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MATCHING THE AIRCRAFT NOISE TO A TARGET SOUND: A NOVEL APPROACH FOR OPTIMAL DESIGN UNDER COMMUNITY NOISE CONSTRAINTS

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Abstract
The aim of the present work is to describe a novel approach for including community noise considerations in the conceptual design of aircraft. A Multidisciplinary Design Optimization (MDO) framework for conceptual design of aircraft, is coupled to a sound-comparison algorithm, in order to lead the configuration to the fulfillment of sound-quality-based criteria. Specifically, a design concept is considered satisfactory if its acoustic emissions match a given target sound. The work is part of the European research project SEFA. In this project, the target sound is synthesized on the basis of an extensive campaign of psychometric tests. Such an approach requires the modification of the whole sound spectrum, and, thus, introduces two main difficulties: i) each sound source must be modeled inside the MDO, in order to properly treat each frequency band; ii) a suitable measure of the similarity between the two sounds must be defined and included into the optimization objective function. In the present work we introduce the Sound Similarity Index (SSI) as the L^∞-norm of the spectral difference of the two sounds. Preliminary results, obtained for a set of suitably defined test functions, show that the SSI is capable to capture both local (*i.e.*, tonal), as well as the distributed (*i.e.*, broadband) differences.

THE MDO PROBLEM AND THE SOUND SIMILARITY INDEX

The aim of a multidisciplinary optimal design is to find the value of the N relevant design variables x corresponding to the minimum of an objective function $\mathcal{J}(\mathsf{x})$, and for which P constraints $g_k(\mathsf{x})$ are satisfied. In the present work, an algorithm for including within the MDO sound–quality–based criteria for the evaluation of the environmental noise generated by an aircraft is introduced. This represent an unusual point of view (at least in the aeronautical community) developed within the European project SEFA (Sound Engineering For Aircraft).

Large part of the research effort performed in this highly innovative, multidisciplinary project is represented by an extensive campaign of psychometric tests aimed at the identification of the most annoying features of a large set of aircraft sounds. On the basis of the results of these tests, a "weakly annoying" sound is synthesized, to be used as a *target* in the design of new *friendly* aircraft (additional details on the target sound synthesis can be found in Bisping [15], whereas for a complete review of the research activity within SEFA project, the reader is addressed to Schütte *et al.*, [14]). The approach used in the present work to include the innovative concept developed in SEFA into the MDO, is based on the estimate of the matching between the noise generated by the design configuration under analysis and the target sound. To do this, the level of the matching of the two sounds has to be somehow measured and included into the objective function. The definition of the criterion used to evaluate the level of similarity represents a crucial point in the present approach. Indeed, the capability of the optimization process to be driven towards "good" configurations strongly depends on the effectiveness of the quantity used as a measure of the "distance" between the two sounds. To identify a suitable index of such a distance, we focus our attention on the difference of the two sound spectra $g(f) = g_c(f) - g_t(f)$, considered as a function defined onto the domain $\mathcal{D}$, and belonging to a normed space $L^p(\mathcal{D})$. Its L^p-norm is, by definition (see, *e.g.*, [11, 12]),

$$\|g(f)\|_p := \left[\int_{\mathcal{D}} |g(f)|^p \mathrm{d}f\right]^{\frac{1}{p}} \tag{1}$$

with $\lim_{p\to\infty} \|g(f)\|_p = max_{f\in\mathcal{D}}\{g(f)\}$. The desired measure of the distance of the two sounds is obtained by introducing the Sound Similarity Index, $\mathcal{I}_{\mathsf{ss}}$, as the L^∞-norm of the difference between the two spectra, previously normalized with respect their L^1-norm *i.e.*, [1]

$$\mathcal{I}_{\mathsf{ss}} := \|\hat{g}_c(\xi) - \hat{g}_t(\xi)\|_\infty = \lim_{p\to\infty}\left[\int_0^1 |\hat{g}_c(\xi) - \hat{g}_t(\xi)|^p \mathrm{d}\xi\right]^{\frac{1}{p}}, \tag{2}$$

where $\hat{g}_c$ and $\hat{g}_t$ are the normalized current and the target spectra, respectively, and ξ is a non-dimensional variable depending on f, introduced to make the $\mathcal{I}_{\mathsf{ss}}$ independent on the measure of the domain. It can be shown that: i) for $p = 1$, a small $\mathcal{I}_{\mathsf{ss}}$ indicates a small difference in global shape of the two spectra; ii) for $p \to \infty$, a small $\mathcal{I}_{\mathsf{ss}}$ indicates small local differences between the two spectra. These peculiarities make the SSI a useful parameter in the evaluation of the *distance* between two sounds, being the noise emission of an aircraft a combination of both tonal and broadband components. Indeed, a proper choice of p makes it possible to have a measure of the concentrated differences, with tonal components missing or misplaced, as well as of the distributed ones. The objective function can be written as

$$\mathcal{J}(\mathsf{x}) = \sum_{k=1}^{M} \alpha_k\, \mathcal{F}_k(\mathsf{x}) + \alpha_{\mathsf{ss}}\, \mathcal{I}_{\mathsf{ss}}(\mathsf{x}). \tag{3}$$

where the $\mathcal{F}_k(\mathsf{x})$ are the non–dimensional functions of x to be minimized (*e.g.*, gross weight, range, fuel consumption, life-cycle costs, etc.), and the α_k are the relative weights, whereas

[1] In the present work we are interested in the similarity of the global shape of the two spectra. Thus, the L^1 normalization does not alter the meaning of the index.

α_{ss} represents the weight given in the optimization process to the target-sound matching. It is worth noting that the $\mathcal{I}_{\mathsf{ss}}$ is a (very complex) function of the design/procedural variables, through the noise models that must be necessarily included into the MDO for each relevant source, and that will be discussed in the next section. Nevertheless, the nature of this dependance does not allow us to consider the SSI as a measure of the *distance* between the current aircraft configuration and the (unknown) target aircraft in the design variables space. In other words, two aircraft can be very similar, and produce two completely different sounds, and viceversa.

THE AIRCRAFT MODEL

The analysis modules included in the MDO to describe the complete mechanics of the aircraft deal with the structural dynamics, the aerodynamics and aeroelasticity, and the mechanics of flight. For the sake of compactness, the theoretical models underlying the implemented algorithms are only briefly outlined, and the interested reader is addressed to Morino *et al.*[1], Iemma *et al.*[4], and Iemma and Diez [3].

The model used for the structural analysis of the wing is that of a three-dimensional bending-torsional beam, with geometric and structural parameters varying in the spanwise direction. These include structural element geometric dimensions (rib area, spar and skin panel thickness, etc.), wing twist, mass properties plus bending and torsional moments of inertia. Clamped boundary conditions have been considered at root in order to take into account the wing-fuselage juncture.

The solution of the structural problem is obtained using the modal approach. The approximate modes of vibration, $\mathbf{\Phi}_m(\mathbf{x})$, are evaluated by a finite-element model of the wing, and used to express the displacement field as $\mathbf{u}(\mathbf{x},t) = \sum_{m=1}^{M} q_m(t)\mathbf{\Phi}_m(\mathbf{x})$. In this analysis we have chosen $M = 10$. The resulting Lagrange equations of motion are $\ddot{\mathsf{q}} + \Omega^2\mathsf{q} = \mathsf{e}$ where q denotes the Lagrangian-coordinate vector, Ω the diagonal matrix of the wing natural frequencies, and $\mathsf{e} = \{e_n\}$ the vector of the generalized forces.

The physical model used for aerodynamics is that of compressible quasi-potential flows, *i.e.*, flows that are potential everywhere except for the wake surface, S_W, enriched by a boundary-layer integral model to take into account the effects of viscosity, and provide an adequate estimate of the viscous drag. Under the assumption that the wake geometry remains fixed in a frame of reference connected with the wing, the numerical solution is obtained through a BEM, to yield $\tilde{\mathsf{f}}_\varphi = \mathsf{E}_{IE}(s)\tilde{\mathsf{f}}_\chi$. The vectors $\tilde{\mathsf{f}}_\varphi = \{\tilde{\varphi}_j\}$, and $\tilde{\mathsf{f}}_\chi = \{\tilde{\chi}_j\}$ collect the values of the velocity potential, $\tilde{\varphi}$, and its normal derivative, $\tilde{\chi}$, at the centers of the surface elements, and s is the Laplace variable (see Morino [9] for details). Note that the $\tilde{\chi}$ includes the effect of the boundary-layer in form of a transpiration velocity. The latter is evaluated following the method presented in Morino *et al.*[10].

The aeroelastic feedback generated by the interaction between unsteady aerodynamics and structural dynamics is also taken into account in the MDO formulation. Under the assumption of linear unsteady aerodynamics, the relationship between the structural Lagrangean variables $\tilde{\mathsf{q}}$, and generalized forces $\tilde{\mathsf{e}}$ can be written as $\tilde{\mathsf{e}} = q_D\ \mathsf{E}(\check{s})\ \tilde{\mathsf{q}}$ where $\check{s} = s\ell/U_\infty$ is the complex reduced frequency (*i.e.*, the adimensional Laplace variable), q_D is the dynamic pressure, and the aerodynamic matrix $\mathsf{E}(\breve{s})$ depends transcendentally on $\breve{s}$, due to the presence of the convection and compressibility delays. In order to efficiently perform the aeroelastic analysis within the optimization procedure, a reduced order model (ROM) for $\mathsf{E}(\breve{s})$ is introduced. By doing this, the aeroelastic stability analysis can be reduced to the study of a root locus, thereby avoiding standard methods (*e.g.*, k and p-k method), which are somehow cumbersome and would unnecessarily complicate the optimization process (see Morino *et al.*[2] for details).

The static longitudinal stability, an essential issue for aircraft, is satisfied by imposing that the derivative with respect to the angle of attack of pitch moment coefficient (evaluated with respect to the center of mass G) be less than zero: $C_{M_\alpha} < 0$ (static stability).

In order to evaluate fuel consumption, the mission profile considered in this work consists of: (i) take-off, (ii) climb, (iii) cruise, (iv) descent, and (v) landing. The range is computed according to the Breguet equation $R = (V_c E/c)\ln(W_i/W_f)$, where V_c is the cruise speed, c is the specific fuel consumption, $E = L/D$ is the aerodynamic efficiency (lift to drag ratio), and W_i and W_f the initial and final weights of the cruise segment, respectively. Finally, expressing the fuel consumptions for the mission segments before and during the cruise segment as fractions of the usable mission fuel weight F_{uf} (indicated as k_1 and k_2, respectively), W_i and W_f can be written as: $W_i = W - k_1 F_{uf}$ and $W_f = W - (k_1 + k_2)F_{uf}$.

The aeroacoustic simulation deserves a discussion apart. The prediction of the noise spectrum perceived at a specified location requires an accurate modeling of several physical phenomena, which are extremely difficult to simulate (turbulence, shock waves, unsteady wakes, etc.). Considering that each module can be called hundreds of times in a complete optimization process, it is clear that a prime–principle–based simulation of the noise generation mechanisms would make the computational burden too heavy even for the most powerful computer systems. In addition, the noise prediction is not related to critical design issues such as safety, reliability, and performances, in mind that the optimization process is essentially driven by the trend of the noise as a function of the design variable, rather than by its absolute value. For all these considerations, we can conclude that the requisite of high accuracy in noise prediction does not represent a critical issue, at least at the conceptual design stage. Thus, within the optimization framework, it is preferable to use efficient, well assessed algorithms based on empirical (or semi-empirical) models. Accordingly, the algorithm used for the evaluation of the noise sources is based on the Fink model (Fink, [5]) for the airframe noise and on the Heidmanns method (Heidmann, [6]) for the fan and compressor noise. Additional source simulation modules for the inclusions of other relevant contributions (buzzsaw noise, jet noise, ...) are under development, as well as scattering and propagation models based on a boundary integral formulation for moving bodies, to include Doppler and directional effects.

NUMERICAL RESULTS

In this section, preliminary results aimed at the validation and assessment of the Sound Similarity Index are presented. First, we evaluate the value of $\mathcal{I}_{\mathsf{ss}}$ for a set of suitable prototype functions, specifically designed to present distributed and/or local differences. The analysis is performed for $p \geq 1$, in order to verify the effectiveness of $\mathcal{I}_{\mathsf{ss}}$. In Fig. 1 the testing target (black line) is compared to the four testing functions chosen, whereas, in Fig. 2 the same comparison is shown after the $\mathcal{L}^1$-normalization. The differences between the functions and the target are presented in Figs. 3 and 4: these are the function used to evaluate Eq. 1 for $p \geq 1$. The results are presented in Fig. 5. It is evident that, for $p = 1$, only function no. 3 yields to a $\mathcal{L}^1 - \mathrm{norm} \neq 0$, according to its difference in global shape with respect to the target (see Fig. 1). For increasing values of p, the local differences make the $\mathcal{I}_{\mathsf{ss}}$ deviate from zero for all the functions analyzed. Note that all the curves show the tendency to an asymptotic value equal to their maximum value, *i.e.*, the maximum difference with the target sound. The highest value of the $\mathcal{L}^{50}$-norm is presented by function no. 3, for which the local difference caused by the spike in the target sound is added to the broadband component. On the contrary, the minimum value belongs to function no. 4, which presents the same global shape (including the spike) simply scaled by the factor 0.5.

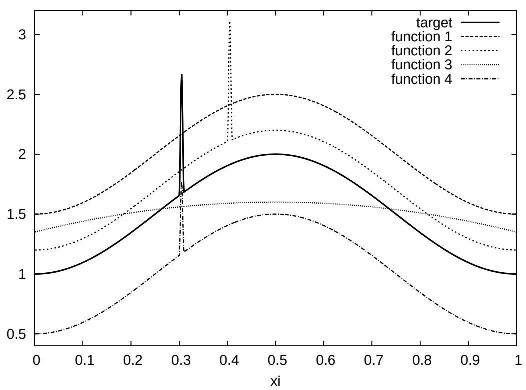

Figure 1: Test functions.

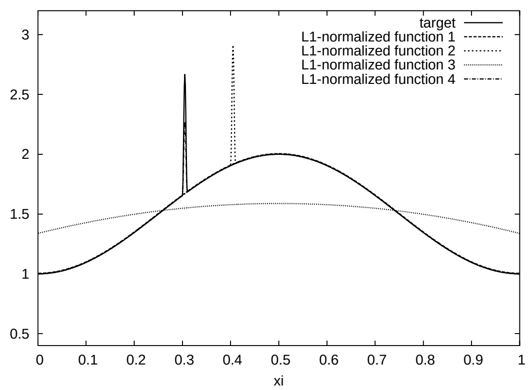

Figure 2: $\mathcal{L}^1$-normalized test functions.

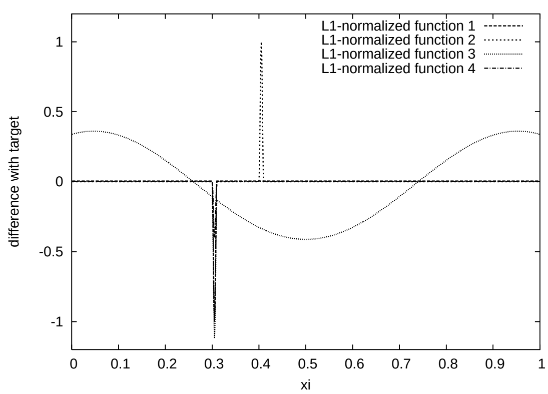

Figure 3: Differences with the target.

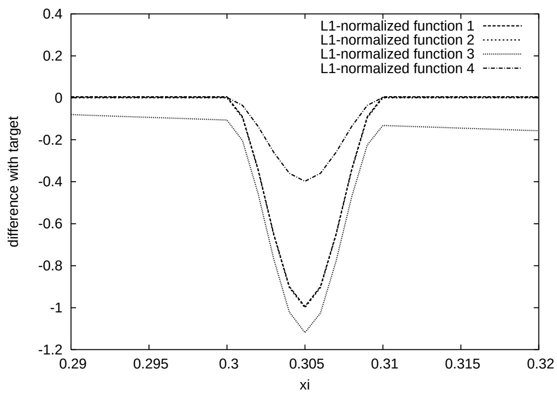

Figure 4: Close-up of Figure 3.

It is interesting to examine the behavior of the difference curves no. 1 and 2. Specifically: i) both have $\mathcal{L}^1$-norm$= 0$, being different from the target only locally; ii) both tend

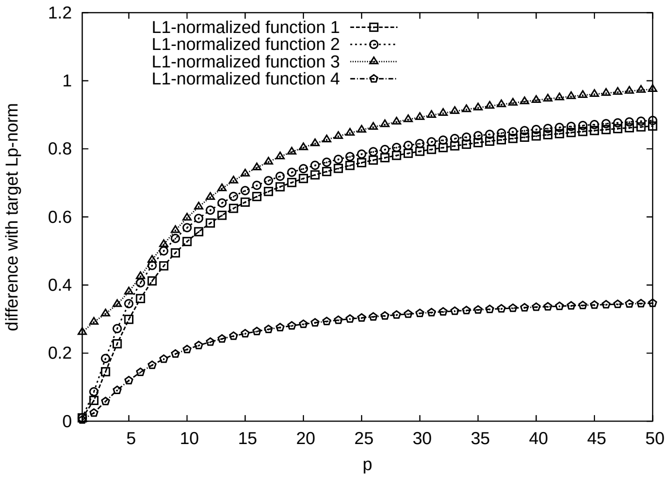

Figure 5: $\mathcal{L}^p$-norm of the test function differences as a function of the exponent p.

to the same asymptotic value, being the max local difference equal to the amplitude of the spikes present in the target sound and/or function no. 2; iii) for $2 \leq p \leq 50$, the $\mathcal{L}^p$-norm of function no. 2 is always higher. An interpretation of point (iii) may be given by considering that function no. 1 and 2 present the same broadband shape, but the latter is more affected by local differences, presenting a spike "misplaced" with respect to the one present in the target.

The results of the analysis above show that the $\mathcal{I}_{\text{ss}}$ is able to capture local and distributed differences of the prototype functions. Now, an early example on the use of the present approach in multidisciplinary design optimization is presented. For a new-generation large aircraft of the A380 category, in approach condition and flying over at an altitude of 3200 ft, only the the airframe noise due to the lifting system and to the vertical tail (see Fink [5]) is considered. We move our analysis in the subspace of the design and procedural variables relevant in these flight conditions and for these noise sources. The SSI between the spectrum of the configuration under analysis and a given target is included in the optimization process as the objective (see Section 1). The static equilibrium of the aircraft is used as a constraint. A Sequential Quadratic Programming (SQP) algorithm (see Refs. [7, 8]) in used to solve the constrained minimization problem. The steady aerodynamic is calculated for cruise condition using the boundary integral formulation described in Subsection and the high-lift devices are taken into account by means of the section flap lift coefficient, c_{lf} (see Ref. [13])

$$c_{lf} := \frac{l_f}{q_D \, c_f} = y_1(c_f/c_w) \, c_l + y_2(c_f/c_w) \, \delta. \tag{4}$$

l_f is the section flap lift, q_D is the dynamic pressure, c_l is the unflapped section lift cofficient, δ is the flap deflection angle and y_1 and y_2 are known function of the ratio between flap chord c_f and wing chord c_w (see Ref. [13], pag.193). We take as target sound an airframe noise as generated by the Fink model for a Boeing 747 in approach condition, and we evaluate the SSI in the optimization process using respectively $p = 1$ and $p \to \infty$. The final spectra are identical for the two cases and converge to the target airframe noise (see Fig. 6), and a faster convergence to the final solution can be observed when using the L^{∞}-norm.

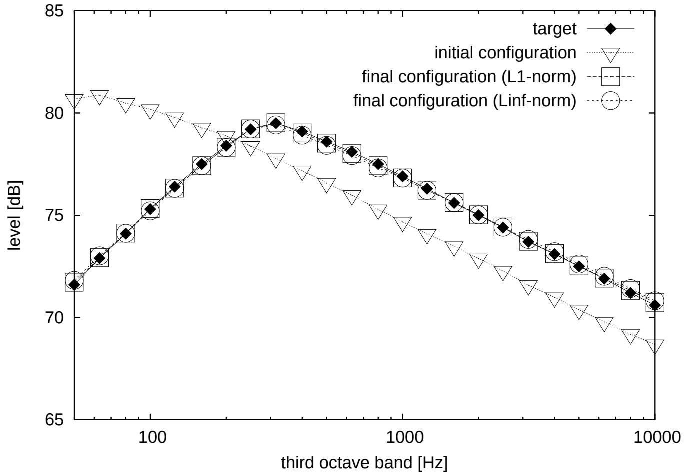

Figure 6: Matching of the airframe spectrum.

CONCLUSION

A novel approach for including community-noise consideration into an MDO framework has been presented. The attention is focused on the improvement of the quality of aircraft acoustic emissions. To this aim, the noise spectrum produced by the aircraft configuration under analysis is compared to a *target sound*. The latter is characterized by a low level of annoyance, and is obtained, within the European project SEFA (Sound Engineering For Aircraft) on the basis of the results of an extensive campaign of psychometric tests. In order to include the estimate of the *distance* between the two sounds into the objective function, a Sound Similarity Index, $\mathcal{I}_{\text{ss}}$, is defined as the L^p-norm of the spectral difference. Numerical tests on a set of prototype functions reveal that the $\mathcal{I}_{\text{ss}}$ is capable to effectively *measure* the distance between the two sounds in case of both local (*i.e.*, tonal) or distributed (*i.e.*, broadband) differences. A very preliminary test obtained with a simplified formulation (only the airframe noise sources are taken into account) shows that the inclusion of the $\mathcal{I}_{\text{ss}}$ into the objective function is able to drive the MDO procedure towards the aircraft configurations producing an acoustic emission satisfying the required matching to the target sound.

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