MULTIDISCIPLINARY PRELIMINARY AIRCRAFT DESIGN WITH INTEGRATED NOISE ANALYSIS CAPABILITIES

P. Krammer, Hamburg University of Applied Sciences, Aircraft Design and Systems Group, Hamburg, Germany
L. Bertsch, German Aerospace Center, Institute of Aerodynamics and Flow Technology, Braunschweig, Germany
C. Werner-Spatz, Technische Universitaet Braunschweig, Institute of Aircraft Design and Lightweight Structures, Braunschweig, Germany

Abstract

Aircraft noise reduction can be achieved not only by noise reduction at the source but also by modification of parameters in aircraft design and performance. Treating both merely independently from each other does not necessarily lead to the best results. Therefore, a balanced approach is necessary to combine both methodologies for multidisciplinary optimisation. Aircraft noise analysis can be conducted with the Parametric Aircraft Noise Analysis Module (PANAM). PrADO (Preliminary Aircraft Design and Optimisation) provides a framework to analyse state-of-the-art aircraft configurations. A newly derived interface for connecting both programs is presented. It allows for the influences of changes in aircraft design on ground noise impact to be fed back into the multidisciplinary design process. The importance of this approach is emphasised since (1) the focus on optimising noise abatement procedures could lead to a dislocation of the ground noise impact without overall noise reduction and (2) the focus on noise emission reduction at the source could have negative implications on performance, weight and costs of the aircraft. This paper presents first applications of this interface by using examples of aircraft parameter variations. Interactions and tendencies related to noise are demonstrated. A perspective of a procedure for optimising an aircraft for minimum ground noise impact is presented.

1. INTRODUCTION

Over the past years, the reduction of perceived aircraft noise has become a central factor in aircraft design and aircraft operations. By focusing on noise reduction at the source (quieter aircraft), land-use planning, noise abatement procedures, and aircraft operating restrictions, the “noise problem” can be identified and analysed. Bearing all aspects in mind gives rise to the so-called balanced approach to aircraft noise management that has been endorsed by the ICAO Assembly in 2001. Today, aircraft noise can be considered as a major problem in air traffic. To adapt to expected traffic growth in air transport at no environmental cost, stakeholders as well as policy makers expect a quieter and still more efficient global airline fleet. This can already be seen in a decreasing average age of aircraft [1].

The expected low noise level of new aircraft is emphasised by looking at numerous airports that have already reached their noise capacity level despite simultaneous runway extensions and terminal infrastructure. Besides the introduction of the more stringent chapter 4 by the Committee on Aviation Environmental Protection, airports have already introduced a noise surcharge through an individual set of measures according to their specific needs [1].

This emphasises the need for outstanding technologies and research to be conducted in the related field of minimising aircraft noise in combination with other constraints such as fuel burn and green house gases, as addressed by the Advisory Council for Aeronautics Research in Europe.

A balanced approach is therefore a requisite where all constraints are considered equally within a multi-disciplinary conceptual design process. This paper presents such a process with first applications on aircraft parameter variations. Influences on flight trajectories due to variations in engine thrust, wing aspect ratio, and wing reference area are depicted in respective figures. In addition, noise contour areas of constant EPNL during approach and departure have been evaluated.

2. TOOLS AND INTERFACES

The Parametric Noise Analysis Module (PANAM) is a tool for aircraft noise prediction. The program requires aircraft geometric parameters, engine characteristics, and flight trajectories as an input. The Preliminary Aircraft Design and Optimisation program (PrADO), provides the means to analyse an aircraft design (parameter, sensitivity, and feasibility studies) and gives access to the required input data for PANAM. With the newly derived interface between both frameworks, execution of PANAM will deliver noise analysis results that can be transferred back to PrADO, allowing noise to become a design constraint or an objective function in a multidisciplinary aircraft design process.

2.1. Multidisciplinary Preliminary Aircraft Design Process

PrADO is an in-house development of the Institute of Aircraft Design and Lightweight Structures [2]. An overview of the design process structure can be found in Fig. 1. PrADO is a multidisciplinary, integrated, iterative design process. At its core is a set of so-called design modules, each of which performs a specific task in the design process. For example, some modules are responsible for creating the geometry description of individual aircraft components. Other modules are responsible for determining the required engine thrust, the aircraft range and fuel consumption, the aircraft structural weight, etc.

Since the modules are task oriented, different methods for a certain task can coexist in a given module, giving the user the opportunity to choose the method to be used for each design problem, which makes it possible to individually select the methodology applied for each design discipline, adapting the balance between computational complexity and result accuracy according to the needs and priorities of the aircraft design being studied. For example, one module with special relevance to this paper is module 28, reserved for predicting aircraft noise.

A method formerly available provides a noise propagation analysis, but requires the user to input a parametric noise source model for the aircraft being studied [3]. With the newly derived interface, a coupling of PrADO and PANAM has been realised. Within module 28, the user has now the option to select between noise analysis conducted with the formerly available method and noise analysis conducted with PANAM.

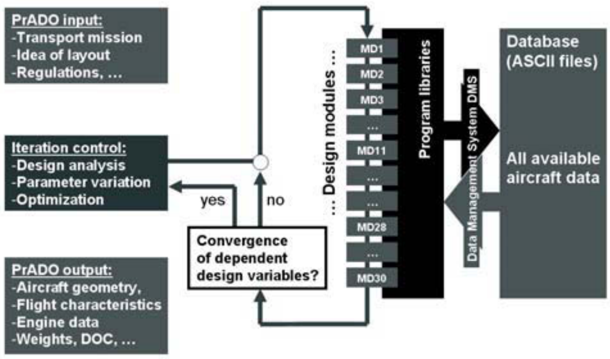

FIG 1. Overview of the preliminary design process

Apart from the design modules, PrADO features a set of programs that control the iteration of the design process, allowing either an iterative analysis of a single design, an automated parameter variation over one or more user-chosen parameters, or a design optimisation with a user-chosen target function and user-chosen design variables. Virtually any parameter available in the database can be selected as a variation parameter, a design variable or a target function. When selecting a target function, the user may also select the optimisation method (several gradient-based optimisation algorithms are available) as well as whether the target function is to be maximised or minimised.

2.2. PANAM

The German Aerospace Center, DLR, has developed the Parametric Aircraft Noise Analysis Module (PANAM) to evaluate aircraft noise early in the design process of new aircraft configurations [4]. The modular setup of PANAM allows for direct integration into a preliminary aircraft design code. Additionally, the program offers stand-alone operation. The current code version features ground noise impact evaluation of conventional aircraft configurations along arbitrary three dimensional flight trajectories. Once implemented into the PrADO design process, PANAM's parametric noise source models will ultimately enable a low-noise aircraft design process [5].

Input data requirement for noise prediction with PANAM is well suitable for preliminary aircraft design. Noise prediction within a design process chain is only feasible if computational requirements are low. Therefore high fidelity methods such as Computational Aeroacoustics are ruled out. Instead each major noise component is approximated with individual semi-empirical source models and source interaction is neglected. Noise components can be simulated individually to rank-order the noise sources. The implemented models reflect the major physical effects on noise generation and radiation based on current knowledge from theory and experiment.

Airframe noise is simulated with DLR in-house noise source models. The underlying database for those models comes from component wind tunnel testing and a dedicated flyover noise campaign in 2006 [6]. The required input parameters are aircraft design parameters and operating condition such as flight speed or flap/slat setting. Engine noise source models are adapted from models found in the literature [7]. Fan noise is predicted with Heidmann's model [8] and jet noise is evaluated with the model of Stone, Groesbeck, and Zola [9]. The engine models require values of thermodynamic, aerodynamic, performance, and engine geometry in input. The implemented airframe and engine noise source models are currently being updated to account for noise shielding effects of advanced engine installation and engine fan lining modifications. New or updated source models can easily be implemented into the code.

Noise emission can be monitored along simulated flight maneuvers due to parametrical noise source modelling. The source models account for modifications to the aircraft geometry as well as for in-flight changes of the aircraft and engine operating conditions. Common noise metrics such as SPL, EPNL, and FAR noise stage classification are evaluated. Noise impact prediction is possible for single observer locations as well as for arbitrary observer arrays to compute contour plots. Optionally, level-time-histories can be captured to enable real-time noise analysis.

2.3. Interface

The interface derived for interconnecting PANAM with PrADO is named according to its designation: Input – Output PANAM (IOPANAM). It has been successfully integrated into the existing module for aircraft noise analyses (module 28) of the PrADO environment.

IOPANAM is responsible for data processing. PANAM requires about 50 input parameters for airframe noise and about 30 for engine noise. Those parameters are gathered from PrADO's databases or, if not readily available, processed by using PrADOs modules and subroutines. The following input data in the form of ASCII input files are requested for noise analysis:

- aircraft geometric parameters such as wing and landing gear dimensions
- engine characteristics in the form of an engine map
- a discretised flight trajectory composed of quasi-stationary aircraft positions that specifies both the aircraft configuration (e.g. gear and flaps extended) and the operating condition (e.g. climb with specified climb speed and thrust setting)
- observer (microphone) locations (can be placed in any order: plane arrays, structured or unstructured that can be used to visualise noise footprints) – not further described in this paper

2.3.1. Aircraft Geometry and Configuration

The current version of PANAM is capable of analysing conventional aircraft configurations. Aircraft wing parameters are among others: wing loading for take-off and landing, wing span, wing sweep, dihedral angle, length of flaps, and slats, etc. For horizontal- and vertical tailplanes span, trailing edge sweep, dihedral angle, and mean aerodynamic chord are required input data. Parameters of flap, slat, and gear position are provided through the trajectory file. As long as no flap (leading- or trailing edge) is extended, the airfoil wing is considered to be in a clean configuration.

The geometric slat and flap model is described by a relative spanwise length and an averaged depth. In the current version of PANAM, a simplification is made by approximating the wing trailing edge over a straight line. A kink would normally subdivide the trailing edge flaps into two pieces with separate tailing edge sweeps.

2.3.2. Engine Map and Characteristics

Each flight point along a specified trajectory is described through aircraft configuration and operating condition. Besides airspeed, Euler angles, and aerodynamic coefficients for the latter, also thrust required is stored for each individual flight point. This information of thrust required has to be associated with an engine condition to gather necessary engine parameters for PANAM. In the current version of IOPANAM such data is calculated and stored in advance in the form of an engine map. Upon request, PANAM accesses relevant engine data within the engine map through parameters (Mach number, altitude, and thrust setting) that are given for the considered flight point along the trajectory.

For predicting fan noise, engine mass flows, fan total temperature rise, and fan rotor speed are crucial. Parameters with a strong influence on jet noise are temperatures, velocities, and cross sections of the fully expanded primary and secondary jet. Parameters that are also essential but do not change with flight condition are rotor-tip relative inlet Mach number at the fan design point, number of rotor blades and outlet guide vanes, rotor-stator spacing, and hub-to-tip ratio, etc. for predicting fan noise.

Fan blade tip speed is a parameter for fan noise prediction with a strong influence. PrADO comprises different implemented turbine engine cycle analysis methods from which thermodynamic parameters are available. By treating the fan as thermodynamically equal as a compressor, it can be characterised by its pressure ratio, efficiency and technical work *w*. Requesting those engine parameters out of PrADOs engine cycle analysis makes it possible to apply the Euler turbine equation.

$$w_{N,fan} = u_{13} c_{13u} - u_2 c_{2u} \tag{1}$$

Absolute velocity *c*, relative velocity *v*, and the rotor speed *u* are connected through the Galilean transformation (equation 2) and are applied on a cylindrical cut of a fan blade as depicted in figure 2.

$$\vec{c} = \vec{u} + \vec{v} \tag{2}$$

Absolute velocity *c* can be further broken down into a radial and an axial velocity component (c_u, c_{ax}). c_u indicates a swirl and c_{ax} is a measure of flow rate. Commercial turbofan engines are usually not equipped with inlet guide vanes. Therefore, the flowfield entering is swirl-free and section two can be described by a pure axial velocity ($c_2 = c_{2ax}$) parallel to the rotational *z*-axis. At section 13 a swirl is already imparted into the air flow, specifying c_{13u}. The exit flow angle ζ is assumed to be identical with the fan blade trailing edge angle. Exit flow angle ζ is therefore a function of the cylindrical cut radius of the fan r_{fan}, and prevailing flow conditions around the fan blade e.g. flow seperation on the trailing edge. The ratio of circumferential and axial velocity can be found by:

$$\tan \varsigma = \frac{u - c_{13u}}{c_{13ax}} \tag{3}$$

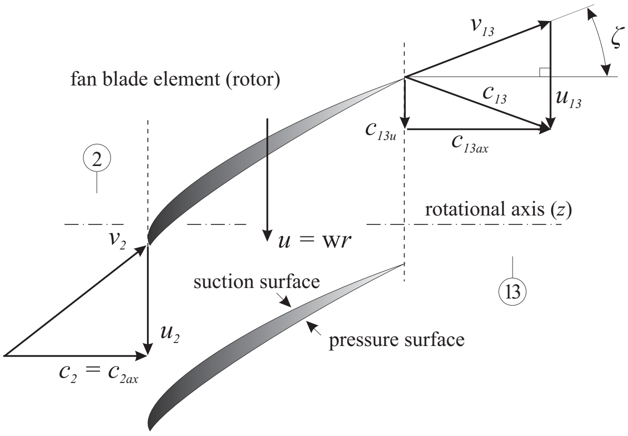

FIG 2. Cylindrical cut of a fan blade with velocity triangles

With above stated equations circumferential velocity *u*, can be determined. After passing the fan stator (section 19), the fluid flow is ideally again almost swirl-free. The absolute velocity at section 19 is therefore aligned with the rotational axis and is additionally a parameter out of PrADOs engine cycle analysis. Assuming that the magnitude of the absolute velocity vector at section 19 is identical with that at section 13, c_{13} can be found out of c_{19}.

The derived circumferential velocity is only valid at one specific point along the fan radius. With an increasing distance to the fan rotational axis the exit flow angle ζ decreases and vice versa. Fan blade geometry, and therefore ζ, is often not known especially when dealing with new engine designs. Maximum rotational shaft speed is often stated in FAA type certificate data sheets of engines. This value has been associated with the static thrust of the engine. The exit flow angle ζ is calculated during engine design at a cylindrical cut in the middle of the fan blade and left constant for all off-design conditions. Although this assumption is very rough (ζ changes permanently due to changes in the flow condition around the fan blade), the obtained results are realistic, as can be seen in figure 3, which shows fan rotational speed N1 over engine thrust at sea level.

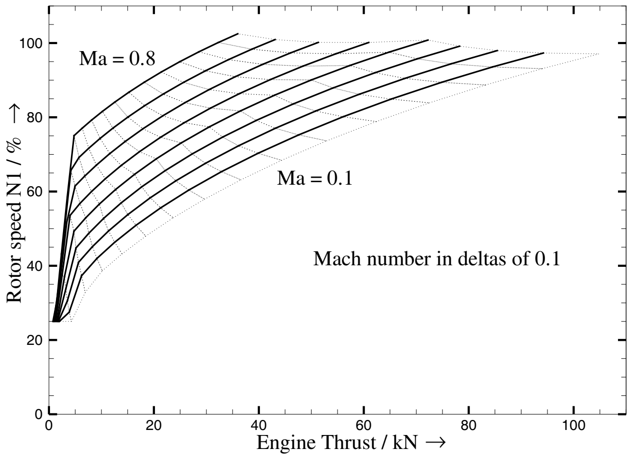

FIG 3. Fan rotational speed N1 vs. engine thrust and Mach number at sea level

2.3.3. Segmented Trajectories

Flight trajectories are discretised into quasi-stationary flight positions. Uniform motion is implied for any point along the trajectory. In principal, flight trajectories can be characterised and split into segments with constant parameters. Each segment is defined with end values that have to be reached (e.g. speed, altitude, etc.) and an aircraft configuration (flap and slat setting, landing gear position, aircraft and fuel masses). Airspeeds are entered by the user as Indicated Air Speeds (IAS), which are then transferred into true air speeds for calculation. Parameters at the beginning of the segment are identical to the end values of the segment before. The delta in flight speed or altitude is used to calculate e.g. necessary acceleration or climb angle. The number of flight positions into which each segment is broken down is parametrically controlled. This allows for direct influence on required computational time with PANAM since the aircraft is considered in every discretised flight point. However, to accurately simulate the continuous noise emission along the flight path the time steps between the flight positions have to stay below a specified threshold (usually: 1 s).

For all departure trajectories, a take-off until reaching the obstacle height is simulated in advance. After this point the user defined climb segments become applicable. For approach trajectories, the aircraft condition at the beginning of the approach has to be defined (e.g. 7000 ft altitude with 260 kts IAS for the reference aircraft). After this point the user defined approach segments are flown until the aircraft reaches an altitude of 2000 ft with an airspeed that equals 1.25 times the stall speed for landing. If the end condition of the aircraft after the last user defined segment does not comply with this final descent configuration, so called interception segments are flown (e.g. decelerating with constant altitude followed by a descent segment with constant speed) to reach those specified values. As a result, the final descent with a three degree glide slope can be initiated followed by the normal landing procedure segments in the following order: flare-out, derotating, and decelerating until the aircraft comes to rest on the virtual runway.

To make sure the aircraft is able to maintain the desired flight track or operating condition, thrust available, and thrust required have to be considered. As each flight point is viewed as stationary, the equilibrium of forces must be fulfilled, which leads to equation 4[1] for evaluating climb angle γ:

$$\sin\gamma = \frac{\cos(\alpha+\sigma)}{mg}\left(T_A - T_R\right) \tag{4}$$

The angle of attack is obtained from the equilibrium of momentum (aircraft in trimmed condition). T_A must not be lower than T_R, otherwise climb angle or climb speed are set too high or the aircraft descends. With T_A greater than T_R, the airplane is accelerating. With T_A equally T_R, a steady climbing flight with constant flight speed is performed. The desired airspeed is associated with only one specific rate of climb or sink rate respectively that is additionally dependent on the aircraft altitude. With all forces determined, load factors, accelerations, velocities, and time increments can be computed. The aircraft is then reconsidered in the subsequent steady flight position.

Basically, all the flight segments can be categorised into segments with a user defined thrust setting and segments where thrust setting is adjusted. Therefore, different parameters than T_A and T_R have to be observed. For a descent with a desired end speed other than the airspeed at the beginning of the segment, descent angle has to be adjusted. To get control over such a flight simulation, the descent is simulated with less sampling points in advance. If the end speed does not meet the user defined speed the descent angle is adjusted according to the bisection method in mathematics. For other descent segments (such as a horizontal deceleration segment) the required deceleration is used as a parameter to comply with (acceleration respectively). In the current version of IOPANAM, speed brakes or spoilers are not considered during approach. A future improvement of the flight simulation routines is therefore necessary

With these segments of “auto throttle” in mind, flight trajectories with fixed flight points can be defined. This allows for comparison between aircraft with different flight

---

[1] α = angle of attack; σ = thrust vector inclination

mechanical characteristics. The flight path can be kept the same whereas the thrust may be different between the considered aircraft.

3. RESULTS OF PARAMETER VARIATIONS

The reference aircraft (A/C 0), for all parameter studies conducted, is a 150 passenger, twin engine subsonic transport aircraft with a design range of about 4800 km at a cruise speed of about Mach 0.78. It is powered by two turbofan engines with 98 kN static thrust. A design analysis in PrADO yields a converged maximum take-off mass of 65.5 tons, an operating empty mass of 36.7 tons, and a fuel mass of about 15.7 tons for the design mission (table 1) with a wing reference area of 122.4 m² and a wing aspect ratio of about 9.4. Ground resistivity to air has been set for all derived noise plots to σ = 150 kN s m^{-4}.

3.1. Noise Analysis at one Reference Point

Initial results of low-noise aircraft geometry studies with PrADO were presented in 2008 [4]. Wing geometry was modified to identify its impact on ground noise pollution. Reference flight path and flight speed have been left constant for each new design. However, due to wing modification, aircraft performance characteristics change. This requires individual thrust settings during flight operation hence different engine noise emissions. Fully automated engine operation analysis was not available during the 2008 study which was therefore limited to airframe noise prediction only.

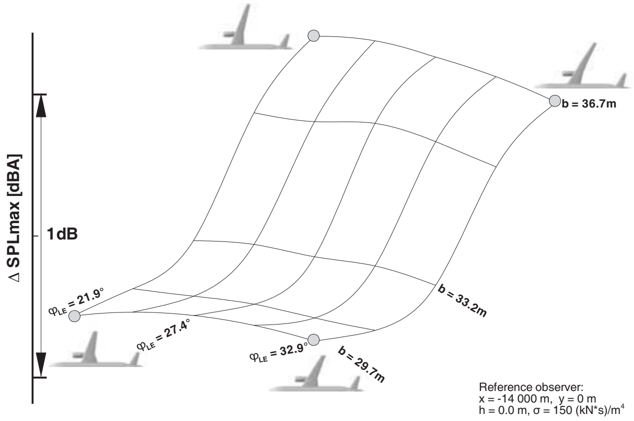

FIG 4. Parameter study: wingspan v. leading edge sweep angle; ΔSPLmax at reference point

With the help of IOPANAM, the aforementioned restrictions can be avoided. The influence of wing leading edge sweep angle and wing span on ground noise impact is evaluated. Results for a Low-Drag-Low-Power approach (LDLP) procedure are shown in figure 4. The maximum SPLs at a reference observer location are predicted for each aircraft along a predefined flight path. Thrust setting and airspeed are adjusted accordingly. With the engine almost at idle, airframe noise remains predominant at the reference observer. Results show similar characteristics compared to the first parameter study in 2008 (see [4], figure 19). A trade-off between good cruise aerodynamics and low-noise characteristics might therefore become necessary.

3.2. Noise Analysis of Noise Contour Areas

For the following noise analysis the ICAO Procedure A at Take-Off / Go-Around thrust setting (ICAO-TOGA) has been selected for all departures and the Advanced Continuous Descent Approach (ACDA) for all approaches.

Design studies have been performed to optimise take-off for low noise. Parameters that have a direct influence on the initial climb angle are excess thrust, airspeed, and aerodynamic drag. Therefore static thrust has been increased besides varying either wing aspect ratio or wing reference area to gain an indirect influence on airspeed and aerodynamic drag. Consequences of performed modifications during the approach are shown. To provide comparability of different aircraft designs with different engine static thrust during approach, the flight path has been fixed for the ACDA where engine thrust is to be adjusted accordingly. This will result in different engine settings and airspeeds along each individual flight point.

By increasing the static thrust of the engine, engine design-point calculation and sizing within PrADO yields different fan diameters. However, rotor-tip relative Mach number at fan design point has been set to that of the reference engine and left constant for all engine variations. This assumption became necessary due to the lack of specific engine data. The consequences of ground noise impact due to engine sizing could therefore be lower as plotted in respective figures. In contrast, one single turbofan engine model can be ordered with different static thrusts from the manufacturer (up to 50 % for the CFM56-5B) while the fan diameter remains constant.

Design Constraints (DC) have been plotted to provide further information for the general understanding of the design variations: take-off field length[2] (DC1 ≤ 3200 m), tank volume (DC3 according to the design range), approach speed (DC12 ≤ 80 m/s). Maximum landing field length (≤ 3200 m) and maximum aircraft altitude of about 12.5 km are not crucial for the design variations.

Noise contour areas of 90 EPNdB during departure and 75 EPNdB during approach were calculated for each design variation[3]. Each aircraft features different characteristics for approach and departure. The design variation for the lowest ground noise impact during departure has been selected according to the results in noise contour area plots. This aircraft design is than compared with the reference aircraft in terms of flight trajectory characteristics and noise contour plots.

3.2.1. Excess Thrust v. Wing Aspect Ratio

Results of the parameter variation of excess static thrust versus wing aspect ratio are depicted in figure 6. Here, wing reference area has been left constant. DC3 is met by all design variations.

The results of a parameter variation make it possible to

---

[2] = the greater of balanced field length and take-off distance.

[3] A total of 25 A/C designs have been calculated to gather noise contour area plots (see scatter in figure 7 and 8)

quickly obtain an overview of the design space being considered. The upper portion of figure 6 allows an immediate identification of optimum aircraft designs for low noise. Additionally, the inclusion of the design constraints identifies designs that are feasible. What can be seen is that minimising ground noise impact for approach would lead to a different design than minimising it for departure. What can also be seen is that the design for optimum noise may not fulfil all constraints. In order to identify the best overall aircraft design, of course other aircraft parameters (mass, fuel consumption, DOC) have to be considered as well, which could also be done in figures similar to the upper portion of figure 6. Due to limitations in paper size, however, characteristic masses, operating costs, and cruise L/D ratios for selected designs at the corners of the design space are summarised in table 1. It becomes apparent that, since A/C 0 can be considered as a design optimised for low mass and economical operation, any design changes for the sake of low noise will inevitably lead to higher masses and/or higher operating cost.

In order to illustrate the capabilities of IOPANAM, the noise analysis results for the aircraft optimised for departure noise (A/C 4 with the highest excess static thrust and wing aspect ratio) are to be discussed, even if this aircraft does not satisfy all design constraints. In comparison with the reference, A/C 4 features a higher climb angle along with a higher True Air Speed (TAS) during take-off. This has a positive influence on the ground noise impact. The noise contour area of 90 EPNdB is decreased by 30 %.

In contrast, A/C 4 needs, due to its higher wing aspect ratio and therefore good aerodynamic quality, a noticeable increase in airspeed during approach (additionally to be noticed in DC12). This is because the simulation segment does not include the option of automated speed brake or spoiler setting (s. o.). Engine thrust setting (compared to take-off) is low and therefore airframe noise becomes significant. Additionally, the aircraft is in landing configuration (C3/4) with flaps, slats, and gear deployed. Sound pressure levels of the clean aircraft are as much as 10 dB below sound pressure levels of the aircraft with deployed high lift devices and landing gear [6]. Clean airframe noise and noise that radiates from high-lift devices follow a v^5 power law[4]. This explains why the ground noise impact of A/C 4 is significantly higher compared with that of the reference aircraft (see noise contour area of 75 EPNdB).

To gather a better generic understanding why A/C 1 has higher contour areas than A/C 0, the departure trajectory (*y* coordinate v. *x* coordinate only, and in gray colour) has additionally been plotted in figure 6. It can be seen that A/C 1 does not meet the climb angle of the reference aircraft. Although the wing weight of A/C 1 is almost 60 % lower than that of A/C 0, maximum take of weight increases by 8 % (table 1). This is due to an increase of required fuel mass for the design mission because of poor aerodynamic quality (decrease in lift coefficient during cruise and lift-to-drag ratio). The higher A/C weight and the poor aerodynamic quality are a restraint of the maximum climb angle.

3.2.2. Excess Thrust v. Wing Reference Area

Results of the parameter variation of excess static thrust versus wing reference area are depicted in figure 7. As discussed above, designs for optimum noise can be immediately identified and do not always satisfy all constraints. By decreasing the wing reference area, DC3 and the required design range cannot be met anymore. Again, minimising ground noise impact for approach would lead to a different design than minimising it for departure. Masses, DOC and L/D ratios for selected corner points are given in table 1.

In this case, the aircraft optimised for the departure would be A/C 2 with the highest excess static thrust and the lowest wing reference area. In comparison with the reference, A/C 2 features a higher lift-off speed (DC1 cannot be met anymore) that is reached on a longer distance on the runway. Because of this initial higher airspeed the aircraft climbs at maximum climb angle at a higher airspeed. Maximum climb angle is increased due to the excess static thrust. The greater airspeed along with an increased maximum climb angle exert a positive influence on the ground noise impact (noise contour area of 90 EPNdB is decreased by 40 %).

For the approach however, aforementioned effects become unfavourable. The approach speed must be increased which has a significant negative influence on the ground noise impact (v^5 power law and engine almost at idle). The noise contour area of about 75 EPNdB is increased by as much as 50 %.

For a better understanding, the departure flight path of A/C 4 has also been plotted in figure 7. A/C 4 features nearly the same maximum climb angle but due to increased wing reference area, lift-off speed is reached during take-off roll earlier and at a significant lower relative TAS. Therefore, A/C 4 climbs at a lower airspeed and remains thus longer above the observer on the ground. This explains why A/C 4 exhibits a higher ground noise impact compared to A/C 2.

4. CONCLUSIONS

The parameter variations conducted in chapter 3 illustrate the capabilities of the enhanced aircraft analysis process. Design changes for the optimisation of noise would result in aircraft designs that do not satisfy all constraints and are not very favourable in context with other criteria such as Direct Operating Costs (DOC) and total fuel consumption for the reference mission as depicted in table 1. The main purpose of those parameter variations is to gain and to present a first overview how noise contour areas are affected by changes in aircraft design. For a better principal understanding, only two parameters have been varied at once in figures 6 and 7.

According to the obtained results, it can be seen that in principle an increase in aircraft speed is favourable for departures where engine noise is predominant. It becomes

---

[4] This means that the mean-square sound pressure is proportional to the fifth power of airspeed.

important to move the noise source away from the ground as quickly as possible, thus preferring designs with increased static thrust and increased aerodynamic efficiency. In contrast, for approaches, where the engine is almost at idle, airframe noise becomes predominant and an increase in aircraft speed exerts a negative influence on ground noise impact.

The increase in static thrust is responsible for an increased maximum climb angle. Variations in wing aspect ratio and wing reference area are basically responsible for different lift-off speeds, which are then additionally decisive for the first climb segment.

Although the approach trajectory has been selected with a constant flight path the following could basically be stated for approach trajectories out of IOPANAM: considering all engines at idle and A/C 3 with a higher wing aspect ratio, the reference aircraft (A/C 0) would have a reduced ground noise impact on an ACDA or LDLP with constant thrust. This is because the aircraft with better aerodynamics would (1) take longer to decelerate and (2) exhibits a lower sink rate which would mean that the aircraft approaches with lower altitudes and thus with lower distance to the observer. This consideration, however, does not include the possibility to decelerate the aircraft by means of deploying speed brakes or spoilers during the approach. The flight path of both aircraft could then be kept nearly identical. Deployed speed brakes or slats, however, have a negative influence on the airframe noise of the aircraft, which could finally become noticeable in ground noise impact.

The obtained results provide a first overview and are only valid for the selected approach and departure procedures. Other characteristics than the above exemplified ones could become visible and moreover maybe predominant on different trajectories such as selecting a climb with maximum climb speed instead of a climb with maximum climb angle as parameter. Additionally, it has to be kept in mind that the noise reducing effect of a higher static thrust might be lowered by considering the change in rotor-tip relative Mach number at fan design point.

5. NOISE AS A DESIGN PARAMETER – A PERSPECTIVE

With the obtained interface IOPANAM, Multidisciplinary Design Optimisation (MDO) with PrADO now allows design parameters such as noise to be considered either as an objective function that is to be minimised and/or a design constraint that needs to be met. This chapter describes the principal structure of such aircraft design procedures that are intended for future applications.

5.1. General Considerations

For noise analysis and the resulting design parameter, different noise metrics (EPNL, SPL(A)) can be applied. Single noise levels may be sufficient when focusing on aircraft optimisation for ICAO noise certification purposes. To demonstrate changes in ground noise impact, it is sufficient to use maximum levels (max.SPL(A)) because they respond more significantly to changes in A/C configuration and condition. In contrast, time integrated levels (EPNL) consider the duration of a noise related event, but smear changes and discontinuities in the resulting sound pressure levels. Differences in aircraft design produce therefore only changes of small amplitude on an EPNL scale, reducing their influence on a MDO process. The response in EPNL might therefore not be sensitive enough. However, this effect can be reduced by working with noise contours. A change of about 5 dB of noise radiating from the source causes a doubling (or halving) of the ground area enclosed by a given noise contour of constant level [10, p. 245]. In contrast, this sensitivity could produce wrong results on contour areas when dealing with less accurate input noise data. This is the reason why noise footprints have not been readily used for aircraft noise certification [10].

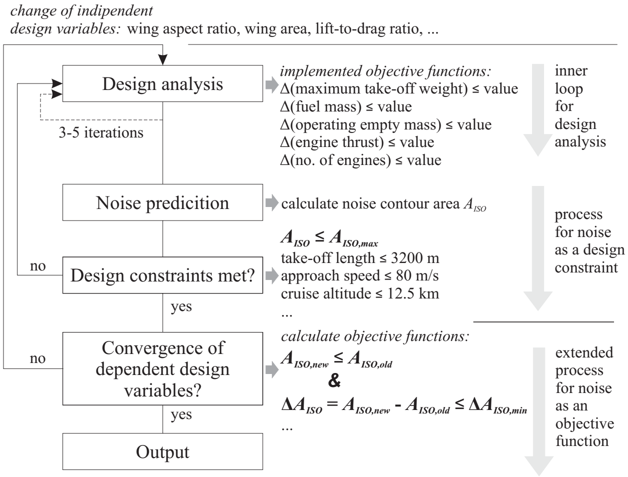

FIG 5. Procedures for optimising aircraft for minimum noise (note that this process has been applied until “noise prediction” for parameter variation results as presented in chapter 3)

EPNL contour lines that are cut at the edge of the observer/microphone mesh are also not exactly accurate to be considered for evaluation. This is because of events beyond the observer mesh that are not recorded or taken into account. By considering contour lines at a higher EPNL the analysed area becomes more concentrated. To catch all minor changes in a high-valued EPNL noise contour, a higher resolution of the microphone array, especially along the flight track, becomes necessary.

Figure 5 depicts the process for considering noise as a parameter in a multidisciplinary design optimisation framework. According to the design philosophy in PrADO (figure 1), the most important structural aircraft masses (max. take-off, fuel, and operating empty mass) must show convergence before the design analysis is finished. By adding noise only as a design constraint the overall process ends after all design constraints are met. The ground area A_{ISO} enclosed by a given noise contour in EPNdB of a constant EPNL is computed after the design analysis. If the area enclosed is lower than a predefined area, the design constraint is met and the design loop is exited if all other possible design constraints are met as well. By running an optimisation (not presented in this paper), an objective function is calculated where, in this case, the noise contour area of selected constant EPNL is to be minimised. The process ends if convergence of dependent design variables occurs i.e. if the difference in noise contour areas is lower than a predefined value. If this is not the case, all independent design variables are varied and the whole process is started over again.

5.2. Optimising Aircraft for Minimum Noise

Before an optimisation process with PrADO for minimising the ground noise impact is initiated, many different aspects have to be considered in advance. The influences on varied aircraft design parameters cannot be directly seen in resulting noise contour areas. This is due to the changes in flight mechanical parameters and more importantly due to the selected and defined flight trajectory. To obtain good results, each aircraft design must be analysed for different approaches and departures. The approach and the departure with the lowest ground noise impact may be considered for a comparison with other aircraft designs. Another influence on the optimisation process is exerted by the EPNL that has to be selected in advance for calculating the noise contour area, which is than used to evaluate all the aircraft designs. Thus, many different possibilities and aspects have to be considered for an optimisation process to obtain good results. This complexity of how effects are interrelating with each other, has been the reason to conduct first a thorough parameter variation to (1) get an idea how the process works and (2) to better understand the interrelations of resulting ground noise impacts.

6. SUMMARY

An interface which interconnects an aircraft design and a noise prediction tool is presented. One of its main tasks is to provide the necessary input for noise analysis, extending data available from the design process through additional flight simulation and engine cycle analysis. Fan rotor speed is approximated by applying the Euler turbine equation. By introducing segmented trajectories, definition and calculation of approach and departure procedures becomes feasible and user friendly due to low input requirements. With the help of the presented interface it is now possible to investigate interactions of noise reduction at the source, modification of aircraft design parameters, and aircraft performance at the same time. For MDO with PrADO, the evaluation of differences in noise contour areas can be used as a parameter for sensitivity studies. The response in noise contour areas of selected aircraft parameter variations has been demonstrated. Thus, tendencies can be identified and influences of perceived noise on the overall aircraft design evaluated. The prerequisites for an optimisation process with PrADO are provided. As a conclusion, a balanced approach towards aircraft noise reduction can now be applied.

7. REFERENCES

[1] Deutsches Zentrum für Luft- und Raumfahrt: Annual Analyses of the European Air Transport Market – Annual Report 2007. Köln : DLR, 2008

[2] Heinze, W., “Ein Beitrag zur quantitativen Analyse der technischen und wirtschaftlichen Auslegungsgrenzen verschiedener Flugzeugkonzepte für den Transport großer Nutzlasten”. Technische Universitaet Braunschweig, Germany : 1994, ZLR Report 94-01

[3] Werner-Westphal, C., Heinze, W., Horst, P., “Structural Sizing for an Unconventional, Environment-Friendly Aircraft Configuration within Integrated Conceptual Design”. Aerospace Science and Technology, Volume 12, 2008, Pages 184-194

[4] Bertsch, L., Dobrzynski, W., Guérin, S., “Tool development for Low-Noise Aircraft Design”. AIAA/CEAS Aeroacoustics Conference 2008, AIAA-2008-2995

[5] Krammer, P., “Integration of a Noise Analysis Module into a Multidisciplinary Aircraft Design Process”. Hamburg University of Applied Sciences, Dept. of Automotive and Aeronautical Engineering, Diploma Thesis, 2008

[6] Pott-Pollenske, M., Dobrzynski, W., Buchholz, H., et al., “Airframe Noise Characteristics from Flyover Measurements and Predictions”. 12th AIAA/CEAS Aeroacoustics Conference, 8 - 10 May 2006, Cambridge, US-MA, AIAA/CEAS Paper 2006-2567

[7] Guérin, S., Michel, U., “Prediction of aero-engine noise: comparison with A319 flyover measurements”. Tech. Rep., DLR, 2007, IB 92517-04/B3

[8] Heidmann, M.F., “Interim prediction method for fan and compressor source noise”. NASA Technical Report TM-X-71763, 1979

[9] Stone, J.R., Groesbeck, D.E., Zola, C.L., “Conventional profile coaxial jet noise prediction”. AIAA Journal, 21(1), 1983, pp. 336-342

[10] Smith, M.J.T., “Aircraft Noise”. Cambridge : Cambridge Univ. Press, 1989

8. APPENDIX

TAB 1. Parameters of aircraft design results (fuel mass, L/D and DOC for the reference mission)

Parameter	Unit	A/C 0 (FIG. 6 & 7)	A/C 1 (FIG. 6)	A/C 3 (FIG. 6)	A/C 4 (FIG. 6)	A/C 2 (FIG. 7)	A/C 3 (FIG. 7)	A/C 4 (FIG. 7)
maximum take-off mass	kg	65494	70895	68175	77670	71088	70419	79571
operating empty mass	kg	36705	33633	39819	47572	40779	39808	47618
fuel mass	kg	15740	24212	15307	17049	17259	17562	18903
L/D	-	14.6374	11.3577	15.8126	16.9556	15.2636	13.9146	15.3663
DOC per seat per km	€/seat/km	0.0264	0.0295	0.0272	0.0294	0.0276	0.0280	0.0301

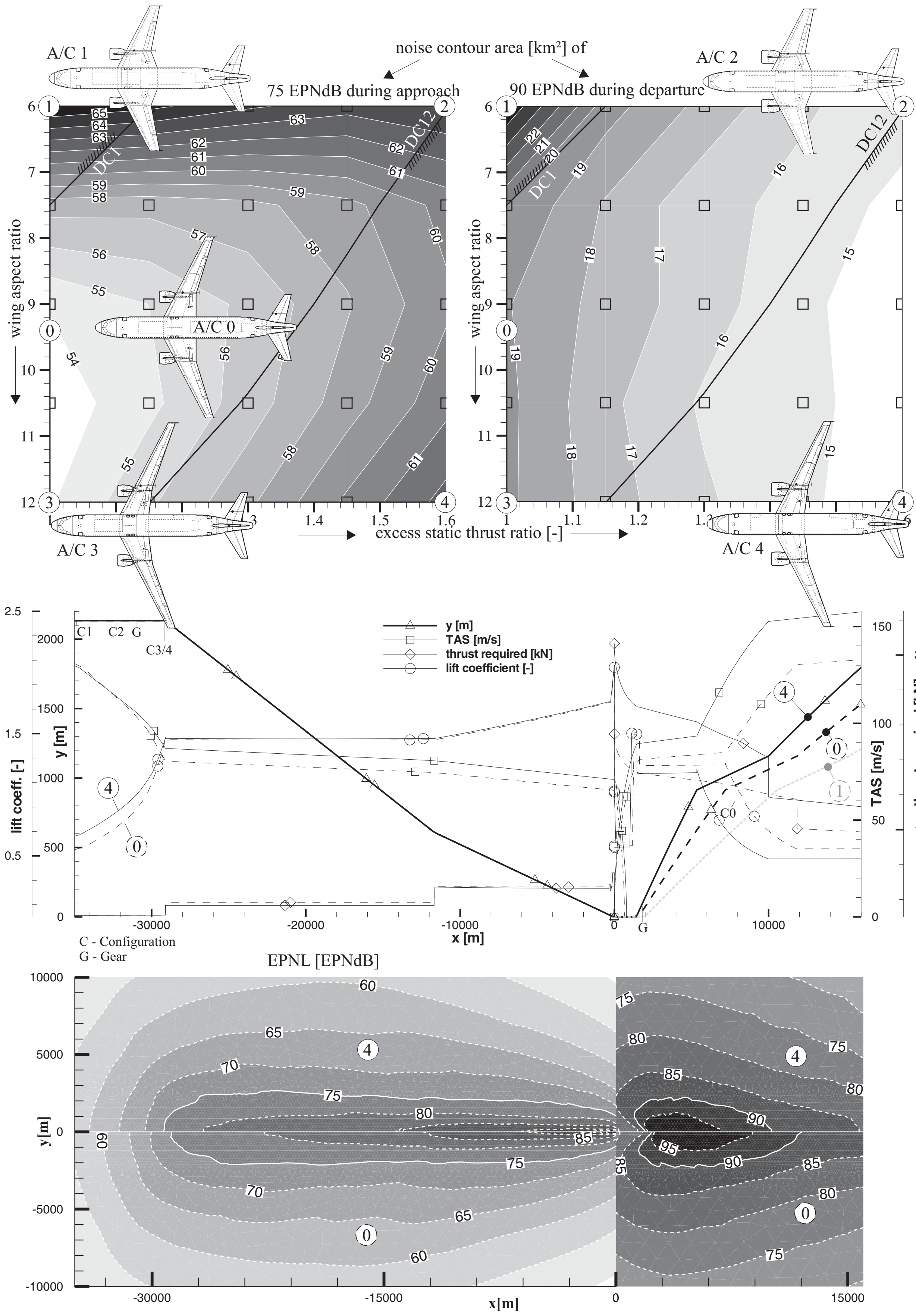

FIG 6. A/C ground noise impact analysis for excess static thrust ratio v. wing aspect ratio

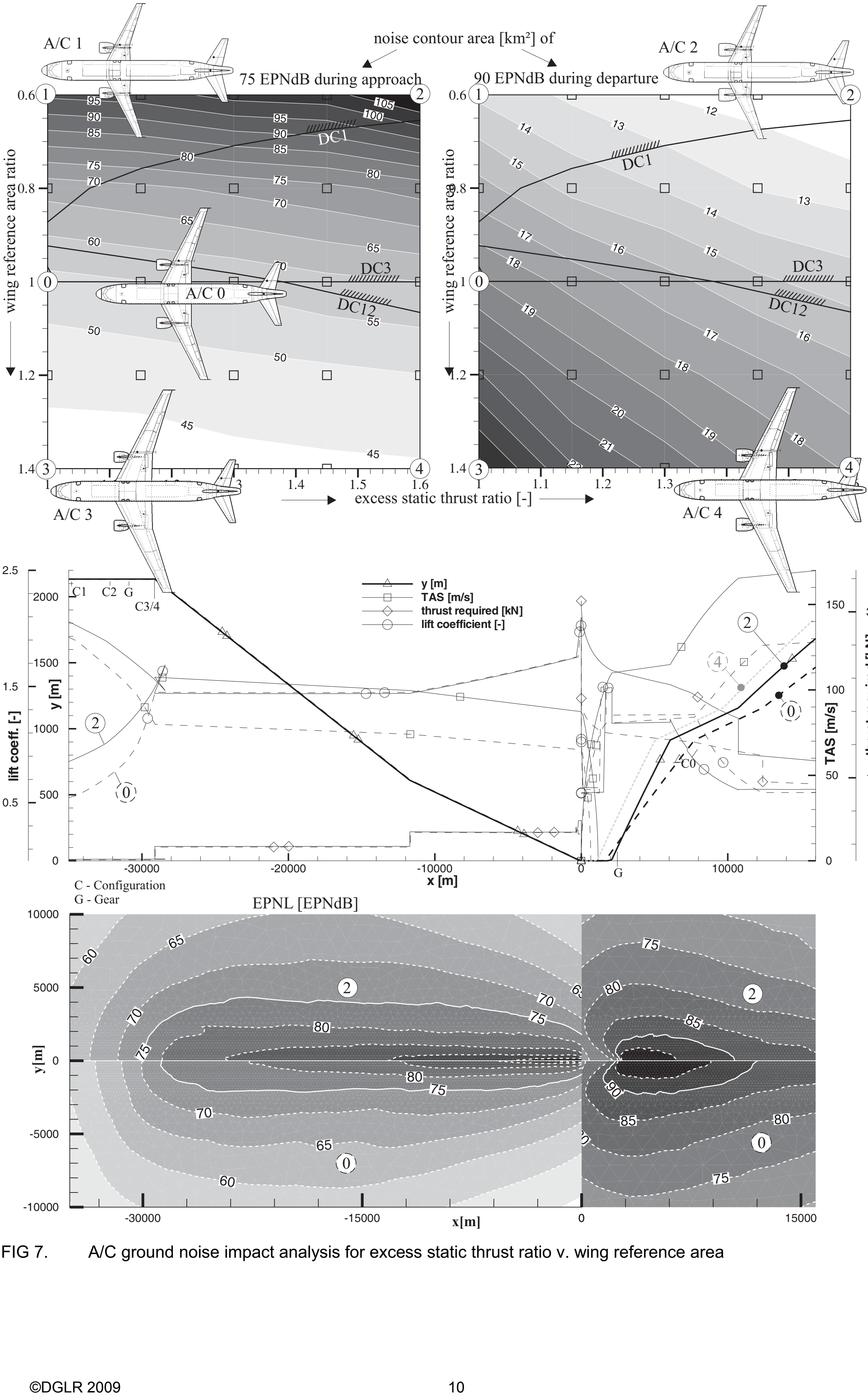

FIG 7. A/C ground noise impact analysis for excess static thrust ratio v. wing reference area