Multi-objective optimization of takeoff and landing procedures: level abatement vs quality improvement of aircraft noise

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ABSTRACT

The present paper deals with an original multi–objective optimization approach to the mitigation of the acoustic impact of commercial aircraft. The method is based on the coupling of the classical noise level reduction approach and an innovative sound-quality assessment method, developed during the EC–funded projects SEFA (Sound Engineering For Aircraft, FP6, 2004–2007) and COSMA (Community Noise Solutions to Minimise aircraft noise Annoyance, FP7, 2009–2012). Indeed, the increase of air traffic and the rapid expansion of urban areas around airports are making the aviation community noise a key aspect of the sustainable development of the transportation system. As a consequence, the scientific and industrial research community is focusing the attention on the development of innovative aircraft configurations, aimed at a substantial reduction of the acoustic impact of aircraft. Unfortunately, such a new concepts will be ready for operation only in the long–term, thus making extremely urgent the identification of alternative strategies to mitigate the impact on the residential community. The present work addresses the problem by integrating into the multi–objective, multi-disciplinary optimization framework developed and validated in COSMA, the sound–matching criterion developed within SEFA, with a noise–level based indicator minimization. Specifically, the two merit factors to be minimized are the norm of the difference between the noise produced by the configuration under analysis and a target sound, and the *EPNL* (effective perceived noise level) at a certification point. The target sounds are obtained by synthesis, using sound engineering techniques aimed at the sound quality improvement, on the basis of the results of the psychometric tests campaigns performed in SEFA and COSMA. The simultaneous reduction of the two objective functions is achieved through a multi-objective optimization problem adopting global evolution methods, as implemented within the MDO environment `FRIDA` (FRamework for Innovative Design in Aeronautics). Results will be presented for procedure optimization in terms of Pareto fronts, for two types of aircraft in both take off and landing conditions.
Keywords: Community, Noise, Level, Airport, Sound, Quality
I-INCE Classification of Subjects Number(s): 52.1, 52.2.1, 63.7

1. INTRODUCTION

The increase in air traffic and the rapid expansion of urban areas close to the airport facilities, as well as the ever-increasing number of daily movements, are making the community noise problem a crucial aspect in the context of the sustainable development of the transport system.

It is no coincidence that over the last ten years, several scientific projects have been sponsored by the European Community in order to develop innovative technologies and operational procedures with both low chemical and low acoustic environmental impact. The work presented in this paper derives from the outcomes of the projects SEFA (Sound Engineering For Aircraft, FP6, 2004–2007) and its follow–up COSMA (Community Noise Solutions to Minimise aircraft noise Annoyance, FP7, 2009–2012). In SEFA, a first attempt in including noise annoyance among the design requirements was made. For the first time, further to the classic noise–level–based optimization criterion, the concept of *quality* of the perceived noise event is exploited to introduce a constraint on both design and operational procedures. Specifically, a new ad–hoc acoustic describer, aimed at the assessment of the acoustic *distance* between two sounds, has been proposed: the idea is to quantify, in the time–frequency domain, the difference between the actual spectrum and a *weakly annoying* target spectrum, the latter identified on the basis of a campaign psychometric tests and advanced synthesis techniques. The concept of noise annoyance has been afterwards extended within the contest of COSMA in

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order to identify realistic airport scenarios. A multi–objective optimization campaign has been accomplished in order to propose novel sequences, of both departure and approach procedures, aimed at the simultaneous abatement of chemical and noise pollution, as well as the noise annoyance. In this context, the present work is being pursued to extend the results obtained in COSMA, including the ability to simultaneously minimize against multiple noise indicators. For instance, one may estimate the noise annoyance and levels in areas characterized by different requirements (*e.g.*, a residential area, a business district, a hospital ...) located in the wide area affected by the aviation noise, even if outside the immediate vicinity. Many time–consuming simulations were performed, and those presented in this paper refer to takeoff and approach procedures of a medium–range aircraft. The aim of the proposed optimization analysis is to simultaneously mimimize the noise level and the annoyance in two different areas.

The paper is organized as follows: after a brief description of the MCDO framework used for the optimizations, the formalization of the minimization problem is discussed, and in the last sections the numerical results, along with suitable comments, are presented.

2. THE MCDO FRAMEWORK: FRIDA

`FRIDA`, FRamework for Innovative Design in Aeronautics, is a Multy–disciplinary Conceptual Design (MCDO) framework aimed at analysis and optimization in aeronautical design. Recently enhanced with the inclusion of aeroacoustic models and an in–house developed turbofan engine simulation module, `FRIDA` can thoroughly describe the aircraft in those applications in which an extended concept of multidisciplinarity is paramount, such as the environmental impact on the territory. In order to describe the physics of the aircraft, the framework exploits, if possible, prime–principle–based models, so that as to be used in the analysis and optimization also of innovative configurations, for which the designers have no available literature data. A brief description of the modules used in the framework is presented below.

Aerodynamics The physical model used for the aerodynamic is that of a quasi-potential flow (1), i.e. the flow that can be considered potential everywhere except on the surface of the wake. The velocity-potential is then calculated using a boundary element method starting from an integral formulation based on the assumptions of incompressible flow and prescribed (and fixed) wake surface.

$$\varphi(\mathbf{x},t) = \int_{S_B} \left(G\chi - \varphi \frac{\partial G}{\partial n} \right) dS(\mathbf{y}) - \int_{S_w} [\Delta\varphi_{TE}]^{\tau} \frac{\partial G}{\partial n} dS(\mathbf{y}) \tag{1}$$

The boundary conditions may include the effects of the boundary layer in the form of speed of transpiration. The use of the correction of the boundary layer makes it possible to estimate the contribution to the viscous drag, which is essential for the study of flight mechanics and performance analysis.

Structural analysis The structural analysis module of the wing is based on a 6-dof torsional-bending beam model with geometric and structural varying parameters along the three spatial directions. These include the geometrical dimensions of the structural elements, the taper of the wing, the characteristics of mass and both the bending and torsional moments of inertia. A linear variation law is used for the geometrical parameters of the wings and the tail. The solution of the structural problem is solved using a modal approach considering constant boundary conditions in the joint sections of the wings and tail surfaces with the fuselage. The approximate modes of vibration are calculated with a FEM model of the wing, by using the representation for the displacements

$$\mathbf{u}(\mathbf{x},t) = \sum_{m=1}^{M} q_m(t)\Phi_m(\mathbf{x}) \tag{2}$$

whose solution allows to obtain the diagonal matrix Ω of the natural frequencies of the wing. Finally, an accurate analysis of the masses distribution, including structures, payload, crew and operational items, allows the estimation of the center of gravity $\mathbf{x}_{cg}$ of the actual aircraft configuration.

Aeroelasticity The aeroelastic analysis is obtained by the interaction between the aerodynamic variables, assumed constants, and the structural dynamics variables. To carry out an efficient aeroelastic analysis, a reduced order model (ROM) is employed for the approximation of the matrix collecting the aerodynamic forces (2). So, the analysis can be reduced to the study of the roots locus, thus avoiding the use of standard (more complex) methods, which represent an heavy computational burden for the analysis or the optimization process.

Flight mechanics The flight mechanics is solved in order to ensure the static and dynamic balance of both forces and moments. The static longitudinal stability, a fundamental requirement for the plane, is provided by imposing that the derivative of the pitching moment with respect to center of gravity $\mathbf{x}_{cg}$ is less than zero:

$$C_{M_\alpha} < 0 \tag{3}$$

The aerodynamic loads are computed for the actual configuration, including the effects of high–lift devices, airbrakes and landing gears by means of suitable corrections (3).

Propulsion The prediction of the characteristic operational parameters of the aircraft engines is much more complicated, due to the intrinsic complexity of the thermofluidynamic phenomena involved, and by the lack of useful data in the literature. To overcome these drawbacks, a simple, but effective, semiempirical model, based on the fundamental physics and some additional data available to the authors was developed. Such a model provides the percentage of throttle once both the flight condition and the engine features are known:

$$t_{\%} = f(\mathbf{X}_{fm}, \mathbf{X}_{eng}) \tag{4}$$

being $\mathbf{X}_{fm}$ the representative vector of the flight mechanics variables (altitude, drag force, actual aircraft weight, acceleration of the aircraft, ecc.) and $\mathbf{X}_{eng}$ the vector of the propulsion system characteristics (number of engines, engine pitch, bypass ratio, maximum thrust per engine at sea level, ecc.). When the throttle is computed, is easy to evaluate the rotational speeds $N1$ and $N2$ of respectively low–pressure and high–pressure spools, knowing the overspeed and idle conditions in terms of revolutions per minute. The velocity of the jets are calculated through the momentum equation.

Aeroacoustics The aeroacoustics includes models for the estimation of both airframe and propulsion noise. The models for the estimation of airframe noise of lifting surfaces, tail, high–lift devices and landing gears is based on semiempirical functions according to the Fink's model (4, 5). Such a model compute the noise in the *far-field* by the superposition of elementary sources, for wich are known spectral and directivity characteriscs. The propulsion noise estimation is based on Heidmann's model (6) for the fan a the compressor noise, on Morfey and Fisher model (7, 8) for the *buzz-saw* noise. The algorithms, in the calculation of the total sound pressure level SPL, also take into account the Doppler effect, the atmospheric absorption (9) and the ground reflection. By suitable postprocessings, SEL and EPNL are also estimated.

3. THE OPTIMIZATION PROBLEM: NOISE LEVEL VS. SOUND QUALITY

The multidisciplinary optimization problem consists in searching the set of variables $\mathbf{x}$ yielding a minimum of the objective function $J(\mathbf{x})$, while all the $N+M$ constraints $g(\mathbf{x})$ and $h(\mathbf{x})$ are satisfied. Multi–objective optimization problems, MOP, involve multiple variables and the satisfaction of many objectives. Using this approach, the constrained minimization problem can be formulated as follows

$$\begin{aligned} \text{minimize } [J_1(\mathbf{x}),...,J_k(\mathbf{x})], &\qquad k = 1,...,K \text{ and } \mathbf{x} \in D \\ \text{subject to } g_n(\mathbf{x}) < 0, &\qquad n = 1,...,N \\ \text{and to } h_m(\mathbf{x}) = 0, &\qquad m = 1,...M \end{aligned} \tag{5}$$

In the MOP, the solution consists of a set of alternatives, these being optimal if there is not a better solution within the variables domain. The optimality criterion, especially in the event that there are more conflicting objectives, can be found in the possibility that exists a set of solutions such that it is possible to further minimize one objective solely at the expense of one of the others. These solutions are called non-dominated and constitute the Pareto optimal solutions. The aim of the present work is the abatement of the acoustic energy and the simultaneous improvement of the sound quality in two different areas, by minimizing respectively an acoustical describer related to the noise level and an innovative sound–matching–based index.

The acoustic indicator used for the level minimization is the Effective Perceived Noise Level (EPNL): according to ICAO Annex 16 Appendix 2, EPNL is a single number evaluator of the subjective effects of aircraft noise on community, and consists of instantaneous perceived noise level, PNL, corrected for spectral irregularities and duration, and its calculation[1] is exhaustively described in literature. The evaluation of the objective function $J1(\mathbf{x})$ is based on the EPNL equation

$$J1(\mathbf{x}) = EPNL = PNL_{max} + 10\log\left(\frac{t_{10}}{20}\right) + F(dB) \tag{6}$$

[1] See the FAR: *Noise standards: Aircraft type and airworthiness certification*, Section A36.4

where t_{10} and $F(dB)$ are respectively the duration of the noise level within 10dB of the peak PNL and a tonal correction factor.

The improvement in sound quality deserves a more detailed discussion: such a concept is a recent approach to the noise–oriented optimization analysis in aeronautics (10), developed within the EU–funded research projects SEFA (Sound Engineering For Aircraft, FP6/2004–2007) and its follow–up COSMA (Community Oriented Solutions to Minimize aircraft noise Annoyance, FP7/2009-2012), where the sound quality has been used as a multi–level optimization constraint (11, 12). Formally, improving the sound quality consists in the estimation of the matching between the noise generated by the aircraft actual configuration and a target sound, synthesized as a result of psychometric tests aimed at the identification of a *weakly annoying* sound. In order to identify the objective function $J2(\mathbf{x})$, a suitable index I_{SS}, representative of the distance between the actual noise emission and the target sound, can be defined as the L^p norm of the difference between the spectra:

$$J2(\mathbf{x}) = I_{SS} = \left[\frac{1}{T}\frac{1}{\Delta f}\iint_D |S_C - S_T| dD\right]^{\frac{1}{p}} \tag{7}$$

In this work, the integral is evaluated by the Gauss-Legendre quadrature. The spectra are matched at three different relative locations of aircraft and observer.

The choice of the points where the objective functions are assessed is free and can be selected arbitrarily. In the present work, the certification points are used to estimate the noise level. This allows for a validation of the estimate by comparison with the certificated EPNL levels. On the other hand, the sound–quality-based objective function is evaluated at a representative location in the middle of a urbanized area close to the airport boundary. The geographic verification of the chosen location shows how it can be representative of many European airports. The optimization constraints are such that prevent the stall during the maneuver as well as not give rise to unrealistic engine operating points:

$$g_1(\mathbf{x}) = \frac{\alpha}{\alpha_{max}} - 1 < 0 \tag{8}$$

$$g_2^t(\mathbf{x}) = \frac{N1}{N1_{max}} - 1 < 0 \tag{9}$$

$$g_2^a(\mathbf{x}) = 1 - \frac{N1}{N1_{idle}} < 0 \tag{10}$$

where the superscripts t and a for the contraint $g_2(\mathbf{x})$ point out respectively the takeoff and the approach procedure. Since this study deals with the optimization of trajectories, such constraints must be evaluated and verified for each instant in which the trajectory is sampled. Actually, instead of solving the original constrained problem, a pseudo–objective function, including the constraints through the penalty function method, is defined in order to address the solution of the corresponding unconstrained minimization problem. The solution of the latter is finally obtained by using two different gradient–free methods. The first is a MultiObjective Genetic Algorithm (MOGA) and the exploited algorithm is the `NSGA-II`, exhaustively described by Kalyanmoy Deb and Pratap (13). The second one is the Particle Swarm Optimization (PSO), introduced by Kennedy and Russel (14), in an original implementation developed by the Resistance & Optimization team (15) of the CNR–INSEAN.

4. NUMERICAL RESULTS AND DISCUSSION

In this section, the optimization related to both takeoff and approach 3D procedures of a mid–range aircraft will be presented. The main characteristics of the aircraft are shown in Table **??**. The optimizations have been conducted making use of a population size of 70 individuals and 1000 generations for the MOGA, and 70 particles for 1000 iteration for the PSO. Regarding both takeoff and approach optimization analysis, will be analyzed three different solution: the $\min[J1(\mathbf{x})]$ and $\min[J2(\mathbf{x})]$ solutions, and a generic compromise solution. It is worth noting that, in the present work, the set of the optimal solutions is given by the intersection between the MOGA solutions and the PSO solutions

$$\mathbf{X} := \mathbf{X}_{MOGA}^{opt} \cap \mathbf{X}_{PSO}^{opt} \tag{11}$$

which does imply, logically, that an optimal solution obtained by one of two methods may not be optimal in the intersection set.

4.1 Takeoff

The analyzed takeoff trajectory consists of 4 segments, starting from the brake–release up to a distance of about 12.0 km from the runway, carried out at the maximum takeoff weight, keeping in into account of the weight loss due to the fuel consumption. The optimization process is aimed to find the optimal trajectories in terms of spatial and cinematic variables of the last two segments (namely the external points of the last two segments), then assuming fixed both the runway movement and the first climb phase. The distribution of the solutions, as well as the normalized Pareto fronts are shown in Figures 1, 2 and 3. The Figure 1 highlights that both the MOGA and the PSO methods lead to comparable trends of the non–dominated solutions, converging to the same region of the solutions space. The Figure 2 and 3 show that is possible to get a wide variety of solutions characterized by low values of noise level without overly penalizing the parameter related to the annoyance. In addition, the global set of optimal solution for this case is wholy provided by the MOGA otptimal set.

The numerical results obtained in terms of optimization variables are presented in Table 1, and the comparison between the 3D optimized trajectories is shown in Figure 4. The foregoing is further confirmed by Figure 4

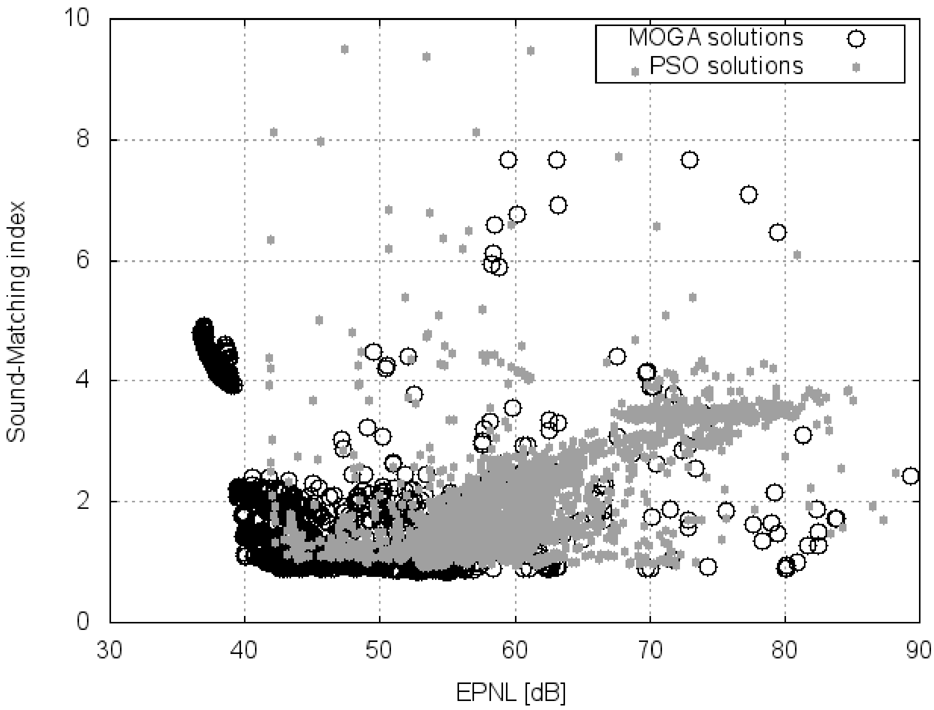

Figure 1 – Optimization analysis of the takeoff procedure for a mid–range aircraft: comparison between the MOGA and PSO unscaled solutions.

Table 1 – Takeoff procedure for the mid–range aircraft: optimization variables and solutions.

Variable	**Lower boud**	**Upper bound**	$\min[J1(\mathbf{x})]$	$\min[J1(\mathbf{x})]$	Generic opt.
x_4	2000.0 m	12026.0 m	12026.0 m	2962.0 m	12026.0 m
y_4	-5000.0 m	5000.0 m	-3264.0 m	-4487.0 m	-3184.0 m
z_4	145.0 m	800.0 m	472.7 m	181.7 m	176.9 m
v_4	70.0 m/s	100.0 m/s	83.2 m/s	83.3 m/s	83.3 m/s
y_5	-10000.0 m	10000.0 m	-9903.0 m	9169.0 m	9374.0 m
z_5	800.0 m	1500.0 m	804.0 m	806.0 m	801.0 m
v_5	100.0 m/s	140.0 m/s	105.0 m/s	100.0 m/s	108.0 m/s

where it is evident how it is possible to obtain very different optimal trajectories. To complete the analysis, the sonograms for the three optimized takeoff maneuvers are shown below in Figure 5, 6 and 7.

4.2 Approach

The approach trajectory is constituted by 5 segments, starting from a distance of about 25.0 km from the runway, carried out at the maximum landing weight, keeping in into account of the weight loss due to the fuel consumption.. This time the optimization process involves the spatial and cinematic variables of the first

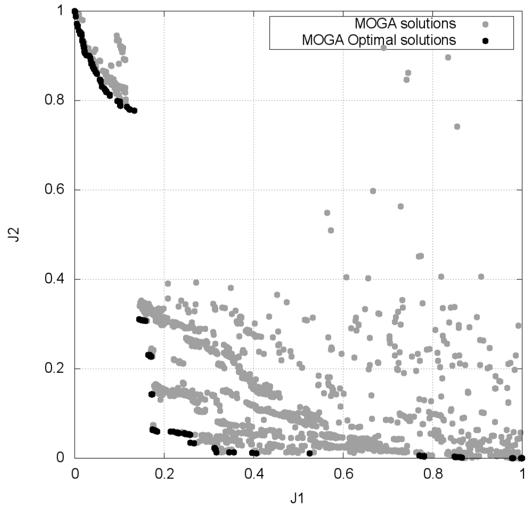

Figure 2 – Optimization analysis of the takeoff procedure for a mid–range aircraft: MOGA normalized solution and Pareto front.

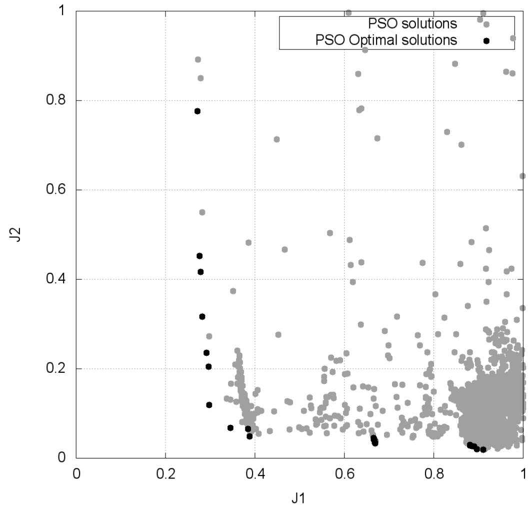

Figure 3 – Optimization analysis of the takeoff procedure for a mid–range aircraft: PSO normalized solution and Pareto front.

two segments (scilicet the first and the second external points of the segments), then assuming fixed the last approach phase. The distribution of the solutions, as well as the normalized Pareto fronts are shown in Figures 8, 9 and 10. The Figure 8 shows how for the approach procedure, both the MOGA and the PSO lead to the same results. For this case, the global optimal solutions pertain to the actual intersection between the sets of solutions obtained with the two different methods, being the minimum of the $J1(\mathbf{x})$ and $J2(\mathbf{x})$ obtained respectively by PSO and MOGA, as shown in Figure 9 and 10. It's interesting noting how the optimal solutions tend to the utopia point. This trend, typical for the case of strongly allies objective functions, is probably due to the great distance of the points of evaluation of the objective functions from the free ends of the trajectories, as well as the lower number of degrees of freedom influencing the tonal components of the propulsion system. The above is reflected in the trajectory patterns shown in Figure 11. The numerical results obtained in terms of optimization variables are presented in Table 2, and the comparison between the 3D optimized trajectories is shown in Figure 11. The sonograms for the three optimized takeoff maneuvers are shown below in Figure 12, 13 and 14.

Table 2 – Approach procedure for the mid–range aircraft: optimization variables and solutions.

Variable	**Lower boud**	**Upper bound**	$\min[J1(\mathbf{x})]$	$\min[J1(\mathbf{x})]$	Generic opt.
y_1	-12000.0 m	12000.0 m	9818.0 m	11285.0 m	11332.0 m
z_1	1250.0 m	1900.0 m	1266.0 m	1738.0 m	1266.0 m
v_1	135.0 m/s	210.0 m/s	138.7 m/s	152.7 m/s	136.9 m/s
x_2	-12000.0 m	-24000.0 m	-19515.0 m	-18518.0 m	-18518.0 m
y_2	-12000.0 m	12000.0 m	8666.0 m	8646.0 m	1770.0 m
z_2	630.0 m	1250.0 m	1258.0 m	1250.0 m	642.0 m
v_2	75.0 m/s	135.0 m/s	113.0 m/s	116.5 m/s	116.5 m/s

5. CONCLUDING REMARKS

Within this work has been introduced a novel methodology aimed at the simultaneous improvement of delocalized, allies or conflicting, noise–oriented merit functions. Starting from the intuitions developed in the EU–funded research projects SEFA and COSMA, the opportunity to take into account more different areas, in which evaluate different objective functions at the same time, has been conceived. Particularly, the takeoff and approach procedure of a mid–range commercial aircraft in the context of urban airport structures were analyzed. A multiobjective optimizations campaign was performed, using as objective functions, a level–based noise describer and the recently developed sound–matching–based index, each one evaluated in different areas

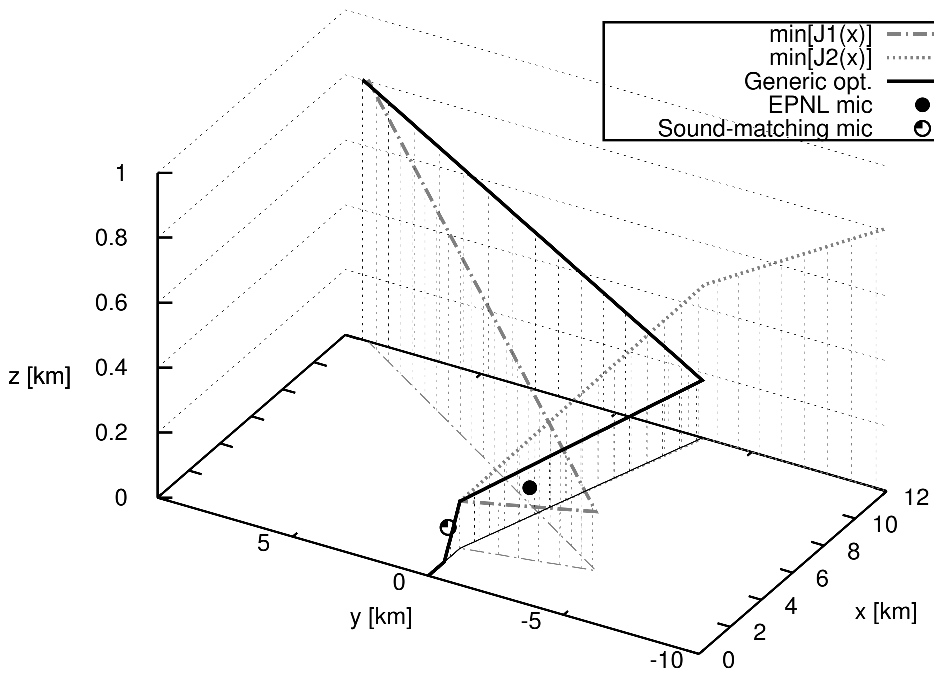

Figure 4 – Optimal trajectories for a mid–range aircraft in takeoff procedure: comparison between minimum EPNL, minimum Sound-Matching Index and a generic optimal solution trajectories.

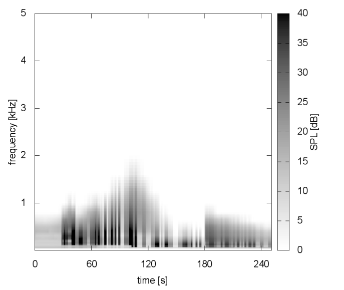

Figure 5 – Minimum EPNL takeoff sonogram.

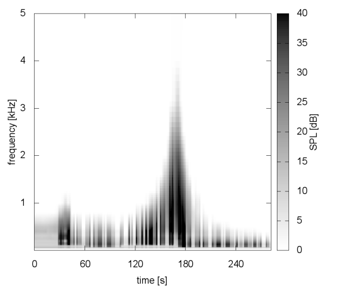

Figure 6 – Minimum SM Index takeoff sonogram.

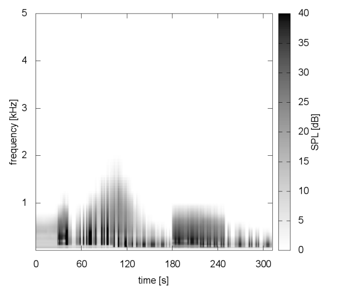

Figure 7 – Generic optimal solution takeoff sonogram.

surrounding the airport. The numerical results obtained highlight that, in principle, is possible to select a wide range of optimal compromise solutions for both takeoff and approach procedures. It is worth noting that the range of optimal solutions is strongly dependent on the position of the points in which the objective functions are evaluated, as well as on the selection of the optimization variables.

ACKNOWLEDGEMENTS

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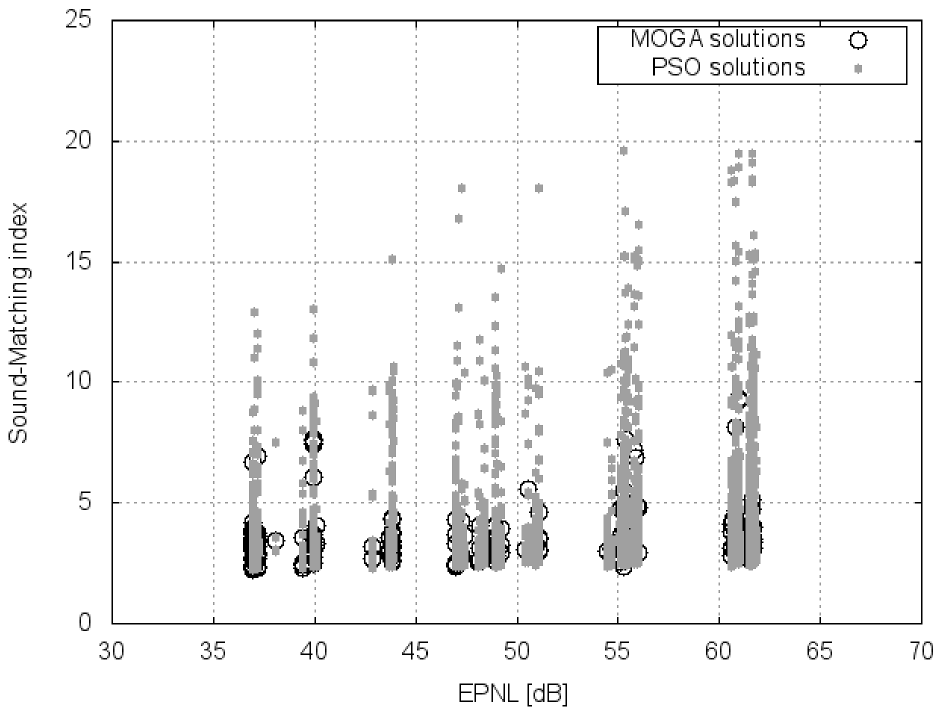

Figure 8 – Optimization analysis of the approach procedure for a mid–range aircraft: comparison between the NSGA–II and PSO unscaled solutions.

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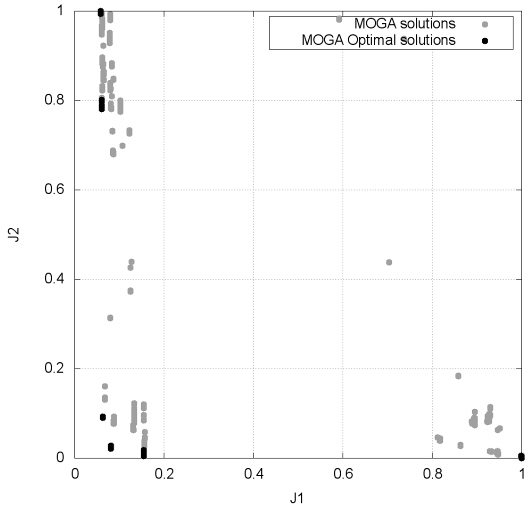

Figure 9 – Optimization analysis of the approach procedure for a mid–range aircraft: MOGA normalized solution and Pareto front.

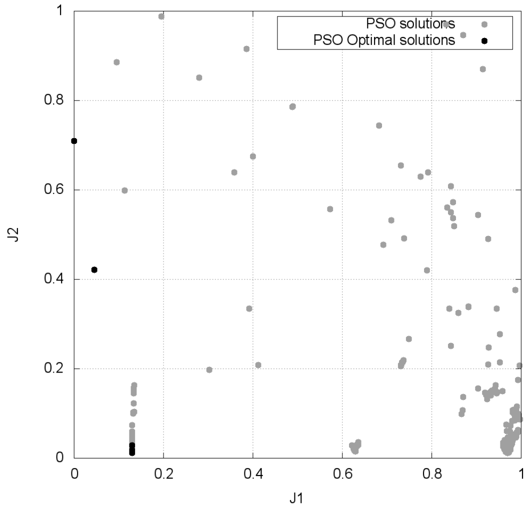

Figure 10 – Optimization analysis of the approach procedure for a mid–range aircraft: PSO normalized solution and Pareto front.

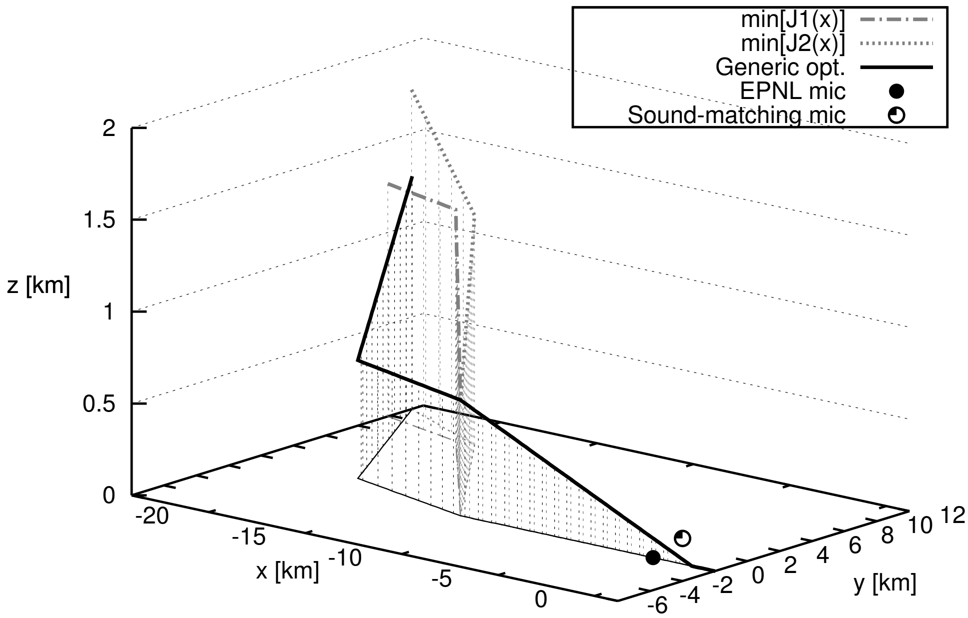

Figure 11 – Optimal trajectories for a mid–range aircraft in approach procedure: comparison between minimum EPNL, minimum Sound-Matching Index and a generic optimal solution trajectories.

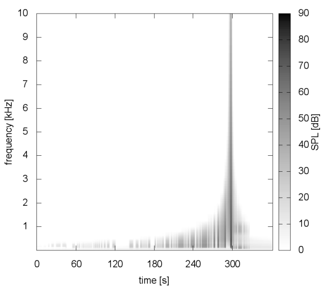

Figure 12 – Minimum EPNL approach sonogram.

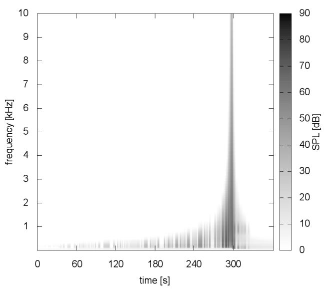

Figure 13 – Minimum SM Index approach sonogram.

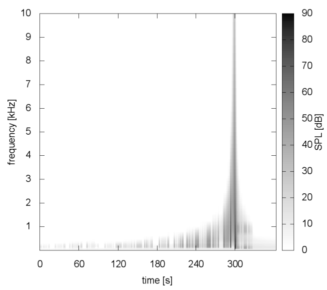

Figure 14 – Generic optimal solution approach sonogram.