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Executive Summary of the Thesis

Aircraft noise modeling through simulation for route optimization

Laurea Magistrale in Aeronautical Engineering - Ingegneria Aeronautica

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1. Introduction

Aircraft noise is the most significant cause of adverse community reactions related to the operation and expansion of airports. Beyond the annoyance, noise exposure can negatively impact children learning, disrupt sleep, and increase the risk of cardiovascular disease [1].
ICAO is aware of this problem and has set The Balanced Approach to Aircraft Noise Management. This approach consists of identifying the noise problem at a specific airport and analyzing different measures available to reduce noise such as:

- Reduction of noise at source
- Land-Use planning and management
- Noise abatement procedures
- Operating restrictions

The goal is to identify measures that achieve maximum environmental benefit most cost-effectively using objective and measured data.
Mathematical models and optimization tools are currently being studied and developed to generate trajectories that minimize noise exposure in communities close to airports. These tools can address ICAO's balanced land use planning and management approach and noise abatement procedures measurements to achieve maximum environmental benefits.

The main objective of this work was to find an aircraft noise model that allows to better estimate the sound level perceived at a receiver on the ground due to aircraft flyover events. The latter is to improve the performance of NOICE, an optimization program that looks for optimum trajectories to reduce noise exposure on communities in airports area[2]. This program until the beginning of the thesis, estimated aircraft sound level assuming a single monopole source with spherical propagation that obeys the inverse square law, consequently, the model to develop must account for noise directivity patterns. Therefore, this noise model should be sufficiently simplified not to worsen the optimization tool's execution time.

1.1. State of the art

An extensive study of aircraft noise models was performed. The research focused on the models' assumptions, approaches, and limitations. Therefore, it was found that some *best practices* models account for noise directivity patterns in a simplified way, with minimal parameters required as inputs [3]. For noise computations, *best practices* models follow the segmentation approach, which means that aircraft's trajectory is discretized through a series of points defining segments for which noise levels are computed. The studied approaches can be categorized between those that based the computations on Noise Power Distances (NPD) curves, such as INM and ECAC models, and those that have developed their regressions over actual measurements, such as FLULA 2 and AzB models. These last models perform spectral analysis to account for atmospheric attenuation effects and ground reflections. In this way, they can characterize noise for a single aircraft or aircraft group.

$$
\begin{aligned}
L_i(R,\theta) &= \sum_{k=0}^{7} A_{k_i}(R) cos(\theta)^k \\
A_k(R) &= H_{k1} \cdot 20\, log(R) + H_{k2} \\
&\quad + H_{k3} \cdot R + H_{k4} \cdot R^2
\end{aligned} \tag{1}
$$

Among all the models studied, the FLULA 2 model estimates the Overall A-Weighted Sound Pressure Level (OASPL) as reported in eq. (1). After correcting the measurements to standard atmospheric conditions and a reference distance R, the coefficients of eq. (1) are computed through regression for varying propagation distances. The geometric definitions are reported in fig. 1.

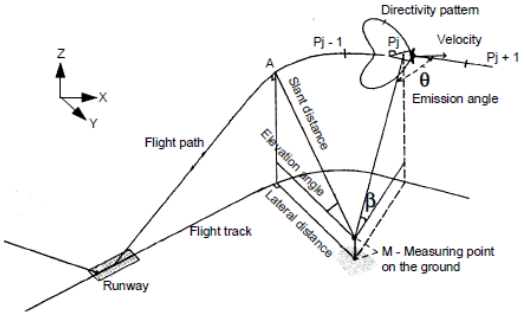

Figure 1: FLULA 2 model geometric definitions [4]

2. ECAC Doc. 29 implementation

According to ECAC Doc 29 guidelines, a model has been implemented to evaluate, compare and validate the current and subsequent results of NOICE program.

The ECAC Doc. 29 provides comprehensive guidance for calculating aircraft noise exposure levels and noise contours for noise assessment. Therefore, it is not a program itself, but it presents the model guidelines for its implementation. It follows a segmentation approach and estimates the noise level following a fully-empirical approach using the Aircraft Noise Performance (ANP) database.

ECAC Doc. 29 is divided into three volumes. The first one introduces Doc. 29 and describes the main noise estimation concepts. The second Volume presents all the modeling guidelines, the third Volume presents validation implementation guidelines.

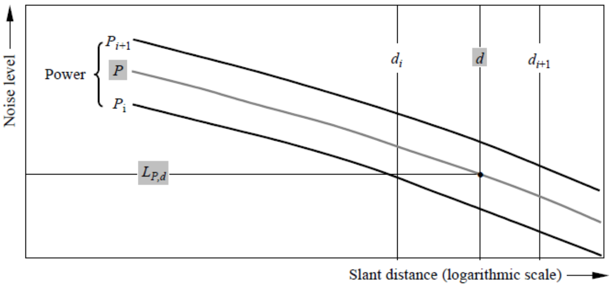

Figure 2: Interpolation in noise-power-distance curves

The ECAC Doc 29 guidelines were implemented in Matlab through two subroutines. The first one corresponds to the trajectory definition, in which the segments and their characteristics are defined for the noise estimation analysis. The second one corresponds to the noise computation subroutine that estimates the maximum sound pressure level L_{max} and Sound Exposure Level (SEL) L_E over an array of sensitive receivers.

$$
\begin{aligned}
L_{max} &= max(L_{max,j}) \\
L_E &= 10 \cdot \left(\sum^{j} 10^{L_{E,j}/10} \right)
\end{aligned} \tag{2}
$$

For the entire trajectory, the L_{max} and SEL are computed as reported in eq. (2), where $L_{max,j}$ and $L_{E,j}$ correspond to noise calculation for each segment according to Volume 2 guidelines [5]. The implementation was validated with the procedure indicated in Volume 3, obtaining error values in compliance with the indicated limits.

Additionally, a routine for flight data records analysis was implemented. This routine allows defining a trajectory to be used with the Doc. 29 guidelines for sound computation purposes. It was implemented in Python, and the flight data is accessed from FlightRadar 24.

3. Noise model derivation

For this thesis, noise measurements were not available; therefore, it was decided to follow a simulation approach for data acquisition and model definition.
The available implemented ECAC Doc. 29 guidelines were used for the simulation approach. Although this tool was designed for such purpose, it was validated according to the ECAC directives and gave noise measurements that allowed following a simulation approach.
ECAC Doc. 29 guidelines do not offer spectral analysis as it is a segmentation-based method. Therefore, the approach followed does not account for spectral decomposition analysis. FLULA 2 model was the reference for the reduced model assessment due to its simplicity and the final estimation corresponding to the OASPL eq. (1). Anyhow, in this case no attenuation and atmospheric corrections were performed due to the lack of spectral analysis. Therefore, the model was be able to estimate the Sound Pressure Level (SPL) knowing the slant distance R and the radiation angle θ, as evidenced in fig. 1
For simplicity, the study focused on departure procedures considering an Airbus 320 model. The metric selected for data acquisition was the L_{max}, and it was used because it depends on a specific segment and geometry between the aircraft and receiver position. The simulations were based on an airport scenario from a defined ground track and a default procedure from the ANP database.

3.1. First approach

The first approach tried to assimilate what would be the noise measurement from a noise monitoring terminal, therefore, simulating noise time-history level. Consequently, the data acquisition measured $L_{max,j}$ for each receiver on the ground and each segment with the respective geometry of interest. When visually comparing the results with the reference from literature, the difference in the shape of the directivity patterns is considerable. This behavior could be explained by a considerable noise level dispersion from the simulation data, especially at low radiation angles. Hence, this approach was not further studied.

3.2. Second approach

The second approach instead focused on the entire trajectory, therefore, for each receiver was extracted just one measurement corresponding to L_{max} with the respective geometry. A denser receiver array and multiple scenarios were defined to obtain a more extensive data frame for the regression. In this case, the results assimilated the references from the literature, and presented better fitting performance, where the R-square went from 86% to 99.6%. This result was further analyzed in order to define a noise model that it is suitable for NOICE.

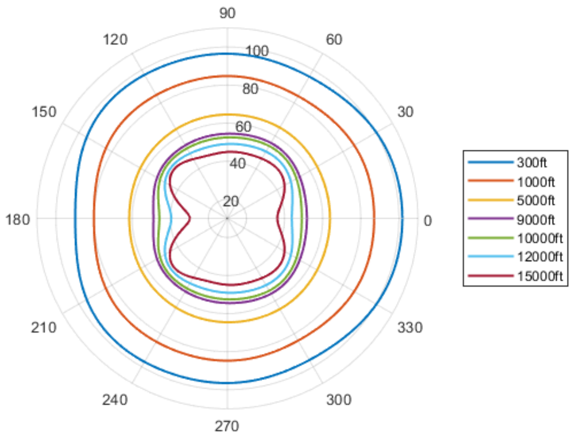

Figure 3: 2nd approach A320 sound pressure level [dB] at different distances

3.3. Implementation

For the model definition, it was noticed that the directivity patterns started to deform as the slant distance increased. Thus, analyzing the "omnidirectionality" by comparing the difference between max and min SPL for a certain slant distance, it was found that at 4000ft, the directivity patterns present the most "omnidirectional shape." Then, this difference increased for larger slant distances as shown in fig. 3. This behavior was associated with the lack of data for more considerable slant distances, especially for angles close to 0° and 180°.
Anyhow, to define a suitable function that characterizes the sound to be used by the optimization tool , it was decided to implement a piecewise function eq. (3). For this function, up to 4000ft it is considered the regression based on FLULA 2 model; from 4000ft up to 13000ft,

$$L(R,\theta) = \begin{cases} \sum_{k=0}^{7} A_k(R)cos(\theta)^k & [dB] \quad R \leq 4000 \\ \sum_{k=0}^{7} A_k(4000)cos(\theta)^k + 20\log\left(\frac{4000}{R}\right) + f(R) & [dB] \quad 4000 < R \leq 13000 \\ 40 & [dB] \quad R > 13000 \end{cases} \tag{3}$$

it is considered the reference SPL at 4000ft for which the inverse square law is applied, assuming spherical spreading plus a correction of the non modeled attenuation effects. For slant distances higher than 13000ft, the SPL is fixed at 40dB, comparable with a quiet rural zone. The final noise characterization is presented in fig. 4

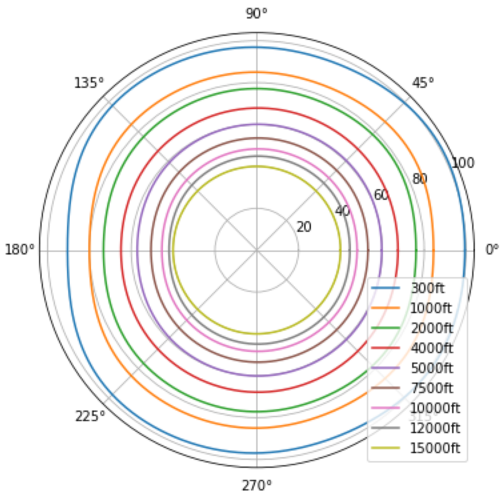

Figure 4: Final A320 sound pressure level model for algorithm implementation

When evaluating the worsening of the computation time due to the use of the new model, it was obtained that, on average, the new noise model is 60 times slower, anyhow, if the times for which the function is called for the entire optimization run is contained, the absolute time difference can be negligible.

4. Study cases

Study cases were performed using the implemented ECAC Doc. 29 guidelines, to evaluate the current NOICE optimal results comparing them with current noise abatement Standard instrument departure (SID). In this case, the scenario studied corresponded to Malpensa Airport, for which the SEL was computed at the locations of the municipalities in the airport area. The study cases also evaluated the contribution of the simplified noise model to assess whether the new noise model significantly changes the optimal trajectory.

Case	Average SEL [dB]	Log-Average SEL[dB]	Distance [km]
35R SID	66.28	72.40	33.23
35R SS	63.03	68.75	21.55
35R SNM	64.01	67.97	23.50
17R SS	71.08	75.43	34.97
17R SNM	68.68	74.28	32.88

Table 1: Comparison results between current SID noise abatement procedures and NOICE optimal results. **SS** Spherical spreading; **SNM** Simplified noise model

Initially, different departure cases were studied to evaluate current SID with optimal results of NOICE considering the spherical spreading (SS) model. The results reported in table 1 shows that effectively, the NOICE optimum routes reduce the SEL over the most exposed communities. In the same analysis, it was obtained that the reduction of SEL in some municipalities leads to the increase in others but in average, the SEL is reduced. Also, special attention should be paid to the setup of the NOICE program, introducing constraints to avoid actions that may jeopardize the safety of the procedure and the flight as happened in this case where the optimal routes turn just before take-off and passes over the parallel runway.
Later, comparisons between the optimal routes considering spherical spreading and the noise model developed (SNM) , fig. 5, showed that the trajectory change of the optimal routes is minimal but the log-average SEL decreases with the simplified model developed approximately 1.35%.

5. Future developments

Part of this thesis work was limited due to the impossibility of accessing and analyzing noise

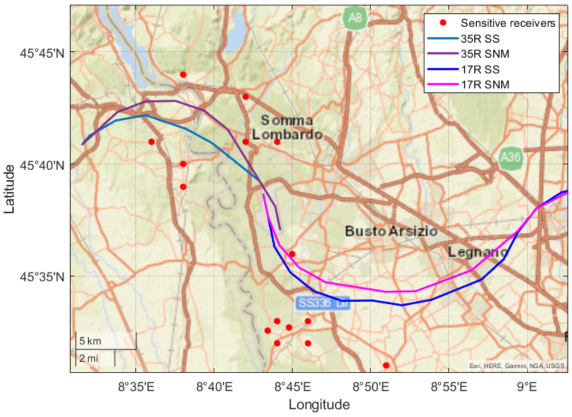

Figure 5: NOICE optimal routes comparison: **SS** Spherical spreading; **SNM** Simplified noise model

measurements. With access to this data type, further analysis and validation could have been performed. Future developments to increase the robustness of the research's main goals will depend on validating the simplified model developed, and the ECAC procedure implemented. Therefore, the next steps of the research should focus on developing tools for data acquisition. In this line, the sound pressure time-history level and the precise aircraft position in time are the needed data to record for noise assessment.

Hence, an embedded system was proposed for data acquisition. This system is based on the use of a Raspberry Pi board. This board was selected for its ability to perform both: a Sound Level Meter and to track an airplane by decoding the ADS-B signal with the appropriate hardware. Among the main challenges for the development of the system, and in general the acquisition of data, it can be highlighted the selection of its hardware components to measure the noise, the power supply, the aircraft flyover detection, and the measurement strategy including its positioning for controlling background noise. For aircraft tracking, the use of the ADS-B signal is indicated for which an ADS-B receiver and 1090 Hz antenna are required for aircraft tracking. Finally, it is also necessary to define the processing of these data to characterize the aircraft in terms of its position and the sound perceived by the system, for which the synchronization of the data as a function of time is indicated. All the data must be stored in a SD card or a cloud to be easily accessed for post-processing analysis.

6. Conclusion

When analyzing the NOICE optimal routes, it was found that sound exposure on the most impacted locations decreased on average. In this way, the SEL decrease in specific locations leads to an increase in others. This work has also evidenced the importance of analyzing the optimal routes under real scenarios for procedures implementation, from which particular constraints can be identified. These analyses also give feedback that could be helpful to improve the overall robustness of the NOICE model, even when all the results of the tool should be validated.

When comparing the results of the optimization tool depending on the sound model used, there are no significant changes in the optimal routes. However, for the cases studied, the new sound model decreases the log-average of the SEL by 1.35%. The increase in computational time, 60 times slower, is a significant relative difference, but if the number of times SPL must be calculated remains contained, it can be recommended to use the simplified model. However, continuous improvement in the optimization algorithm performance is crucial. Additionally, there is room for improvement by testing other approaches to obtain a simplified noise model with lower computation effort.

The following research steps will depend on the availability and analysis of measurements. Thus, the future work proposal focuses on conceptualizing an integrated system for data collection based on a Raspberry Pi board, which provides good advantages for developing a low-cost embedded system. In this way, it will be possible to validate both the data used for the definition of the model, the implementation of the ECAC process with actual measurements, and, in turn, it would be possible to try new modeling procedures.

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