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A comparative study of semi–empirical noise emission models based on the PANAM and sonAIR aircraft noise simulation tools

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ABSTRACT

In the context of aircraft noise simulations, an accurate representation of the aircraft noise sources is crucial so that reliable predictions can be obtained. In this contribution, we present a comparative study between the predictions provided by the emission models based on the DLR's in–house PANAM tool and the sonAIR simulation software. Both are based on semi–empirical descriptions of the engine and airframe noise contributions, meaning that the emission levels are modeled separately for each noise source according to the operational conditions of the aircraft. This allows the comparison of the emission models not only in terms of the aircraft's overall noise levels, but also regarding its different noise sources. The comparative study considers models representing the noise emissions of an A319 aircraft, which are provided by both simulation tools but further simulated within the sonAIR software environment in order to yield noise immission levels on a large calculation area. In general, a good agreement is observed for the departure procedure due to the similar performance of the engine noise models. In contrast, larger differences are observed during the approach procedure and at larger distances from the runway, which might be explained by differences in the airframe noise models.

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1. INTRODUCTION

The accurate simulation of aircraft noise is a complex task as a multitude of physical phenomena needs to be properly modeled. For this reason, different aircraft noise simulation methodologies exists, mainly differing regarding the degree of fidelity on which the aircraft noise emissions and the sound propagation are modeled [1]. The higher the degree of fidelity, the higher is the computational effort and the complexity of the input data required, and vice–versa.

Aircraft noise simulation tools based on the scientific method are characterized by the use of semi–empirical models. Each model describes the noise emissions of specific sound sources according to the operational condition of the aircraft. By adequately modeling the major noise sources individually, it is possible to approximate the overall noise of an operational aircraft, as previously demonstrated by Refs. [2–5]. Moreover, semi–empirical models are parametric meaning that they provide noise emission levels as a function of geometrical and operational parameters. This allows the investigation of the noise emissions of individual sound sources, which is a feature particularly desirable for noise design and optimization purposes. After the prediction of the aircraft noise emissions, propagation effects are employed in order to obtain the resultant noise immission at arbitrary observer positions on the ground.

In this work, a comparative study between the noise immission predictions provided by two semi–empirical aircraft noise emission models is presented. The emission models are based on the DLR's in–house Parametric Aircraft Noise Analysis Module – PANAM tool [2] and the sonAIR simulation software [6]. One aircraft type is selected for this study, the Airbus A319, due to the fact that both the DLR's noise prediction framework and the available sonAIR noise emission model for this aircraft type were validated through extensive comparison with measurements by Bertsch [2] and Jäger et al. [5]. Nevertheless, the main contribution of the comparative study presented in this paper is to further extend these previous works by performing a cross–verification of the emission models not only in terms of the overall aircraft noise immissions, but also regarding the contribution of the engine and airframe noise components separately. The methodology employed for the comparative study is described in Section 2 while the results are presented and discussed in Section 3. Finally, the conclusions about the findings of this work and outlook are provided in Section 4.

2. METHODOLOGY

An overall description of the simulation process used for the comparative study performed in this work is presented in Figure 1. As a summary, the methodology is composed by three main simulation processes:

- a PANAM–based noise emission model is predicted using the simulation framework described by Bertsch [2]. It comprises the aircraft design synthesis (using the Preliminary Aircraft Design and Optimization tool – PrADO [7]) and the noise emission prediction using the PANAM tool [2];
- the flight trajectories and corresponding operational conditions of the A319 aircraft under approach and departure procedures are calculated using the DLR's FlipNA tool [8]; and
- aircraft noise simulations are conducted within the sonAIR software environment [6] to obtain the noise immission contours on the ground. The simulations are conducted using both PANAM– and sonAIR–based noise emission models. Moreover, the same flight profiles are prescribed to both emission models for the approach and departure procedures.

As the sound propagation is calculated using the simulation process employed by the sonAIR software, it is possible to ensure that solely the influence of the different emission models on the noise immission predictions is observed. In the following, a detailed description of individual aspects concerning each simulation process is provided.

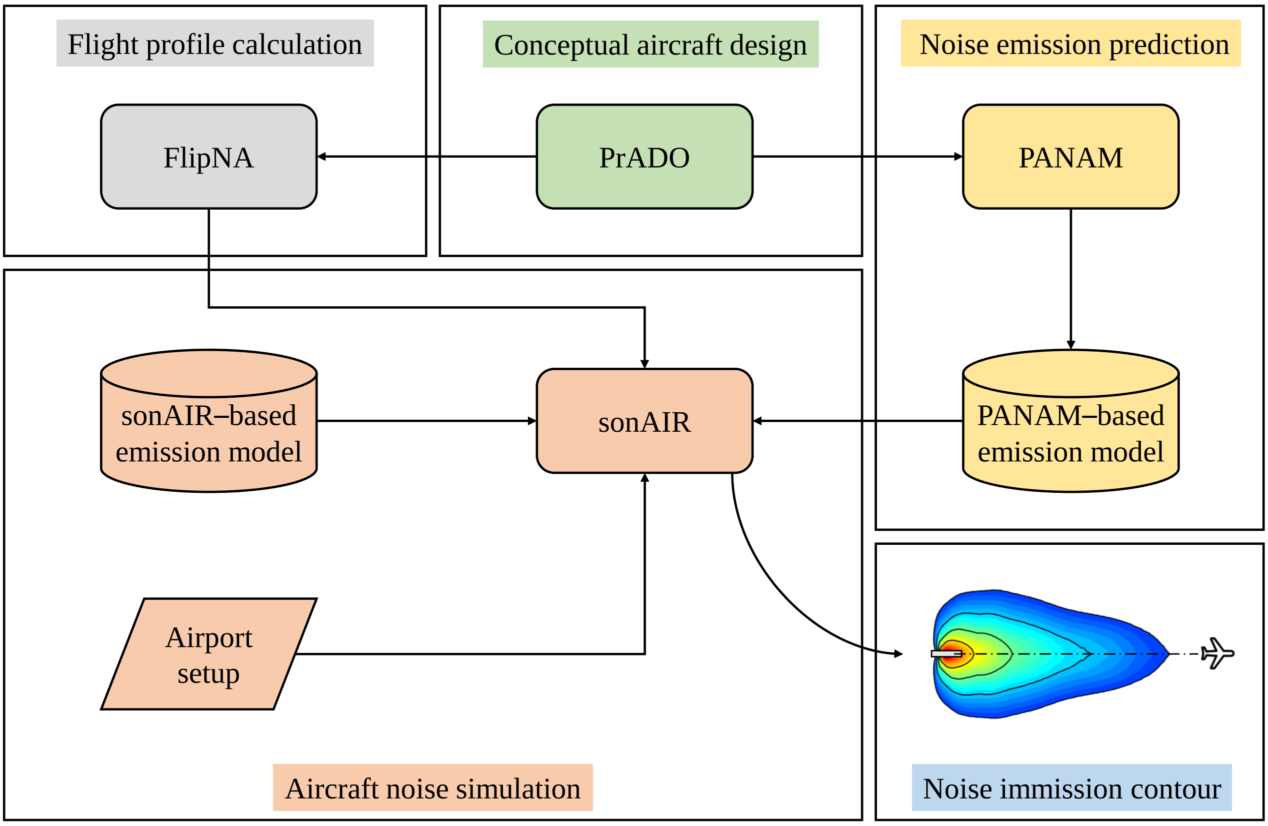


Figure 1. Schematic flow–chart of the overall simulation process used in this study.

2.1. PANAM–based noise emission model

The PANAM tool is capable to provide realistic aircraft noise emission predictions when provided with inputs concerning the aircraft's geometry, weight, engine geometry and performance, and aerodynamic performance. The underlying noise emission prediction methodology employed by PANAM is based on a set of semi–empirical models which describes the emissions of individual sound sources according to the operational condition of the aircraft. After the noise emission prediction, sound propagation effects can be applied in order to obtain the resultant aircraft noise immission at arbitrary receiver positions on the ground. Due to the parametric nature of the noise prediction framework employed by PANAM, the investigation of the noise emissions and immissions of individual sound sources is possible.

In this study, the PANAM model representing the noise emissions of the A319 aircraft is based on the one described and validated by the work of Bertsch [2]. It is based on a PrADO design of an A319 aircraft mounted with CFM56–5A turbofan engines, and maximum takeoff weight (MTOW) and maximum landing weight (MLW) of 64882 kg and 61764 kg, respectively. A summary of the semi–empirical models used for the prediction of the PANAM–based emission model used in this study is provided in Table 1.

Table 1. Summary of the semi–empirical models used for the prediction of the PANAM–based emission model.

Noise source	Model
Trailing edge devices (broadband noise)	DLR models [2, 9–11]
Leading edge devices (broadband noise)	DLR models [2, 9, 12]
Landing gear (broadband noise)	DLR models [2, 13]
Fan (broadband noise)	Modified Heidmann [14]
Fan (tonal noise)	Modified Heidmann [14]
Jet (broadband noise)	Modified Stone [15]

In order to perform simulations within the sonAIR software environment using a PANAM–based emission model, noise emission levels as a function of frequency f (1/3 octave bands from 25 Hz to 5 kHz) are predicted separately for the engine, $L_{\mathrm{w,eng}}(f)$, and the airframe, $L_{\mathrm{w,afm}}(f)$, components by PANAM in terms of sound power levels, $L_{\mathrm{w}}(f)$. This is done by first computing free–field noise emissions in terms of directional unweighted sound pressure levels, $L_{\mathrm{p}}(f)$, on a reference sphere with a radius of 1 m and origin at the aircraft's center of gravity [2]. The predicted $L_{\mathrm{p}}(f)$ values are further converted to $L_{\mathrm{w}}(f)$ levels using the following relationship:

$$L_{\mathrm{w}}(f) = L_{\mathrm{p}}(f) + 10 \cdot \log_{10}(4\pi). \tag{1}$$

Finally, the PANAM–based emission model is created as a look–up table containing the $L_{\mathrm{w,eng}}(f)$ and $L_{\mathrm{w,afm}}(f)$ emission levels predicted for all possible combinations of parameters describing the sound directivity and the aircraft's operational conditions within a relevant range of discrete values. The sound directivity parameters are: polar angle θ and azimuthal angle ϕ (spherical coordinates, for more details see Ref. [2]). The flight parameters are: fan rotational speed N1, air density at the flight altitude ρ, and the aircraft's Mach number Ma. Additionally, noise emission levels concerning the flap handle (FH) and the landing gear (LG) configuration are included so that the aerodynamic configuration of the aircraft is explicitly accounted for. Therefore, the PANAM–based emission model used in this study corresponds to a full sonAIR model (see Section 2.2). Based on this procedure and dedicated interfaces, arbitrary PANAM emission models can be processed within sonAIR for upcoming studies considering novel technology and low–noise aircraft designs that are otherwise not available within the sonAIR's database of emission models, as previously demonstrated by Refs. [16, 17].

2.2. SonAIR–based noise emission model

The aircraft–specific noise emission models available in sonAIR are based on a set of multiple linear regression equations derived from a measurement dataset of real air traffic covering a wide range of typical aircraft operations [18]. A comprehensive validation study of the sonAIR emission models is provided in the work of Jäger et al. [5]. The sonAIR models describes the overall aircraft noise emissions as frequency–dependent (1/3 octave bands from 25 Hz to 5 kHz) and three–dimensional directivity patterns as a function of flight parameters. For this purpose, they account for the engine and airframe noise contributions separately, which are modeled as the sum of a source term and a radiation angle term. The airframe and the engine noise contributions are separated from the overall aircraft noise based on the assumption that the airframe noise dominates over the engine noise emissions when the aircraft's engines are running in idle with N1 $\leq$ 40% [19].

The sound emission levels of the engine components are modeled by sonAIR as [19]

$$L_{\mathrm{w,eng}}(f) = \underbrace{L_{0,\mathrm{eng}}(\mathrm{Ma}, \mathrm{N1}, \mathrm{N1}^2)}_{\text{Source term}} + \underbrace{L_{\theta,\mathrm{eng}}(\theta, \mathrm{N1}, \mathrm{N1}^2) + L_{\phi,\mathrm{eng}}(\phi, \mathrm{N1})}_{\text{Radiation angle term}}, \tag{2}$$

where the source term is modeled as a function of the fan rotational speed N1 and the aircraft's Mach number. Furthermore, the radiation term is modeled as a function of the polar angle θ, and the azimutal angle ϕ (spherical coordinates, see Ref. [18] for more details).

As the derivation of the emission models is based on a dataset containing different levels of detail available about the aerodynamic configuration of the aircraft, the airframe noise models are formulated in two versions: 1) full models, and 2) reduced models. In the former, the aerodynamic configuration of the aircraft at any segment of the flight trajectory is taken into account, while in the later, it is not explicitly considered. Therefore, the reduced models represents the average aerodynamic configuration settings of the aircraft at any given point of its flight trajectory, as available on the dataset used for their development. In this study, a reduced sonAIR model is used. The sound emission of the airframe components are modeled in the reduced form by sonAIR as [19]

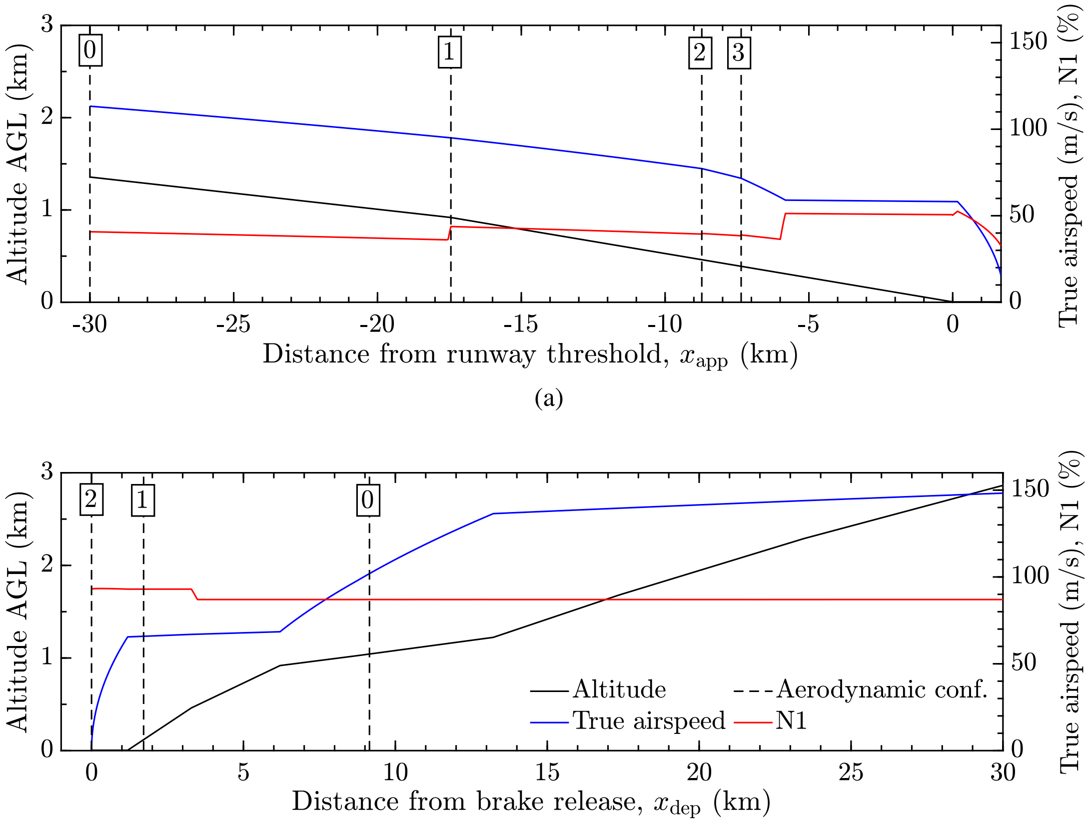
$$L_{\mathrm{w,afm}}(f) = \underbrace{L_{0,\mathrm{afm}}(l\mathrm{Ma}, l\rho, \mathrm{proc})}_{\text{Source term}} + \underbrace{L_{\theta,\mathrm{afm}}(\theta)}_{\text{Radiation angle term}} \quad , \tag{3}$$

where the airframe source term is modeled as a function of the base–10 logarithm of the aircraft Mach number lMa, and air density $l\rho$, and of the flight procedure. Furthermore, the radiation term is modeled as a function of the polar radiation angle. Therefore, sonAIR models the airframe noise emissions considering a two–dimensional sound directivity and attributes most of the lateral directivity to the engine noise emissions.

In this present study, the sonAIR model A32X_CFM56–5A_AD is used. This model was established as a reduced model representing the whole Airbus A320 family of aircraft equipped with CFM56–5A engines due to the lack of sufficient data available for each individual aircraft type [18]. Moreover, this model was adjusted and validated by Zellmann et al. [20] in order to account for the airflow deflector (AD) retrofit of the A320 family. This device is used to suppress aeroacoustic cavity tones originated at the fuel overpressure protector cavities located at the pressure side of the wing profile. Since such cavity tones are not modeled by the airframe models used by PANAM, the sonAIR model A32X_CFM56–5A_AD is considered adequate for the comparative study conducted in this work.

2.3. Flight profile calculation

The operational conditions are calculated using the FlipNA tool [8] based on the PrADO design of the A319 aircraft (see Section 2.1). The FlipNA tool is able to realistically model the operational conditions of an aircraft along a prescribed flight path when provided with inputs regarding the aircraft's engine performance, aerodynamics, and weight. The flight profile used in this study for the approach procedure (see Figure 2a), is calculated following a continuous descent flight procedure considering 80% of the aircraft's MLW (i.e. $\approx$ 49411 kg). For the departure procedure (see Figure 2b), the ICAO–A noise abatement departure procedure considering 80% of the aircraft's MTOW (i.e. $\approx$ 51906 kg) is used. The possible aerodynamic configuration settings of the aircraft considered on the flight profiles shown in Figure 2 are presented in Table 2, where Boolean values are used to describe the landing gear (LG) settings, i.e. LG=0 (retracted) and LG=1 (deployed). For the comparative study addressed in this work, the flight profiles presented in Figure 2 are assigned to both PANAM– and sonAIR–based emission models.



(a)

(b)

Figure 2. Operational conditions of the aircraft along the (a) approach and (b) departure flight trajectories.

Table 2. Description of possible aerodynamic configuration settings.

Aerodynamic conf.	**Flaps (deg)**	**Slats (deg)**	**Landing gear**
0	0	0	0
1	15	20	0
2	15	20	1
3	35	25	1

2.4. Aircraft noise simulation

The noise immission predictions are obtained using the ArcGIS–implemented version of the sonAIR software [6]. SonAIR is formulated in 1/3 octave bands and models the aircraft noise emissions and the sound propagation separately. The total aircraft noise emission is obtained by energetically summing the airframe and engine noise emission contributions. Additionally, the Doppler effect and the flight effect are considered and the sound propagation is computed using the sonX model [6]. Finally, a time–step method is used for the noise simulation of single aircraft flight events.

In the sonAIR simulation environment, an airport layout with a single–runway of 3.3 km length and 60 m width is defined. The terrain around the airport is set with a flat ground topography and an homogeneously prescribed grass land cover, with a flow resistivity of 200 $\mathrm{kg \cdot s^{-1} \cdot m^{-2}}$. Moreover, a quiescent (wind–free) and homogeneous atmosphere with temperature of 20 °C, atmospheric pressure of 1 atm, and relative air humidity of 60% is considered.

SonAIR describes the aircraft trajectory in discrete three–dimensional points by merging a ground–track with a flight profile. The ground–track represents the flight trajectory as a series of discrete points projected in the (horizontal) ground–plane. For this study, straight ground–tracks are considered for both the approach and departure flight procedures. The flight profile contains information about the aircraft's operational parameters along the discrete ground–track points, namely: cumulative distance from the runway, altitude above ground level (AGL), true airspeed (TAS), fan rotational speed N1, atmospheric variables (air density and sound speed at the flight altitude), and the aircraft configuration (flap and landing gear settings). Finally, the noise immission footprints are computed for each individual flight event on a grid of receiver positions with a spatial resolution of 150 m and at a height of 4 m above the ground.

3. RESULTS AND DISCUSSION

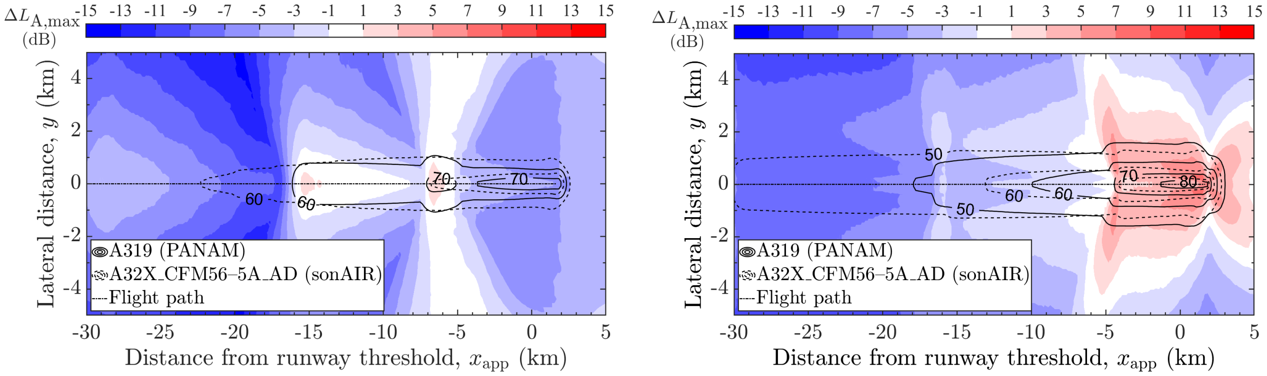
The comparative analyses presented hereafter are conducted in terms of the A–weighted maximum sound pressure level, $L_{\mathrm{A,max}}$. Moreover, the differences between the noise immission contours obtained using the different emission models are further expressed in terms of the $\Delta L_{\mathrm{A,max}}$ indicator, which computes the difference between the results obtained by the PANAM–based emission model, $L_{\mathrm{A,max,PANAM}}$, and the sonAIR–based emission model, $L_{\mathrm{A,max,sonAIR}}$, as

$$\Delta L_{\mathrm{A,max}} = L_{\mathrm{A,max,PANAM}} - L_{\mathrm{A,max,sonAIR}}, \tag{4}$$

meaning that positive $\Delta L_{\mathrm{A,max}}$ values indicates that the results obtained using the PANAM–based emission model are higher than the results obtained by the sonAIR–based emission model and vice–versa. The results obtained for the approach and departure procedures are presented in Figure 3 and Figure 4, respectively.

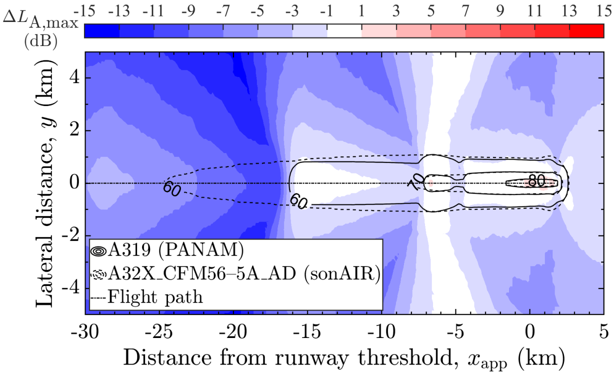
Concerning regions below the flight path, the results obtained for the airframe contribution during the approach procedure (see Figure 3a) shows an acceptable agreement between the models for distances of -16 km $\leq x_{\mathrm{app}} \leq 1$ km. In this range, the maximum difference between the emission models is 5 dB although differences between ±1 dB are mainly observed. As the PANAM model accounts explicitly for the aircraft configuration, this indicates the robustness of the reduced sonAIR model to predict the airframe noise contribution even though the aircraft configuration is indirectly accounted for. This is especially the case for -16 km $\leq x_{\mathrm{app}} \leq -6$ km, when a good agreement between the airframe models is observed while the aircraft configuration changes and N1 $\leq 40\%$ (see Figure 2a). The later is assumed as the threshold value during the sonAIR model development to separate the engine and the airframe noise contributions. For large distances from the runway threshold, when $x_{\mathrm{app}} \leq -16$ km, the sonAIR model present higher levels than the PANAM model by up to 9 dB. This may be explained by the fact that no measurement data for large distances from the runway, when the aircraft configuration is set to clean, was available to establish the sonAIR model [18]. Nevertheless, inherent simulation uncertainties associated with the parametric modeling approach behind PANAM could also explain the large differences between the models [21].

Regarding regions below the flight path, the results obtained for the engine contribution during the approach procedure (see Figure 3b) shows that the sonAIR model presents higher levels than the PANAM model at regions far–away from the runway threshold till $x_{\mathrm{app}} \approx -4.5$ km by up to 9 dB. The airframe contribution dominates the noise immission for these regions, with absolute levels at least 10 dB higher than the engine contribution. For $x_{\mathrm{app}} \geq -4.5$ km, the sonAIR model attributes a higher portion of the total noise immission to the airframe than to the engine, leading to lower values of the engine noise in relation to the PANAM model.



(a) Airframe immission.

(b) Engine immission.

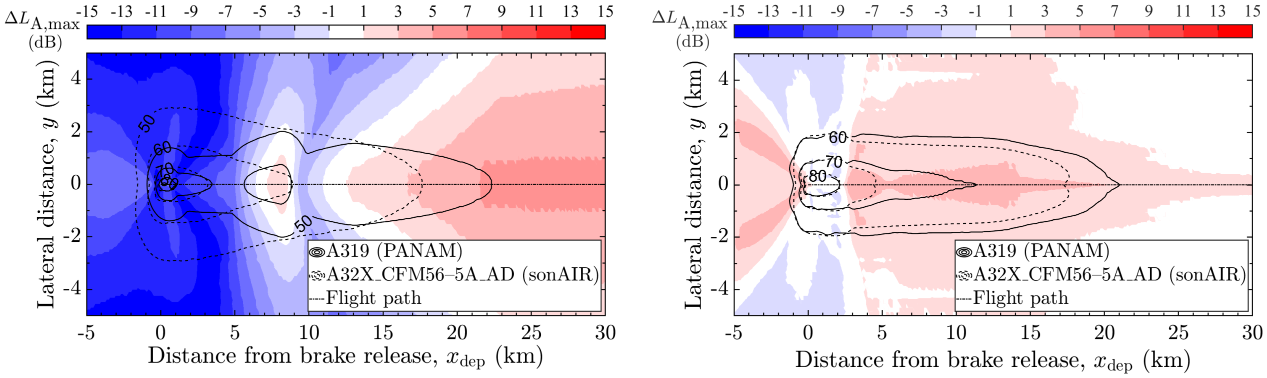


(c) Total immission.

Figure 3. Comparison of noise immission contours for the approach procedure in terms of $L_{\mathrm{A,max}}$: absolute levels obtained using the PANAM–based emission model (solid black lines) and the sonAIR–based emission model (dashed black lines); coloured contours expresses the difference between the results obtained by the different noise emission models in terms of $\Delta L_{\mathrm{A,max}}$.

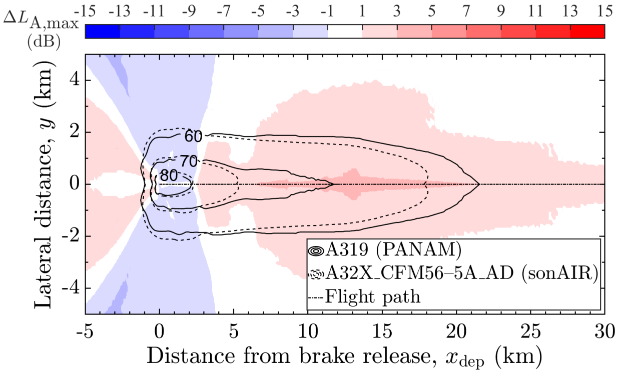
The results obtained for the total aircraft immission during the approach procedure (see Figure 3c) and at regions below the flight path resembles the ones obtained for the airframe immission when -30 km $\leq x_{\mathrm{app}} \leq -4.5$ km. For -4.5 km $\leq x_{\mathrm{app}} \leq 2$ km, both contributions from the engine and the airframe are relevant and the difference between the models is not higher than ±3 dB. The discussion about the results obtained for the approach procedure addressed so far only regions below the flight path. Further disagreements are observed at the lateral areas parallel to the flight path, when $y \neq 0$ km, for all noise contours presented in Figure 3, indicating differences between the sound directivity patterns of the two emission models.

During the departure procedure, the dominant sound source is the engine noise. This can be observed by the fact that the total immission (see Figure 4c) resembles almost entirely the engine immission results (see Figure 4b). Therefore, the similar performance of the engine models leads to a maximum difference of ±5 dB for the total aircraft immission in the whole assessed calculation area. Nevertheless, the differences observed between the engine and the total immission results in the whole calculation area are due to differences of the airframe immissions. This is particularly observed for distances of -5 km $\leq x_{\mathrm{dep}} \leq 5$ km, where the sonAIR model presents much higher values than the PANAM model. In this case, large differences between the airframe immission models are observed in terms of magnitude and directivity pattern.



(a) Airframe immission.

(b) Engine immission.



(c) Total immission.

Figure 4. Comparison of noise immission contours for the departure procedure in terms of $L_{\mathrm{A,max}}$: absolute levels obtained using the PANAM–based emission model (solid black lines) and the sonAIR–based emission model (dashed black lines); coloured contours expresses the difference between the results obtained by the different noise emission models in terms of $\Delta L_{\mathrm{A,max}}$.

The $\Delta L_{\mathrm{A,max,env}}$ differences computed within $L_{\mathrm{A,max}}$ = 60 dBA envelopes (i.e. area where at least one of the emission models, either based on PANAM and/or sonAIR, predicts $L_{\mathrm{A,max}} \geq 60$ dBA) are statistically summarized in Figure 5. In this analysis, the number of receiver positions (N) on which the $\Delta L_{\mathrm{A,max,env}}$ differences are computed varies according to the analyzed emission model and flight procedure. As a complement, Table 3 provides the mean, median and standard deviation (SD) values obtained from this analysis.

Table 3. Summary of statistical indicators from the $\Delta L_{\mathrm{A,max,env}}$ differences computed within $L_{\mathrm{A,max}}$ = 60 dBA envelopes.

	$\Delta L_{\mathrm{A,max,env,airframe}}$				$\Delta L_{\mathrm{A,max,env,engine}}$				$\Delta L_{\mathrm{A,max,env,total}}$			
Flight procedure	N	**Mean**	**Median**	**SD**	N	**Mean**	**Median**	**SD**	N	**Mean**	**Median**	**SD**
Approach	1736	-3.06	-2.80	3.07	810	1.86	3.30	3.54	2045	-2.50	-1.30	3.19
Departure	918	-8.51	-10.50	4.89	3098	2.10	2.3	1.29	3286	1.38	1.90	1.61

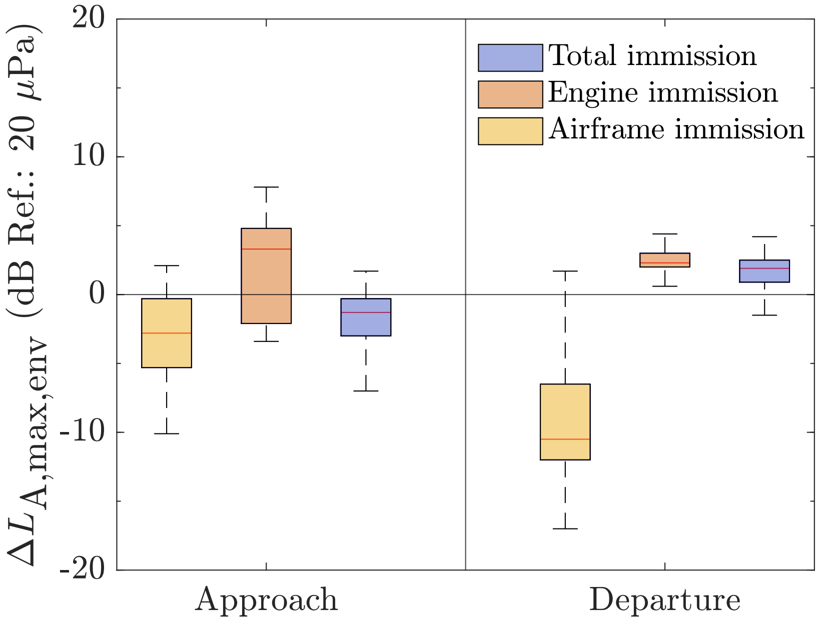


Figure 5. Box–whisker–plots summarizing the $\Delta L_{\mathrm{A,max,env}}$ differences between the noise emission models at all receiver positions within $L_{\mathrm{A,max}}$ = 60 dBA envelopes where at least one of the emission models predicts $L_{\mathrm{A,max}} \geq 60$ dBA.

Figure 5 shows that the emission models have acceptable $\Delta L_{\mathrm{A,max,env}}$ differences for both the departure and the approach procedures. In this case, the mean and SD differences are observed to be $\Delta L_{\mathrm{A,max,env,dep,total}} = 1.38 \pm 1.61$ dB and $\Delta L_{\mathrm{A,max,env,app,total}} = -2.50 \pm 3.19$ dB, for the departure and approach procedures, respectively. For the departure procedure, the engine noise is the dominant sound source and the large mean and SD differences of the $\Delta L_{\mathrm{A,max,env,dep,afm}}$ does not seem to have a significant impact on the $\Delta L_{\mathrm{A,max,env,dep,total}}$. Moreover, the low dispersion of the $\Delta L_{\mathrm{A,max,env,dep,eng}}$ around the median value indicates a good agreement between the engine noise emission models not only in terms of magnitude but also in terms of sound directivity. Thus, the good agreement for the departure procedure can be attributed to the similar performance of the engine noise models. For the approach procedure, a more complex interaction of different dominant noise sources occurs along the flight path, and the good agreement of the overall aircraft noise predictions is attributed to the similar performance of both the airframe and the engine noise models.

4. CONCLUSIONS AND OUTLOOK

In this work, a comparative study between two validated semi–empirical noise emission models based on the PANAM tool and the sonAIR simulation software is conducted. For this purpose, a reduced sonAIR model and a PANAM model representing the noise emissions of an A319 aircraft are considered while the aircraft noise simulations are conducted within the sonAIR simulation environment. The noise immissions on the ground yield by the emission models are compared in terms of $L_{\mathrm{A,max}}$ on a large calculation area. Moreover, not only the total aircraft noise immission is compared, but also the airframe and engine noise immissions separately.

The results indicates that the noise emission models have acceptable $L_{\mathrm{A,max}}$ differences for both the approach and the departure procedures, particularly on regions below the flight path. Concerning the overall aircraft immissions during the departure procedure, the emission models presented an acceptable agreement in terms of absolute noise levels while differences no bigger than 5 dB are observed on the whole calculation area. The good agreement between the overall noise immissions is attributed in this case to the similar performance of the engine emission models. For the approach procedure, the differences between the emission models are observed to vary substantially along the assessment area. Nevertheless, an acceptable agreement of the overall noise immissions is observed for distances between −16 km and the runway threshold. In this case, differences within 1 dB are mainly verified while the maximum difference is not higher than 3 dB. A statistical analysis of the $\Delta L_{\mathrm{A,max,env}}$ differences computed within $L_{\mathrm{A,max}} = 60$ dBA envelopes (i.e. area where at least one of the emission models predicts $L_{\mathrm{A,max}} \geq 60$ dBA), shows that the emission models have mean and SD differences of $L_{\mathrm{A,max,env,dep,total}} = 1.38 \pm 1.61$ dB and $\Delta L_{\mathrm{A,max,env,app,total}} = -2.50 \pm 3.19$ dB for the departure and approach procedures, respectively.

The comparative study presented in this paper provides general insights about the differences between the methodologies employed by PANAM and sonAIR to model the aircraft noise emissions. Future comparative analysis considering other aircraft types or only full models could provide further evidence on the accuracy of the methodologies employed by PANAM and sonAIR, especially if measurement data is available. Based on the findings of this paper, it is expected that a comparison of the sound emission directivities will provide deeper insights about the underlying differences between the models. Moreover, the comparison of noise immission results shall be complemented by considering other relevant noise metrics such as the A–weighted sound exposure level.

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