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Engineering Notes

Tool Development for Low-Noise Aircraft Design

Lothar Bertsch,* Werner Dobrzynski,† and Sébastien Guérin‡
DLR, German Aerospace Center

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I. Introduction

NOISE analysis in the course of conceptual aircraft design enables an early identification of promising low-noise configurations within given technological and economical boundaries. The main objective is not to precisely predict the ground noise levels of a selected aircraft but to enable a comparative noise evaluation of various aircraft designs. At the conceptual design level, only a few key parameters are fixed so that major geometry modifications are still feasible. This flexibility results in significantly varying aircraft design concepts, which can be directly evaluated and compared in a multidisciplinary design process. The most promising configurations are identified out of these different design concepts and can be selected for further investigation with high fidelity methods or wind tunnel tests.

To have noise as an additional constraint in aircraft design, the German Aerospace Center is currently developing a prediction tool named parametric aircraft noise analysis module (PANAM). High fidelity methods such as computational aeroacoustics or time-accurate computational fluid dynamics are ruled out due to their CPU requirements, which are not compatible with a rapid iterative conceptual design process. PANAM makes use of a noise component breakdown; i.e., noise contributions from the major airframe and engine components are calculated separately, and interactions between these components are currently still neglected. Furthermore, noise is predicted with semi-empirical parametric noise source models. Such models capture the major physical effects and correlations yet allow for a fast noise prediction. Parametric formulations enable prediction of the various effects on noise radiation caused by the variations of aircraft configuration and operating conditions throughout simulated flight operations.

Compared with existing noise prediction frameworks, e.g. NASA's aircraft noise prediction program, airframe noise is predicted with the latest source models developed by DLR. Modeled airframe noise sources are wing and control surfaces, trailing and leading-edge devices (slat and flap), spoiler, and landing gear. A source model for flap side-edge noise is currently under development. Furthermore, in addition to common noise evaluation methods, new approaches are implemented in PANAM. The variation of noise levels versus time can be captured and animated. This allows for real-time evaluation of the influence of aircraft operating conditions on noise radiation. Thereby, noise-related effects can be identified and analyzed. The noise-level time histories for selected locations as well as animated noise footprints can be generated.

II. Description of PANAM

The current version of PANAM is applicable to the noise evaluation of conventional aircraft configurations along arbitrary three-dimensional flight trajectories. The effect of engine noise shielding through airframe components is yet to be implemented. The PANAM framework allows for a straightforward integration of additional or updated noise source models reflecting progress in modeling the physics of noise source mechanisms and their parametrical dependencies. The modular setup allows for either self-contained operation or for direct integration in a multidisciplinary design code such as the code preliminary aircraft design and optimization (PRADO [1]) developed at the Technical University of Braunschweig, Germany. The PRADO integration allows for fully automated low noise optimization of aircraft configurations in the preliminary design process. The stand-alone version of PANAM provides a simple graphical user interface for MS Windows.

A. Airframe noise source modeling

Within the last decades, radical engine noise reduction was achieved with the appearance of high bypass ratio engine concepts. For modern aircraft with high bypass ratio engines, airframe noise plays a major role. Therefore, airframe noise source modeling becomes crucial for overall aircraft noise prediction.

Airframe noise levels are simulated with the latest semi-empirical noise source models as developed by DLR [2]. Each airframe source model provides the noise contribution from the corresponding component. Aeroacoustic interaction between the components is neglected. The noise from all components can be summed up to obtain the overall airframe noise signature. The underlying database for these semi-empirical source models originates from aircraft flyover noise measurements and airframe component wind tunnel testing as performed by DLR. This database comprises noise characteristics derived from modern aircraft and their components. The source models are not fully empirical but reflect the major physical effects on noise generation and radiation based on current knowledge from theory and experiment.

B. Engine noise source modeling

Currently, two noise components are taken into account in the engine noise module. These two components are dominant for turbofan engines. The first source is jet noise predicted with the model of Stone et al. [3]. The second source is fan noise and is predicted using Heidmann's model [4]. These two semi-empirical models require thermodynamic, aerodynamic, performance, and geometrical values as input. The thermodynamic aeroengine synthesis is carried out using a one-dimensional performance calculation program. It is an off-design performance simulation code based on a given design point and was developed at the DLR Institute of Propulsion Technology [5]. In [6], the application of the engine noise model to the A319 data has shown that the prediction of jet noise is sufficiently accurate, whereas fan noise is significantly overpredicted. One of the reasons is that the current fan noise model does not account for sound attenuation by the liners mounted in the inlet and the outlet bypass ducts. Other possible reasons are that the CFM56-5A5 fan could be less noisy than the fans investigated by Heidmann and, also, that the

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*Configuration Design, Institute of Aerodynamics and Flow Technology, Lilienthalplatz 7, 38108 Braunschweig, Germany; lothar.bertsch@dlr.de.

†Technical Acoustics, Institute of Aerodynamics and Flow Technology, Lilienthalplatz 7, 38108 Braunschweig, Germany; werner.dobrzynski@dlr.de.

‡Engine Acoustics, Institute of Propulsion Technology, Mueller-Breslau-Strasse 8, 10623 Berlin, Germany; sebastien.guerin@dlr.de.

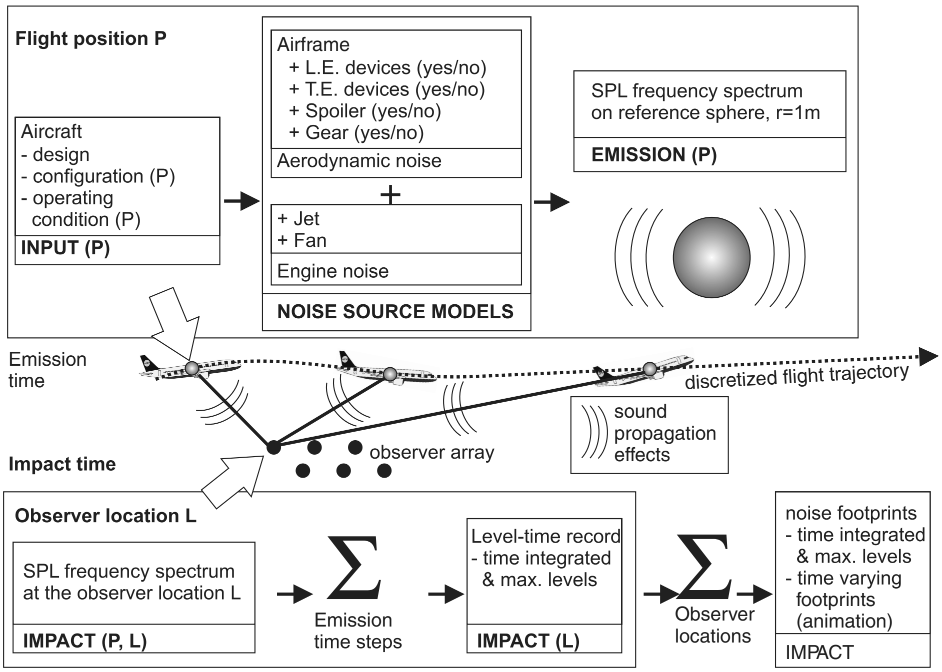
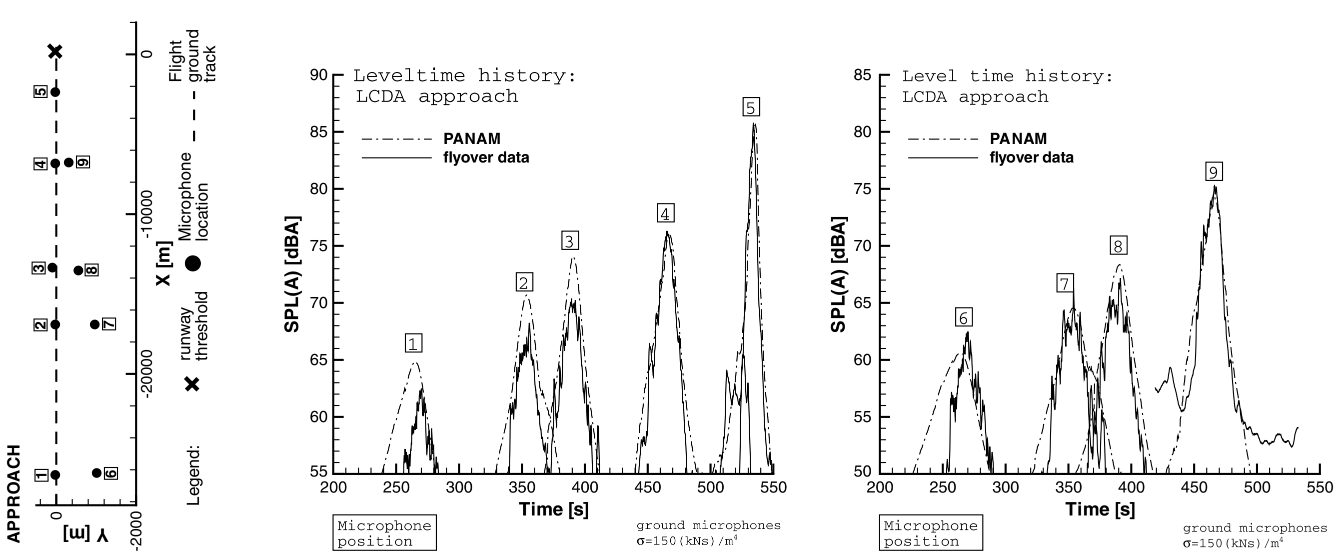


Fig. 1 PANAM structure.

fan noise model does not account for forward flight effects. To overcome these issues, the DLR engine acoustics department is currently developing a new fan noise model [7] for modern and future aeroengines.

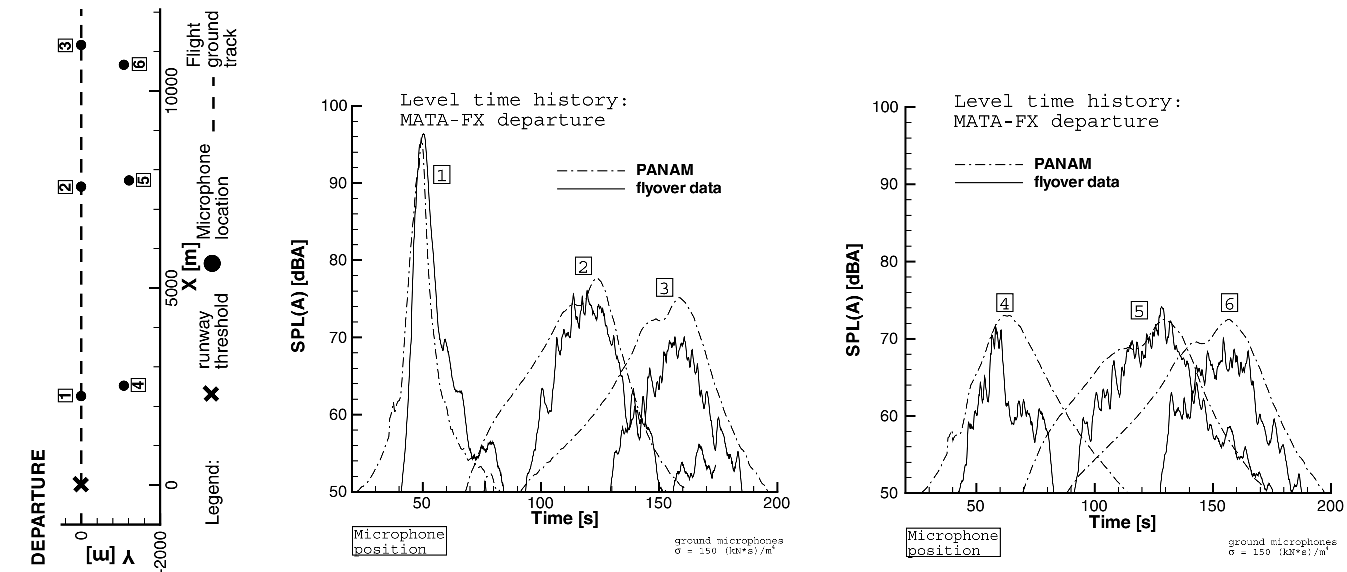
C. Input parameters

PANAM was set up to perform optimization processes based on parameter values provided by the design code PRADO in each iteration. For independent use, such input parameters have to be provided by the user. Required input data for the noise prediction are airframe and engine design parameters, flight trajectory, and observer locations. Required airframe and engine parameters depend on the implemented noise source models. The DLR airframe noise models require about 50 input parameters, whereas engine noise is computed with about 30 input parameters. The parameters describe both the geometry and the configuration/operating condition of the aircraft. Although the number of required parameters seems to be relatively high, the level of complexity of these parameters is well-suited for preliminary aircraft design. Existing preliminary aircraft design codes, such as PRADO [1], provide all of the required input data. The flight path is discretized into single quasi-stationary aircraft positions. For each position the aircraft configuration and operating conditions are provided assuming that all parameters remain constant during this small increment in time. A sufficiently fine discretization of the flight trajectory into the quasi-stationary aircraft positions is crucial for an adequate accuracy of the result. Definition of each aircraft position and observer location in vector notation within an earth-fixed coordinate system allows for the evaluation of arbitrary three-dimensional flight trajectories. Noise impact can be computed for arbitrary observer locations in a horizontal plane. For an array of observers, noise footprints can be vizualized. PANAM can handle



a) Observer locations b) Fight ground track c) Sideline

Fig. 2 Approach level time history: PANAM vs experimental data, continuous descent approach with late gear extension (LCDA).



a) Observer locations b) Fight ground track c) Sideline

Fig. 3 Departure level time history: PANAM vs experimental data, modified Air Transport Association departure with flexible thrust (MATA-FX).

structured as well as unstructured observer arrays to allow for any needed grid adaptation.

D. Noise Prediction

Noise impact at each observer location is computed for each quasi-stationary aircraft position. It is assumed that the received sound amplitude is constant within each transmission time step ($\approx$0.5 s). The transmission time step starts when the observer receives the signal from one aircraft position. This time step lasts until the emitted sound from the consecutive aircraft position has reached the observer location. According to the aircraft configuration and engine operating condition the relevant noise sources are accounted for and the sound level on a reference sphere is computed. To transfer this noise emission on the reference sphere to noise impact at a specific observer location, sound propagation effects have to be considered. PANAM accounts for the effects of geometrical spreading [8], ground attenuation [9], atmospheric absorption [10], and convection effects [8] (convective amplification and frequency Doppler shift) if required.

For each time step the far-field sound pressure level frequency spectrum is computed. The frequency spectrum covers the audible range. Levels are provided in $1/3$-oct. bands together with the corresponding overall sound pressure level (OASPL). Weighting functions for the simulation of human sound perception can also be applied to the spectrum[§]. The maximum overall noise level is defined as *SPLmax*. The time variation is analyzed and integrated to finally obtain the effective perceived noise level. These steps have to be repeated for each one observer location to provide noise contours on the ground. The noise prediction concept of PANAM is shown in Fig. 1.

III. Validation

The code was evaluated based on A319 noise data obtained from a dedicated flyover test campaign [11] performed by DLR in 2006. Approach as well as departure procedures from this test campaign were simulated with PANAM using the recorded flight data. The aircraft geometry was modeled with the design code PRADO, and the engine parameters were provided by DLR's engine department. The OASPL time histories are predicted and compared with the measured flyover noise data at given observer locations.

Noise prediction for one selected approach trajectory is shown in Fig. 2. The predicted levels for microphones in close distance to the aircraft are in good agreement with the measurements. The discrepancy between measured and predicted levels increases with distance between microphone and aircraft. Sound propagation between aircraft and microphone is affected by the actual meteorological conditions, e.g., wind and temperature gradients. With increasing distance between source and observer the sound propagation effects become more dominant. These effects cannot be captured with PANAM's simple approximations for sound propagation effects. This could be the reason that noise impact at distant observer locations is overpredicted. Figure 3 shows the noise level history for a departure trajectory. Again, microphones in close distance to the aircraft show better agreement with the experimental data due to sound propagation effects. Overall, take-off noise levels are slightly overpredicted due to PANAM's current engine noise model.

Noise impact on the ground is furthermore influenced by ambient noise, terrain features, and complex ground properties at the observer location, which also cause some uncertainty in the test data. Since these effects cannot be accounted for, the validation of noise prediction tools through acoustic flyover tests becomes very difficult. Nevertheless, overall aircraft noise can be reasonably well simulated with PANAM.

IV. Application

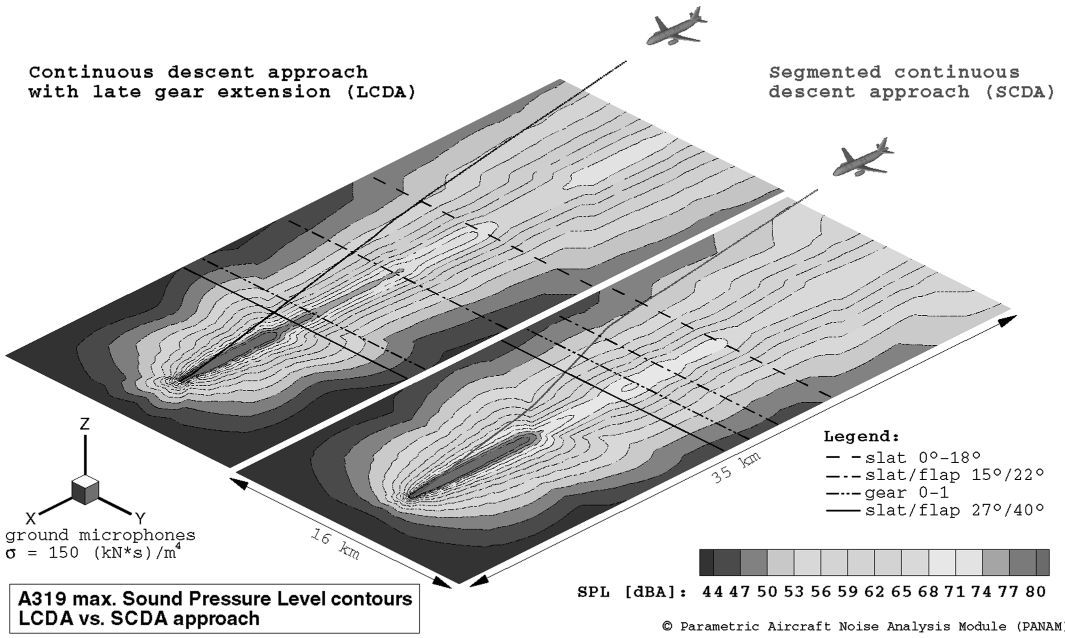
Two selected applications are presented in the following. More applications can be found in the literature [12–14].

A. Real-time noise evaluation

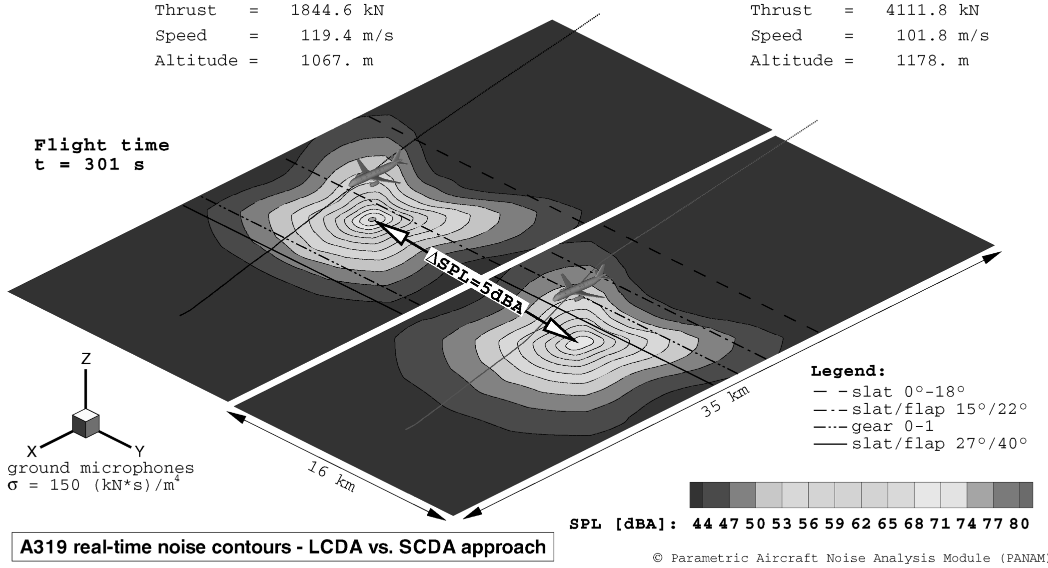
The SPLmax contours for two approach trajectories are shown in Fig. 4a. Neither a time integrated level nor the SPLmax is adequate to capture details of the time varying noise impact on the ground, which is considered important with respect to local noise pollution effects on the ground. A low-noise optimization of both the aircraft design and the flight trajectory is only feasible if all those details are taken into account. To capture these details, it is necessary to have a look at the real-time sound pressure level distribution SPL(t). PANAM can provide level time histories for arbitrary observer locations. This allows for real-time evaluation of aircraft configuration changes and their influence on noise generation. If required, this can be done for each noise source separately.

The real-time contour plots can be animated in time to rapidly identify the noise-relevant effects and the rank order of different

[§]e.g., *A*-weighted, tone correction, etc.



a) Max. SPL



b) Real-time noise contours

Fig. 4 Short-range transport aircraft noise contours: LCDA vs segmented continuous descent approach.

sources involved in noise generation. Real-time SPL contours for one selected time step along the selected trajectories are presented in Fig. 4b. Information on thrust setting, speed, altitude, and aircraft configuration is provided with each time step for further analysis. The influence of the different trajectories on the noise contours can be identified in the animation and then studied in detail.

B. Low-noise design

Finally, PANAM was integrated into PRADO to account for noise aspects in the design of new aircraft. Initial results of a fully automated parameter study with PRADO are presented here. Selected parameters are the leading edge sweep angle φ_{LE} and the wing span b. Obviously, the influence of the geometry variation on the ground noise impact changes along the flight path depending on the current aircraft operating condition. For the investigation of low-noise wing geometries an area of the flight path has to be identified where wing noise is a major aircraft noise component. Such an area was identified approximately 14 km prior touch down. The noise impact in this region is mainly influenced by airframe noise with the engine running at idle. For the low-noise airframe geometry study only aerodynamic noise components are evaluated; i.e., engine noise was neglected. The aircraft passes the selected observer location ($x = -14$ km) with flaps at 15°, slats at 22°, constant true airspeed, and gear still retracted. The predicted SPLmax is then fed back into the design code PRADO and used for initial low-noise sensitivity

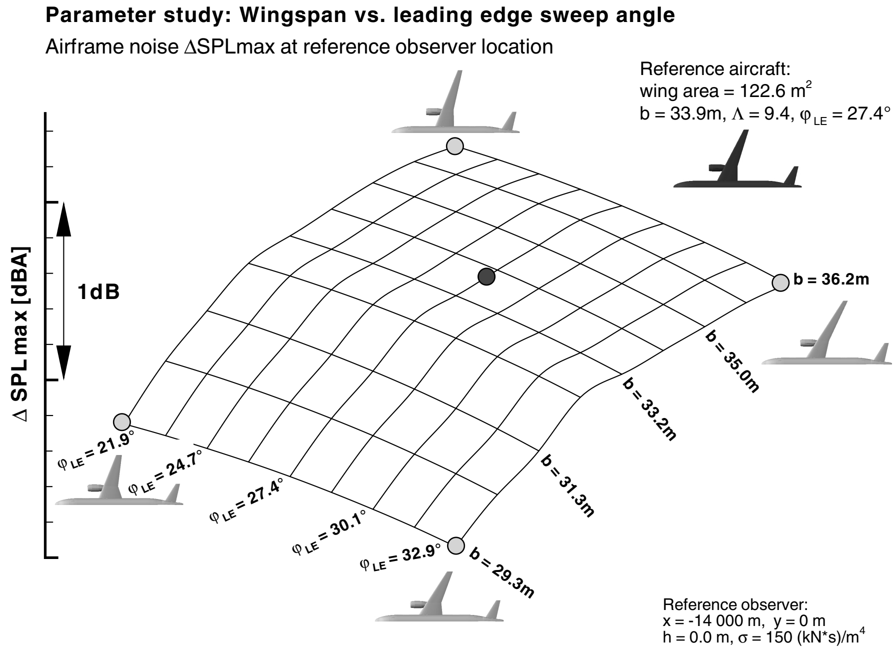


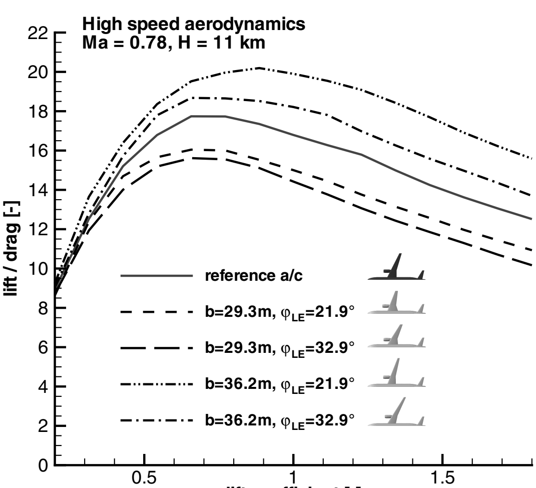
Fig. 5 Influence of parameter variation on airframe ground noise impact: ΔSPLmax at reference observer location.

studies. Figure 5 shows the differences in SPLmax at the reference location caused by the wing design changes. Slat and flap lengths increase with wing span, i.e., causing more noise from the high lift elements. The influence of wing leading edge sweep on noise generation is more dominant since the effective Mach number is determined by this angle. Reduction of the wing leading-edge sweep will increase the flow velocity normal to the leading edge. This will ultimately increase slat and clean airfoil noise.

The impact of the geometry modification on aircraft operation empty weight (OEW), fuel consumption, and cruise aerodynamics is evaluated for the selected reference mission¶. Obviously, geometry modifications (as considered in this example) to reduce airframe noise have considerably negative effects on the aircraft flight performance (see Table 1). A trade-off between achievable aircraft weight, cruise performance, and low-noise impact on the ground is inevitable.

Table 1 Influence of parameter variation on operational empty weight (OEW), fuel consumption, and cruise aerodynamics.

	Span [m]	φ_{LE} [°]	OEW [kg]	Fuel [kg]
Reference	33.9	27.4	41,277	17,173
Design	Span [%]	φ_{LE} [%]	OEW [%]	Fuel [%]
1	−13.569	−20.0	−6.473	+3.505
9	−13.569	+20.0	−6.231	+5.957
73	+6.785	−20.0	+4.724	−3.057
81	+6.785	+20.0	+6.248	−0.000



V. Conclusions

PANAM is presented to demonstrate DLR's low-noise conceptual aircraft design capabilities. The main objective of the code is a comparative noise evaluation of various aircraft designs and not the precise prediction of ground noise levels for a specific aircaft. The program is developed for a rapid analysis of the design, identification of low-noise trends as early as possible, and fully automated integration into an existing aircraft design framework (PRADO).

Semi-empirical, parametric source models are implemented. Modification of the noise source or/and of the operating conditions can be taken into account by these parametric source models. New or updated source models can straightforwardly be implemented into the code. The most common noise metrics are computed. A special feature of PANAM is the ability to capture and visualize time-varying noise contour plots. This provides the user with information that is lost when working with maximum or time-integrated levels only. Overall aircraft noise radiation can reasonably well be simulated. The integration of a new developed acoustic lining model and a DLR ray tracing tool to account for noise shielding effects is expected to improve the prediction quality.

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¶Reference mission: 4815 km range, 13,000 kg payload, 0.78 flight Mach, 12,500 m max. cruise altitude

**German Aerospace Center (DLR), Institute of Flight Systems, Braunschweig [11]

††German Aerospace Center (DLR), Institute of Propulsion Technology, Cologne [5]

‡‡German Aerospace Center (DLR), Institute of Aerodynamics and Flow Technology, Braunschweig [9]

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