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Wedemeijer, Ryan; van der Grift, Rebekka; Snellen, Mirjam

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IMPROVING AIRCRAFT NOISE MODELS THROUGH DIRECTIONALITY MEASUREMENTS

Ryan Wedemeijer
Aircraft Noise and Climate Effects, Delft University of Technology. Kluyverweg 1, 2629 HS, Delft, The Netherlands
E-mail: R.Wedemeijer@student.tudelft.nl
Rebekka van der Grift
Aircraft Noise and Climate Effects, Delft University of Technology. Kluyverweg 1, 2629 HS, Delft, The Netherlands
E-mail: R.C.vanderGrift@tudelft.nl
Mirjam Snellen
Aircraft Noise and Climate Effects, Delft University of Technology. Kluyverweg 1, 2629 HS, Delft, The Netherlands
E-mail: M.Snellen@tudelft.nl

Aircraft noise impacts a growing number of residents around airports. The impact is estimated using noise models such as the European standard Doc 29. These models make use of empirically derived Noise-Power-Distance tables to estimate noise in the areas around the airport. Correction factors are used to account for directionality effects such as engine installation effect and lateral attenuation. Research comparing measured and modelled directionality of the aircraft noise is limited. This research aims to investigate the potential contribution of directionality effects on differences between measured noise levels, obtained around Schiphol Airport using the NOise MOnitoring System (NOMOS), and noise levels predicted by Doc 29. This is done by considering NOMOS measurements at different locations around the airport and use these to retrieve noise levels at the source, i.e., the so-called standardized levels. These noise levels are then used to map the noise levels in lateral and longitudinal directions. By performing the same procedure for modelled sound levels, it is possible to observe differences in directionality patterns. The thus found directivity effects differ significantly from the currently modelled directivity effects. These insights can be used to increase the accuracy of the Doc 29 model without increasing its complexity.
Keywords: Aircraft noise, Measurements, Directionality, NOMOS

1. Introduction

In 2019, Schiphol Airport received a record number of nearly 300.000 complaints from nearby residents.[1] Unsurprisingly the biggest portion of these complaints are related to noise from aircraft taking off or landing at the airport. To limit noise pollution in nearby areas, so-called noise abatement procedures can be used. These procedures are designed using best-practice noise models such as the European model Doc 29 [1]. While noise models aim to reflect reality as closely as possible, noise measurements are needed to provide real-time information and evaluate the accuracy of these models. Noise measurements around Schiphol are handled by the aptly named NOise MOnitoring System (NOMOS). With these measurements, it is possible to evaluate a single fly-over event and compare that with a result from the model implementation.

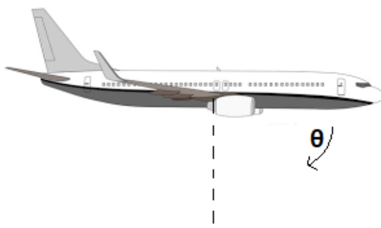
An important element in improving noise abatement procedures is to have a better understanding of noise emitted and propagated when the observer is located at different angles with respect to the aircraft. This so-called directionality of aircraft noise is an important factor in the noise levels experienced on the ground. This research

[1] Parool, 2020: https://www.parool.nl/nieuws/schiphol-ontving-recordaantal-klachten-in-het-afgelopen-jaar

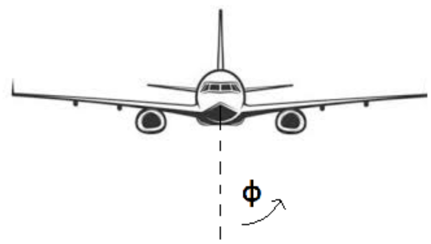
will focus on potential improvements of aircraft noise models, such as the Doc 29 noise model, by analysing the differences in modelled and measured noise for a selection of departing aircraft types for different directions with respect to the aircraft.

2. Background

Most sound sources are not omnidirectional, meaning that the sound level that is observed depends on the relative position of the source to the observer. Aircraft are no exception, as the level of the received signal is strongly dependent on the observer locations. Some best-practice models consider directionality for 2 different angles [2], i.e., the longitudinal or polar angle θ (0° -1 80°) and lateral angle ϕ (-90° - +-90°, 0° pointing straight down). Figures 1a and 1b show how both angles can be used to define directivity for any observer located below the aircraft.



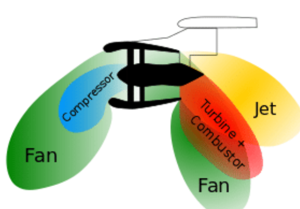
(a) Longitudinal directivity angle θ



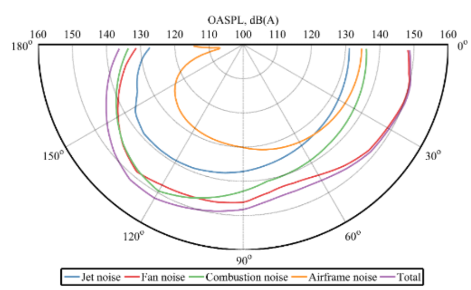
(b) Lateral directivity angle ϕ

Figure 1: Definition of directional angles of the aircraft.

In general, two distinct types of aircraft noise sources contribute to the noise emitted by aircraft, being engine noise and airframe noise. For a turbojet engine, distinguishable sound sources are the fan, compressor, combustion chamber and the rear turbine. As the illustration in Figure 2a shows, the observed engine noise is very dependent on the position of the observer. Fan noise is the dominant sound source when the observer faces the front of the engine. It consists of broadband and tonal sound, the last one caused by the rotation of the fan blades. Jet noise has multiple components where lower frequencies result from shear flow from air exiting the nozzle, and higher frequency components are shock-associated noise from local supersonic flows.



(a) Noise directionality of turbofan engine [3]



(b) OASPL at different polar angles [4]

Figure 2: Directionality of engine noise for different polar angles.

Airframe noise is the result of aerodynamic flow phenomena around the airframe such as boundary layers, trail wakes and cavities. For the fuselage and a clean wing (no flaps/slats deployed) the resulting noise levels are expected to be much lower than the engine noise, even at low engine power settings. When flaps and/or slats are deployed, the observed noise level due to aerodynamic noise can be up to 10 dB higher [5]. The noise contribution of the landing gear is roughly equal to the noise caused by flow around a fully deployed slat, but this can be decreased by up to 5 dB by measures such as wrapping lightweight cloth around the landing gear structure to reduce disturbances [6].

An important distinction between engine and airframe noise is that engine noise is considered to only be dependent on the polar angle θ while observed airframe noise is also dependent on the lateral directivity ϕ. For most flight phases, and especially during take-off and climb stages, engine noise is the dominant factor. Figure 2b shows an example of predicted Overall A-weighted Sound Pressure Level (OASPL) for a Boeing 747-400 taking off at full throttle at a 1-meter radius for different polar angles. Note that the OASPL level due to jet noise in particular radiates to the back of the aircraft, causing a higher sound level at higher polar angles [4],

3. Methodology

The aim of this research is to quantify how aircraft noise directionality contributes to the difference between noise measurements and Doc 29 by using real data. NOMOS provides noise data around Schiphol Airport, as well as information about the flight path and aircraft id. This information serves as input for the Doc 29 model.

3.1 Doc 29 model

ECAC Doc 29 is a fully empirical method to model aircraft noise at different flight stages and is the current best practice model used by all ECAC member states [7]. While this model is a lot simpler than models such as ANOPP and NOISEMAP, it does create relatively accurate noise contours when used for a large number of flights (for example all traffic in one year). A single event is defined by the sound generated by one aircraft movement, observed at one observer location. This is calculated by dividing a flight track into multiple segments and computing the noise for each segment. All these steps are described in chapter 4 of [1] and outlined in figure 3, with the diamond shapes indicating the inputs needed for the Doc 29 model.

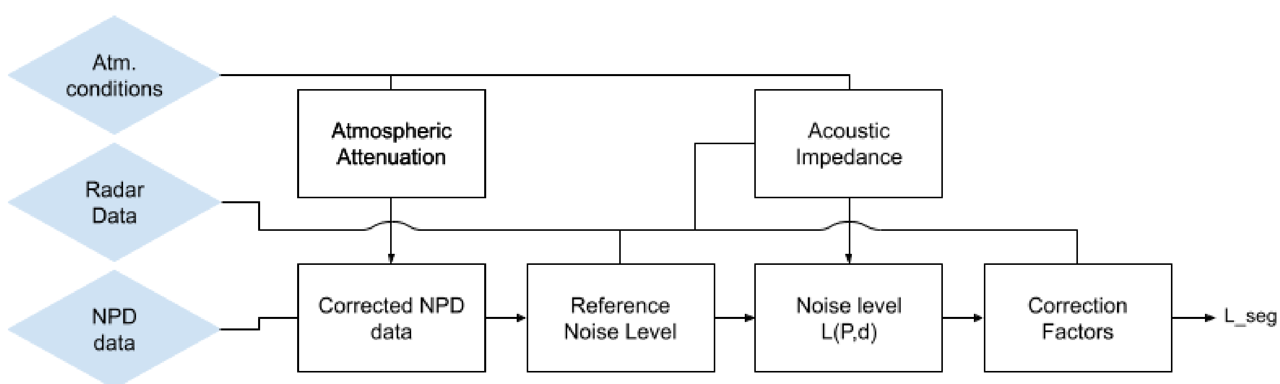


Figure 3: Doc29 Segment sound level flowchart

The basis of the Doc 29 model are the Noise-Power-Distance tables. These data give the expected noise levels of a segment for a specific power setting and distance to the aircraft. NPD event levels are based on measurements made directly beneath the aircraft, where the distance is effectively just the aircraft's altitude. To account for any directionality effects, Doc 29 has two correction factors. The first is a general engine installation correction which adjusts for directionality in the lateral direction for different engine placements (wing-mounted or fuselage-mounted engines). The second, more dominant, effect is the lateral attenuation correction, accounting for propagation effects.

The methodology used in Doc 29 is built on experimental data developed for sound propagation over soft, level ground and based on the elevation angle (β) and the lateral displacement from the ground track l [8]. The effect of distance (not absorption and spherical spreading, since these are accounted for the in the NPD tables) and the effect of the elevation angle are split. The total lateral attenuation $\Delta(\beta, l)$ is a multiplication of the distance factor $\Gamma(l)$ and the long-range attenuation factor $\Delta(\beta)$. Figure 4 shows the modelled effect of lateral attenuation for different elevation angles and different lateral displacements. Note that this correction is rather small for elevation angles close to overhead position.

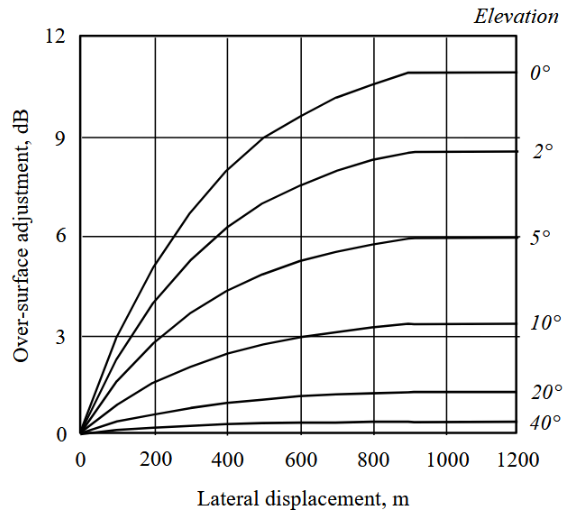


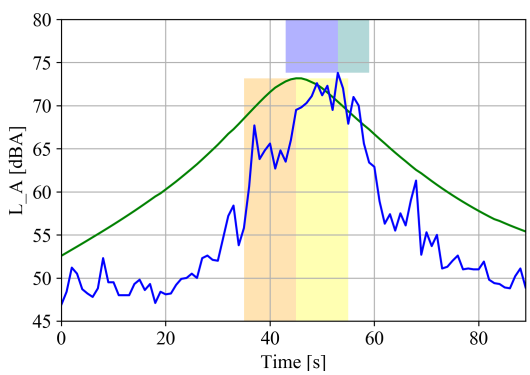
Figure 4: Variation of $\Delta(\beta, l)$ [1]

3.2 Measurement processing

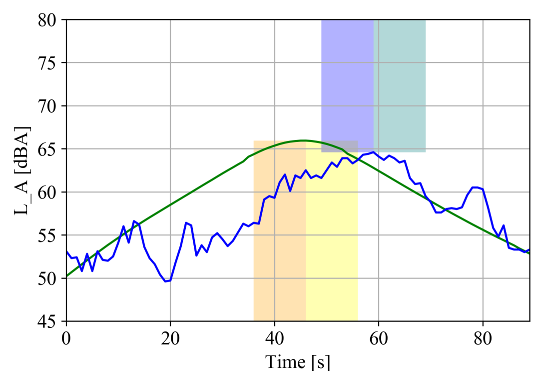
NOMOS has over 40 measurement locations (NMTs), placed all over the western provinces of the Netherlands. Flights from four common aircraft types around Schiphol Airport (B737, B738, A320 & E190) and five different NMT locations were selected to get a representative data set. These NMTs were chosen based on their relative location to different runways and flight tracks, as well as their reliability. All of them are close to departure routes with a fairly straight flight path, which reduces the effect of steep banking turns. A map of the chosen NMTs is shown in Figure 5. Note how NMTs 2, 10 and 12 are relatively close to the runway, while NMTs 25 and 21 are further out.

For a select number of days in 2022, measurements are collected. As NOMOS is a continuous measurement system, to ensure a good measurement, the measurements used for this research are selected such that they adhere to the following requirements:

- ISO 20906 weather conditions
- Flyby within 1 km of NMT (slant range)
- Event detected by NOMOS at least 25 seconds long
- Limited turning
- Departing aircraft only



(a) L_A progression of NMT 2 flyover by a B737



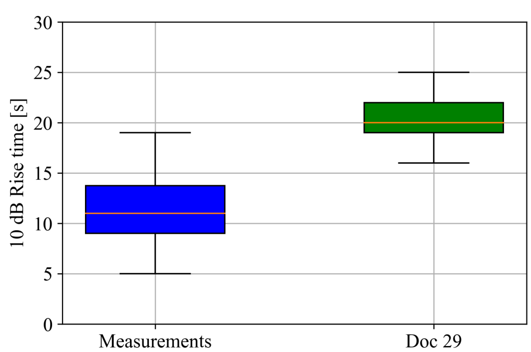
(b) L_A progression NMT 12 flyover by an E190

Figure 6: Measured (blue) and modelled (green) noise levels of flyovers

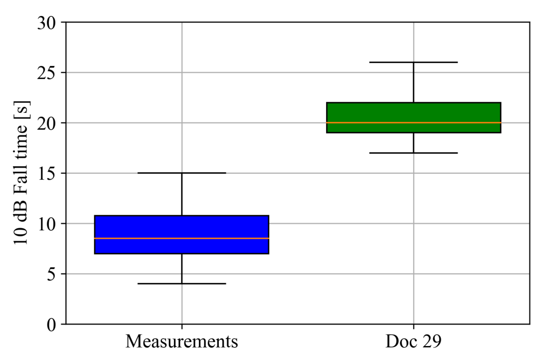
A 3-hour time period of sound data from NOMOS is downloaded and analyzed. For fly-overs found by NOMOS during this period, the track data for the flight is used as input for the Doc 29 model together with weather data from that time period. As such, modelled and measured fly-over noise can be compared per measurement. For this, 90 seconds are considered, centred around the time instant at which the model predicts the sound level to be maximum. Examples of a single event can be seen in figure 6a and 6b. The blue line is the recording from the NMT and the green line is the L_A as predicted by the Doc 29 model. The 10 dB rise and fall times are indicated in blue (measurement) and orange/yellow (Doc 29).
For the model input, the distance is found from the radar tracks. Finding the thrust level of the aircraft needed for the Doc 29 model is not trivial [9]. For this research, the thrust levels during departure are assumed constant at a rate of 75% of maximum thrust. As this research is focused on the shape of the event, rather than the specific height of the peak, the effect of the assumed thrust is considered to be less of importance.

Figure 5: NMT locations

An interesting observation is the difference in shape between the modelled and measured events. In the early and late stages of the event, where the aircraft is at larger polar angles, the model overestimates the noise. This phenomenon is very apparent by looking at the so-called rise and fall times. These are the times it takes for the sound level to rise from 10 dB under the maximum noise level to the maximum, or fall 10 dB from the maximum noise level. The results for such analysis for a large set of fall and rise times can be seen in 7a and 7b.



(a) Rise time



(b) Fall time

Figure 7: Boxplots of the rise and fall times for the B737 at NMT 2.

There clearly is a discrepancy between modelled and measured rise and fall times. This shows that it is very likely that the directivity effects are underestimated by the Doc 29 model. To get a better insight into this effect, the collected data is analysed per angle.

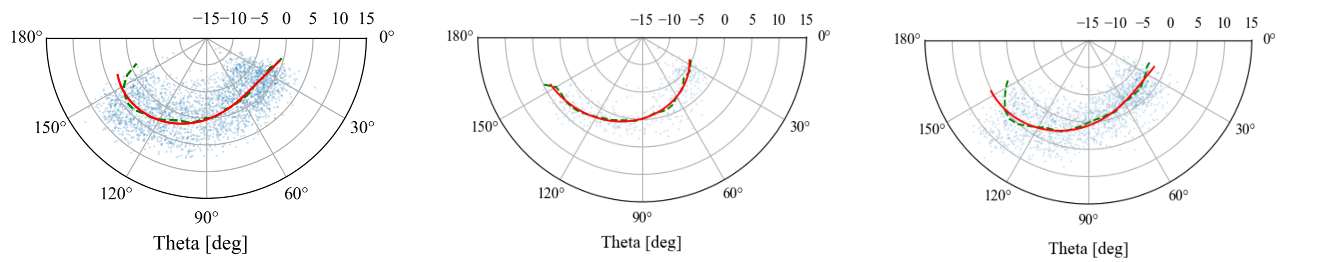
4. Results

For each valid flyover measurement, the track is split into 1-second segments. This results in multiple measurements each with different lateral (ϕ) and longitudinal θ angles, distances of the aircraft to the NMT and recorded noise levels. To be able to compare the noise levels at these different angles, the noise levels are propagated back to the source level. This calculation assumes a homogeneous atmosphere and limited weather effects.

Between the multiple NMTs, differences in relative noise levels were found. This could be due to reflections or inconsistencies in the propagation calculation to the source. To be able to accurately compare the effect of directionality, the average sound levels were calculated for the overhead position: 90° for the longitudinal direction and 0° for the lateral direction. The levels are then normalised by integrating over all measured angles and set to 0 dB(A). This is to avoid unnecessary level corrections.

At large elevation angles, the noise levels become very similar to the background noise as seen in Figure 6b. For this reason, only segments within 10 dB up- and downtime are taken for this analysis. This roughly corresponds to the θ range of 30° to 150°. The resulting plots can be seen in Figure 8 where each measured segment is presented as a blue dot. Within these data sets, two types of trends are found. First, the average noise level is taken per 5° band, seen in the green dotted line. Second, a linear regression is applied through the points (red). A model test (χ^2-test) showed that a third-degree polynomial linear regression should be selected for the fitting. These two trends match closely, thus implying a good fit for the linear regression.

Differences are seen between the different aircraft types. Currently, in Doc 29, the directivity correction factors are the same for all (wing-mounted) aircraft types. Based on these results, this assumption is not correct and each aircraft type should be analysed separately.



(a) B737 (b) A320 (c) E190

Figure 8: Standardized measured noise level [dBA] of different flyovers vs θ in blue dots. The red line indicates the polynomial fit. The green line indicates the average level.

For the lateral direction ϕ, insufficient data was collected. While a single flight track provides a large variation in longitudinal angles, non-turning flights mean that the aircraft flew over the NMTs at similar lateral angles resulting in all measurements per NMT falling within 10°. Only for NMT2 larger variations in ϕ were observed, which is the result of aircraft rapidly increasing their altitude during the timespan since this NMT is closest to the runway. An example of a plot for lateral angles can be seen in Figure 9. The clearly visible clusters are the measurements for the different NMTs. As a result, there is not enough information to find a correction factor for this orientation.

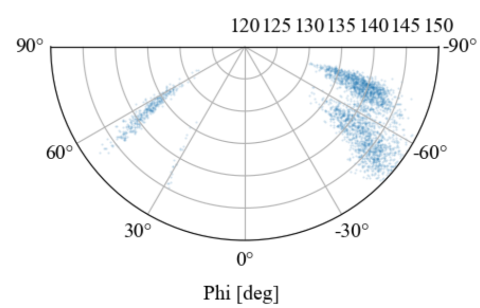


Figure 9: Variation of the measured source sound level [dBA] over lateral angle ϕ.

The found polynomial for θ was implemented as an extra directivity correction within Doc 29. This gives the updated model prediction as seen in red in Figure 10. Two main differences between the corrected model and the uncorrected (green) model are visible. First is the difference in shape. The slope before the peak in the corrected model contains a 'dent'. This is due to the shift from negative correction for angles $\theta < 90°$ to a positive correction from when the aircraft's relative position is $\theta > 90°$. This results in a shorter rise time which matches the measurement (blue) more closely. The fall time (the slope after the peak) seems to be similar to the uncorrected model.

The second observation is that the peak of the event is shifted. This is due to the larger noise production aft of the aircraft. The new longitudinal correction factor captures this. The time stamp of the new peak matches the peak of the measurement more accurately. Further, this new peak has a slightly higher $L_{A,max}$ than the uncorrected model but the effect is minimal. Although every measurement is different, this single event is typical for most observed events in the data set.

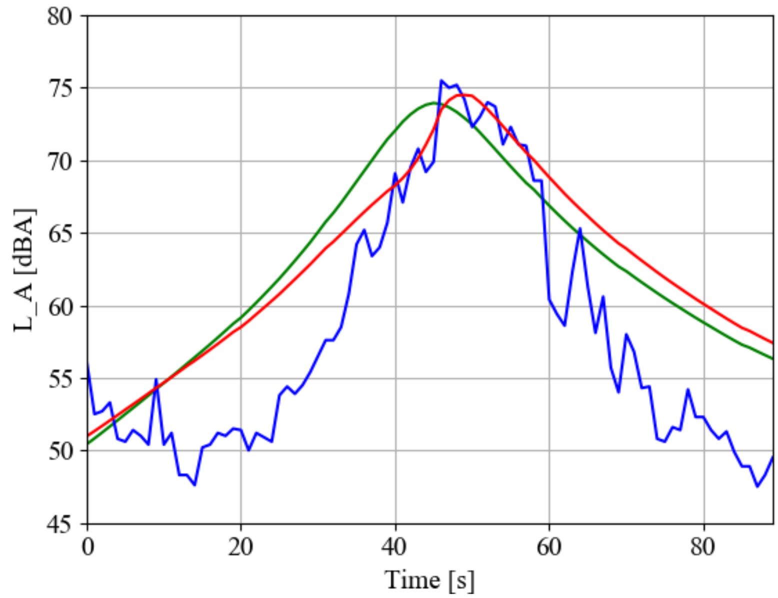
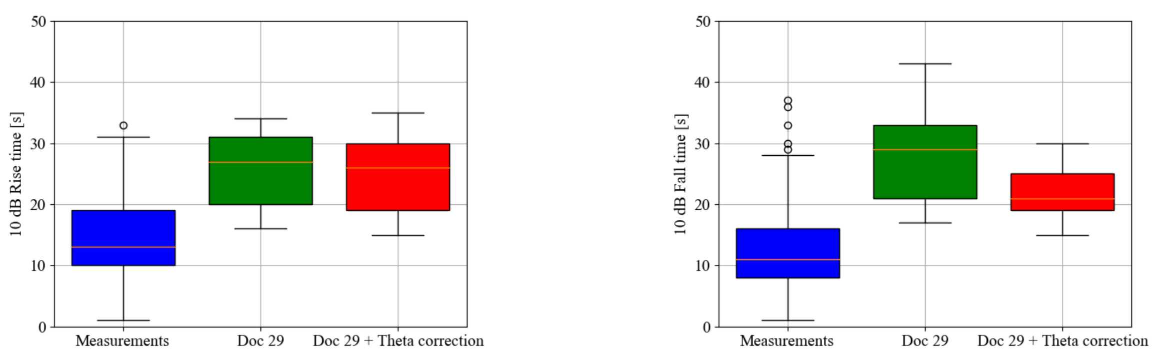


Figure 10: L_A progression of NMT 2 flyover by a B737 with model adjustment (red) compared to the uncorrected model (green) and the measurement (blue).

When analysing the effect of the new longitudinal correction factor on the rise and fall times in Figure 11, a decrease is visible. For the rise time, this median decrease is minimal (about 1 second), while for the fall time, a decrease of about 8 seconds is visible. Both are thus an improvement although still a large gap exists between the corrected model and the measurement.



(a) Rise time

(b) Fall time

Figure 11: Boxplots of the rise and fall times for the B737 at all NMTs for the corrected and uncorrected model.

5. Conclusion

ECAC Doc 29 is the current best practice noise model used by all ECAC member states. Similar to other empirical models, the modelling of directivity effects is very limited, potentially resulting in deviations between model predictions and measurements. In this paper, Doc 29 model predictions are compared with noise measurements around Schiphol airport for departure operations of four different aircraft types.

The measurements show that for lower elevation angles the sound level is in general overestimated by the Doc 29 model. This leads to an overestimation of the 10 dB rise and fall times and the sound exposure level by the model. For elevation angles of around 90°, so when the aircraft is flying close to overhead, the maximum noise level observed is fairly accurate. To improve upon these model predictions, measurements are analysed for directivity effects.

A common approach to analyse directivity effects is to split the elevation angle into the longitudinal and lateral directions. As observed in the literature, especially the former has significant directionality effects. By combining measurement data from multiple measurement stations around Schiphol Airport, a relatively accurate approximation for an additional correction for longitudinal directivity was found. Applying this extra correction shows that the modelled noise level more accurately predicts the sound level and the timing of the maximum observed sound level.

With the current data, it was not feasible to obtain a good approximation for the directional effects in the lateral directions. This is due to the fact that there is no data for flights directly over the microphones, so there is only data for limited angles. Future research could include placing an array of microphones perpendicular to the flight path of departing aircraft. It is also recommended to repeat this exercise for aircraft in the approach phase, where the engine setting is much lower and airframe noise is more dominant.

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