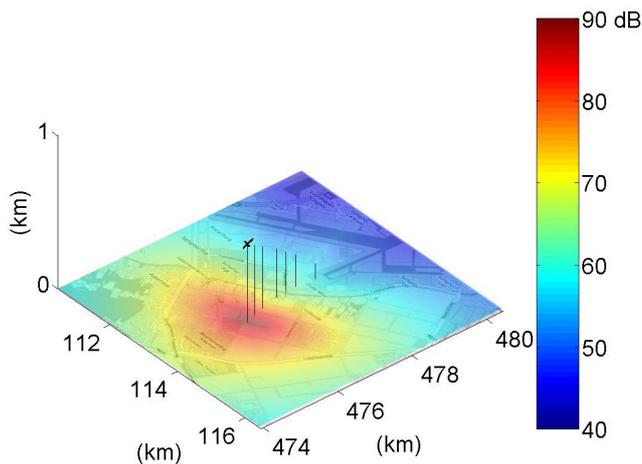

Fig. 5. Calculated A-weighted sound level on the ground (assumed hard), at one moment during a flight. Vertical lines represent heights of the aircraft along the flight path.
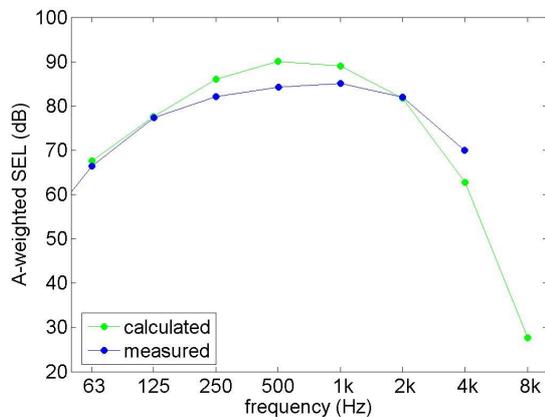

Fig. 6. Calculated and measured immission spectrum of the A-weighted SEL at location 5, for a flight of a Boeing 737-800 aircraft.

4   Propagation model

In the Imagine project [1], two different models were proposed for calculating the *relative sound level* (or the excess attenuation in Eq. 2): an accurate *reference model* based on numerical calculation of sound propagation, and a more practical *engineering model* that can be used for extensive calculations of noise contours. The models take into account effects of atmospheric refraction and ground reflection.

In the present study we consider only the situation of a microphone mounted on a hard plate. This considerably simplifies the calculation of the relative sound level, as direct and reflected sound waves coincide in this case, so pronounced interference minima and maxima are absent in the spectrum.

Figure 7 shows the geometry of sound propagation from an aircraft to a microphone on a hard plate on the ground. For high elevation angles, the relative sound level approaches 6 dB, corresponding to pressure doubling caused by the reflected sound wave. For low elevation angles, sound waves diffracted by the edges of the finite plate cause deviations from the value of 6 dB.

Figure 8 shows numerical results of the relative sound level for octave band 500 Hz, for three wind speeds: 0 m/s, +5 m/s, and -5 m/s (positive wind speed represents downwind sound propagation). The graphs were computed with a parabolic equation method [5], and show the relative sound level as a function of elevation angle. The graphs include results for three plate dimensions ($d = 0.6$, 0.85, 1.2 m), five source heights (20, 50, 100, 200, 300 m), and horizontal source-receiver distances up to 1 km. For the ground surface outside the hard plate we assumed a ground impedance typical for grassland (Delany and Bazley model with flow resistivity 200 kPa s m^{-2}; see Ref. [5]). It should be noted that we used a parabolic equation method based on the axisymmetric approximation [5], so the computations were performed on a two-dimensional grid in the vertical plane through the aircraft and the microphone.

For high elevation angles Fig. 8 confirms the value of 6 dB. For low elevation angles, the relative sound level is lower than 6 dB. It is interesting that the curves for different geometries fall more or less on a single curve, so the elevation angle is a good parameter to predict the relative sound level. So far we have used a constant relative sound level of 6 dB in the model, but the numerical results shown in Fig. 8 will be implemented in a future version of the model.
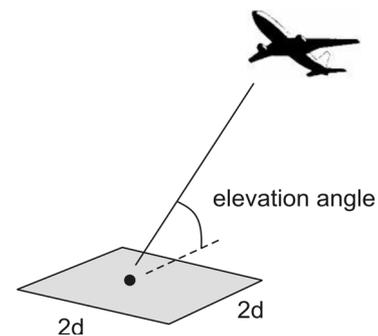

Fig. 7. Geometry with aircraft and microphone (black dot) on a hard plate on the ground. The plate is square with a side of $2d$. In this study we used $d = 0.6$ m.
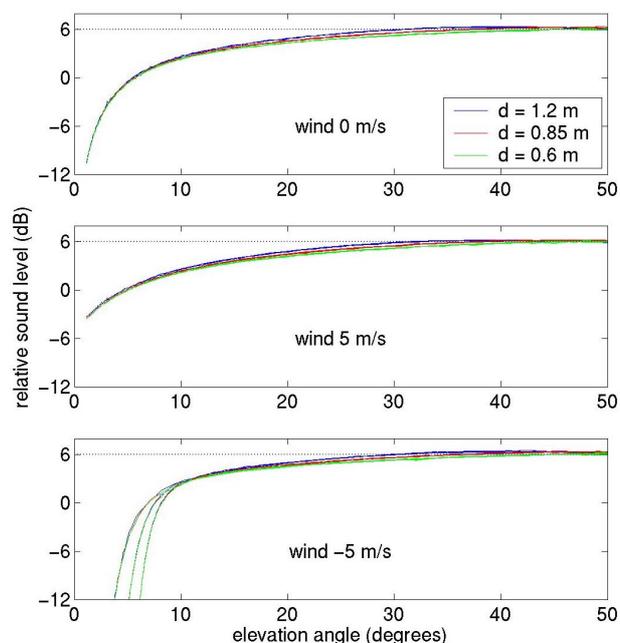
Fig. 8. Calculated relative sound levels at 500 Hz as a function of elevation angle for three windspeeds. Curves of different colors can hardly be distinguished, but the main message of the graphs is that the curves fall more or less on a single curve.

5   Reduced thrust

Sound emission of an aircraft depends on the thrust produced by the aircraft's engines. Typically, an aircraft takes off at 95% of its maximum thrust, and with increasing altitude the thrust is reduced. In this study we did not have actual power settings of the aircraft during flight, so we had to resort to standard flight procedures.

Using the standard flight procedures tabulated in Ref. [6] we produced the graph in Fig. 9, which shows the sound level reduction relative to maximum thrust as a function of aircraft height, for nine aircraft classes (weight class / noise class). The graph shows level reductions up to 10 dB, so thrust variations have a major effect on sound emission. Clearly the level reduction is not a simple function of height.
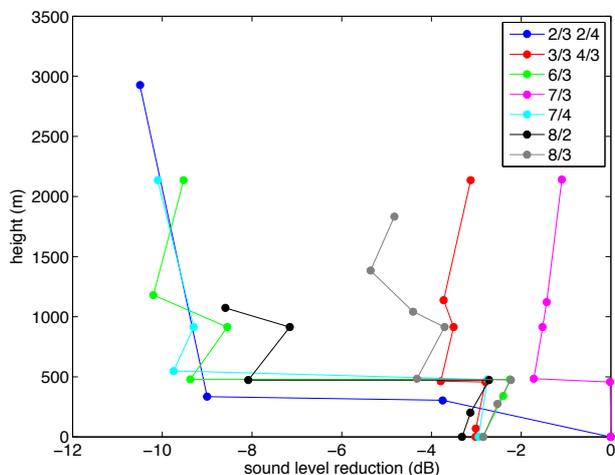

Fig. 9. Sound level reduction relative to maximum thrust, for nine aircraft classes (weight class / noise class), as derived from standard flight procedures [6].

6   Optimization of hemisphere

As described in Sec. 3, we have used a reverse engineering scheme to derive first order estimates of the emission hemispheres from NPD tables. We are presently working on a more accurate approach to determine emission hemispheres, based on results of measurements as performed in this study.

Figure 10 shows the path of one of the flights, and measurement positions 1 – 5 on the ground. As the aircraft moves along the flight path, a range of emission directions on the hemisphere is covered. This is shown in Fig. 11. The five colored traces on the hemisphere correspond to the five measurement positions in Fig. 10. Although the hemisphere is not fully sampled by the five traces, the data should provide a basis for improving the first order estimates of the hemisphere. We are currently exploring numerical schemes for such an optimization.
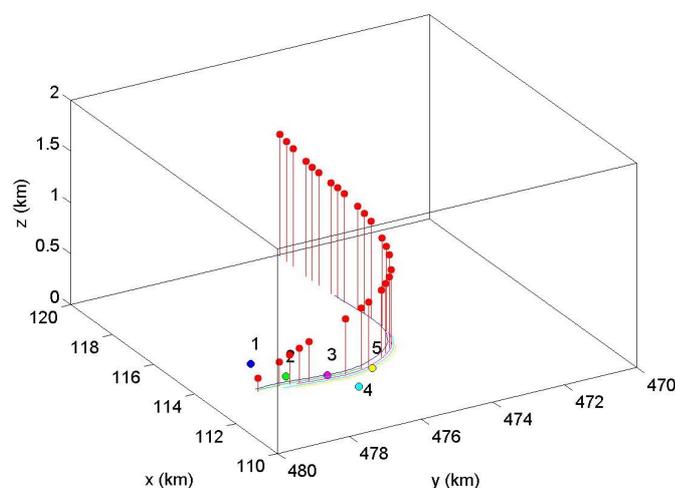

Fig. 10. Three-dimensional representation of a flight path of a Boeing 747-400 aircraft, and measurement locations 1 – 5 on the ground.
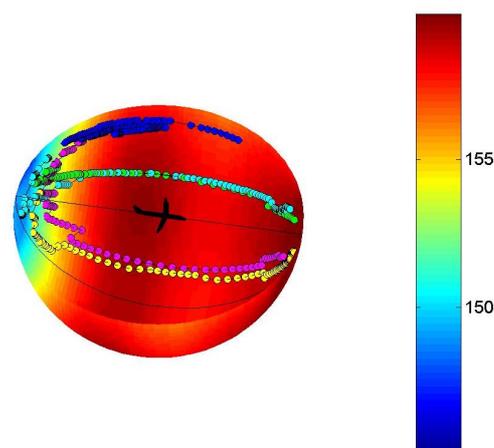

Fig. 11. Emission hemisphere of a Boeing 747-400 aircraft (at maximum thrust) as determined by reverse engineering from NPD tables. The color represents the broadband A-weighted sound power level (sum of octave band levels). The colored dots represent the emission directions to the five microphones 1 – 5 (see Fig. 10) as the aircraft moves along the flight path.

7   Conclusions

We have presented a practical application of a new approach to aircraft noise modelling, based on a directional emission model and a propagation model. We have shown that it is possible to obtain model spectra that are more or less in agreement with measured spectra.

Future work will aim at improving the agreement. The propagation model should be improved both for microphones mounted on a hard plate and for elevated microphones. The emission model should also be improved. We have indicated how sound measurements may be used to improve first order estimates of aircraft emission hemispheres.

References

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