AERO-MECHANICAL OPTIMIZATION OF A
CONTRA-ROTATING OPEN ROTOR AND ASSESSMENT OF ITS
AERODYNAMIC AND ACOUSTIC CHARACTERISTICS

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ABSTRACT
Within the frame of the ongoing 7th Framework European Project DREAM, the paper presents a synthesis of Cenaero, DLR and Onera’s joint effort to demonstrate the aerodynamic and acoustic optimization potential of a contra-rotating open rotor. Within WP 3.2 led by Snecma, the objective was to maximize the propellers efficiency at Top-of-Climb (TOC) conditions and to minimize the noise emission at Take-Off (TO) focusing on interaction noise while fulfilling the thrust and torque split specifications at both operating points. These objectives were successfully met by the development and exploitation of efficient multi-objective 3D RANS-based surrogate-assisted optimization strategies. In order to assess the aerodynamic and acoustic characteristics of both baseline and optimized geometries, coupled U-RANS simulation and farfield prediction based on an integral Ffowcs-Williams-Hawkings approach were then carried out. The results demonstrate that although the acoustic criterion driving the optimization process did not lead to an improvement of the noise characteristics over the whole directivity range, it may be regarded as a cost-effective way to incorporate noise-related aspects into the design intent.

NOMENCLATURE
ACARE Advisory Council for Aeronautics Research in Europe
BPF Blade Passing Frequency
CFD Computational Fluid Dynamics
CROR Contra-Rotating Open Rotor
EA Evolutionary Algorithm
FW-H Ffowcs Williams Hawkings
LE/TE Leading/Trailing Edge
(OA)SPL (Overall) Sound Pressure Level
The present contribution fits into the frame of the ongoing 7th Framework European Project DREAM, whose first objective is to design, integrate and validate new engine concepts to reduce fuel consumption and CO₂ emissions 7% beyond the ACARE 2020 objectives while its second major objective is a 3dB noise emission reduction per operation point.

In order to meet the strong environmental targets set by the ACARE, various propulsor-related technologies are indeed currently being investigated by almost all major industrial organizations and research institutes. Essentially two different concepts are in the focus of current research activities. Firstly all kinds of advanced and ducted turbofans, such as low-speed fans, contra-rotating fans and fans to be integrated into alternative engine cycles (e.g. recuperative engines). Additional to advanced turbofans, open rotors then lately came back into the research focus due to their inherent advantage with respect to propeller efficiency. In the 1980’s when fuel prices rose considerably, a turboprop engine that used a pair of contra-rotating propellers was developed (Celestina et al. 1986; Nicoud et al. 1987; Smith 1987). However, such engines, also termed propfans or unducted fans, were essentially not produced commercially due to unresolved technical issues and because fuel prices decreased, reducing their commercial advantage. One of the main challenges for open rotor technology is to retain the high efficiency levels at flight velocities at which common midrange aircrafts equipped with conventional bypass engines are operating. The other challenge is to significantly reduce noise levels (both, cabin and far field) to a level at least being comparable with current turbofan technologies. Progress has been made in both fields (aerodynamics and acoustics) by applying modern design methodologies, starting from 3D-Euler simulations (Celestina et al. 1986) to the application of highly sophisticated 3D URANS flow solvers coupled with far field predictions methods (Stuermer and Yin 2009; Zachariadis et Hall 2009; Brailko et al. 2004). A methodology using a 3D inverse method for open rotor aerodynamic and acoustic optimization has been applied successfully showing great potential in order to reach the aforementioned objectives (Mileshin et al. 2008).

The present work focuses on both the aerodynamic as well as the acoustic optimization by combining existing expertise in the field of fan design and analysis with sophisticated optimization strategies based on evolutionary meta-heuristics. It has been carried out in the frame of SP3 Direct-Drive Pusher Open Rotor led by Snecma and more specifically in the concept studies carried out along the WP 3.2. Partners include Airbus, CIAM, Cenzaero, DLR, Dowty, EPFL and Onera while the aero-acoustic tests are to be conducted in the TsAGI facilities, Russia. The design studies have essentially been structured in two phases. Following literature survey and baseline configuration definition, a preliminary aero-acoustic optimization phase, termed phase 2, aimed at identifying the most relevant parameters and providing a first quantitative assessment of trades, in terms of noise versus aerodynamic performance benefits. Phase 3, starting with the definition by Snecma of a new baseline geometry combining test concepts highlighted in phase 2 and integrating new manufacturing and mechanical constraints, was then dedicated to the detailed design.

The design rationale and the setup of the aero-mechanical optimization chains implemented by Cenzaero and DLR, targeting major contra-rotating open rotor challenges, will be described along with
the design methodology in Section 1. Results and selected concepts will be presented, analyzed and compared in Sections 2.1, 2.2 and 2.3 respectively for the preliminary tip shapes studies performed by ONERA followed by the phase 2 and phase 3 optimizations. CEN AERO and DLR both carried out phase 2 and phase 3 optimizations, which showed to be a clear asset to the project as results cross-validation helped to confirm identified trends and improve understanding of the physics beyond the different tools used. Focus is set on DLR phase 2 results and CEN AERO phase 3 results as these were respectively the most promising geometries obtained.

DLR and ONERA computational methodologies and results for the selected concepts assessment will then be presented in Section 3. More specifically, the far field directivities and spectra for a linear microphone array evaluated essentially at the TO certification point will be thoroughly analyzed and compared for the baseline and optimized geometries, in Sections 3.2 and 3.3 respectively. Although the acoustic criterion driving the optimization process did not lead to an improvement of the noise characteristics over the whole directivity range, it will be shown that this objective function may be regarded as a cost-effective (in terms of computational investment) and efficient way to integrate noise-related aspects during the design phase. Conclusions and future prospects will finally be drawn.

1 OPTIMIZATION RATIONALE

The objective was to incorporate at best contra-rotating open rotor design challenges by maximizing the propellers efficiency at TOC conditions and minimizing the noise emission at TO, focusing on interaction noise while fulfilling the thrust and torque split specifications at both operating points. Exploiting a pair of contra-rotating propeller blades offers the benefit of isolated quieter propellers thanks to the reduced propeller speed. However the interaction noise between the blade rows of a contra-rotating propeller creates additional noise and constitutes a key player in the acoustic emissions.

The rotor/rotor interaction is inherently unsteady and the relevance from the acoustic point of view of the information that could be extracted from steady state, mixing plane simulations clearly remains an open issue. However, as a first step to integrate an acoustic cost function based on the mixing plane simulations, affordable for the automated design process, a simplified criterion was proposed and defined by Snecma (Farvacque 2009). This criterion essentially aimed at being representative of interaction sources, expected to be the dominant source of noise in TO condition. Incorporating ideas from Lowson’s equation for the noise radiated by a moving dipole, which allows to obtain farfield acoustic information from the unsteady force fluctuations on the blade, and Sears formulation of unsteady response to an incoming gust (Atassi 1991; Farassat and Brentner 1998; Magliozzi et al. 1991), this criterion is based on the amplitudes of the front propeller wake velocities harmonics and, while it should be ideally evaluated as close as possible to the LE of the aft propeller, it has to be evaluated before the averaging of the mixing plane. In the present work, the pseudo-acoustic criterion was hence evaluated at a constant axial position plane just upstream of the mixing plane. Following a harmonic decomposition of the relative speed fluctuations projected on the normal to the mean flow, only the first two harmonics of the wake disturbances are considered.

Due to its simplicity, such a criterion does not take into account any dipolar directivity pattern, mean flow incidence on the aft rotor, phase interferences along the span and chord of the blades, aft propeller blade number and blade to blade interferences. However it constitutes a first attempt to incorporate interaction noise reduction into the design intent at an affordable computational cost.

The baseline configuration, termed V 1.1, was defined by Snecma. The first rotor counts 12 blades while the second rotor holds 10 blades. For both phases, two regimes, Top-of-Climb (TOC - 35000ft altitude) and Take-Off (TO) have been considered. The two objectives considered for both preliminary and design phases were the minimization of the pseudo-acoustic cost function defined at TO and the maximization of global efficiency at TOC, whose spanwise distribution is defined as the
average force generated by the two rotors divided by the average torque (pressure and friction forces taken into account):

$$\eta = \frac{(F^x_1 + F^x_2)V}{(F^\theta_1R_1 + F^\theta_2R_2)\omega}$$

where $F^x$ denotes the blade surface integral of the pressure and viscous forces projected in the axial direction, $V$ the freestream velocity, $F^\theta \cdot R$ the blade surface integral of the torque along the engine axis, $R$ the radius and $\omega$ the rotational speed ($\omega_1 = \omega_2$). The given equation represents the propeller efficiency which was derived according to the definition used for classical propeller aerodynamics and was extended to two consecutive rotors. Within the present paper all results shown refer to the given definition of propeller efficiency, which in fact includes the propulsive efficiency as well as a contribution from the rotor isentropic efficiency (which itself results from losses due to the non-ideal compression of the fluid). A comprehensive discussion about different CROR efficiency definitions and their calculations based on CFD simulations is given in References (Zachariadis et Hall 2009) and (WaiBauski et al. 1987). At both regimes, the global thrust value had to be included within $[100\%;115\%]$ of required thrust while the torque ratio/power split had to be constrained within $[0.9-1.1]$ at TOC and $[0.85-1.15]$ at TO respectively to be representative of a direct drive architecture.

The aero-acoustic phase 2 optimization was performed with limited geometric constraints (TE/LE elongation bounds, maximum 1 curvature change) as its essential aim was to gain insight into the specification and the aerodynamic/acoustic key drivers.

For phase 3, mechanical constraints and further geometrical constraints were incorporated in addition to the above aero-acoustic specification:

- a series of lower and upper bounds on thickness at 0%, 30%, 70% and 100% of blade height,
- maximum Von Mises stresses (evaluated at rig scale) allowed to reach half of the elastic limit of the material (metallic blades),
- constraints on the axial and tangential positioning of the center of gravity of the parameterized blades.

1.1 Tools and Methodologies

The approach at DLR for the CROR optimization as used within the present study was the following: Within the optimization loop the in-house multi-objective optimization procedure AutoOpti (Voss and Aulich 2006; Lengyel et al. 2009) was applied. The optimizer itself featured an evolutionary algorithm combined with the support of surrogate models to accelerate the overall optimization progress, which is vital in the context of optimizations involving highly dimensional conceptual spaces.

Both objectives were evaluated based on steady state 3D RANS computations applying DLR’s CFD method TRACE (Ashcroft and Schulz 2004; Röber et al. 2006; Schnell 2004) with a $k-\omega$ turbulence model. In terms of grid resolution, two different setups were used within the present study: a rather coarse grid which was employed during the optimization and which comprised 500,000 cells in total. For this setup wall functions were applied on all solid surfaces with $y+$ values well above 50. The intention here was to reduce the computational effort within the optimization in order to process as many individuals as possible in a given amount of time. Only selected and promising members were then re-evaluated after the optimization with a more appropriate and much finer grid (2.9 million cells), in most cases confirming the optimization trends obtained with the coarse grid setup. DLR used its in-house blade parameterization and within phase 3 the finite element method CalculiX was introduced in the optimization chain for additional stress evaluation along with corresponding stress limits and geometrical constraints being introduced to ensure a manufacturable blade geometry. A more detailed description of the different methods applied and their use in the context of CROR applications can be found in (Schnell et al. 2010).
Minamo (Pierret et al. 2006; Iliopoulou et al. 2008; Lepot et al. 2009), Cenaero’s in-house optimization platform, implements mono- and multi-objective EAs efficiently coupled, in an online framework, to interpolation/regression and physics-based surrogates and drove the automated CROR computational set up developed at Cenaero. An in-house blade shape modeler was exploited and for the 3D RANS simulations ($k-\omega$ Wilcox model), the elsA code (Cambier and Veuillot 2008) developed by ONERA has been employed while for the mesh generation, the AutoGrid software was used. Following mesh convergence study, a 3 million point mesh was selected and the choice set was not to resort to wall law functions considering the likely separated flow field to be estimated at TO point. To implement the complete aero-mechanical specification, an assessment of the maximum Von Mises stresses in test rig conditions had to be carried out. The rotational speed was rig-scaled and adapted to the wind tunnel static temperature plus a 10% speed margin and linear FE evaluations have been performed with SAMCEF (ASEF module), the blades considered as clamped at their root. As the fillet was not modeled, a multiplicative factor of 2 was applied locally in the hub section elements to account for the local stress peaks. Dedicated in-house tools were developed in order to automatically robustly create for each studied geometry the corresponding structural mesh by a morphing approach and to transfer the blade pressure distribution from the elsA computation to the SAMCEF model.

Parameterization Cenaero and DLR both parameterized front and aft propellers (2D sections and stacking) while the pitch angle was also left free independently at TO and TOC conditions, leading to a conception space holding over 100 parameters. Although the tools were different, the parameterizations applied were quite similar, typically allowing for modifications of metal angle at LE and TE, thickness distribution scaling and remodeling, stagger angle modification and chord scaling. In order to incorporate the preliminary design lessons learned (see Section 2.1), phase 3 design was carried out with increased stacking control flexibility in the tip region.

2 OPTIMIZATION RESULTS

2.1 Tip Shape Studies

Since the cutting of the front propeller tip vortex by aft propellers was expected to be of great contribution to the interaction noise, a preliminary optimization study was carried out to test the sensitivity of the front propeller wake to tip shape modifications.

Blade design was defined by 20 stacked profiles distributed between root and tip. The shape was interpolated on these profiles by spline curves. Only the profile positions in the last two sections (located at 0.9717 R and 1.0017 R, respectively) were changed during this study, the others being kept at their initial position (referenced as INI shape in figure 1(a)). Only the tip region, beyond 90% of the radius (R), was modified. A first set of modifications was computed to identify the performance sensitivity to single parameter modifications. The impact of each modification without re-staggering the blade was evaluated in TO conditions using elsA (Cambier and Veuillot 2008) steady calculations. The aft propeller was not modified.

As expected the “PLUS” (see figure 1(a)) modification of the twist slightly improved the thrust coefficient of the front propeller while the “MINUS” modification had the opposite effect. The change in the anhedral position and the sweep had no significant effect. The efficiency of the front propeller was not affected by these small modifications. Flow fields in a plane normal to the engine axis downstream of the modified blades were compared. In each case, the “MINUS” modification turned out to reduce the pressure fluctuation and the entropy production in the tip vortex region. The combination of these three modifications was used to build the COMBI design which was this time re-staggered. The entropy production and the azimuthal pressure fluctuation in the wake of tip region were diminished (see figure 1(b)). In order to incorporate these interesting results, enhanced flexibility of the stacking parameterization of the propeller tips was integrated into the phase 3 designs.
2.2 Design and Lessons Learnt from Phase 2

The DLR results of the phase 2 optimization in terms of the Pareto front are shown in Figure 2. In total approximately 1600 individuals were successfully evaluated at both operating conditions with a corresponding re-staggering of both blades. The individuals Pareto-ranked one, which fulfill the specified requirements such as delivered thrust and torque split are marked in green, the initial member represents V1.1 in a parameterized form and from which the optimization was started, is shown in black. A substantial improvement could be observed when adding the surrogate models, which resulted in the second point clustering in the lower right corner, were all Pareto ranked one members gathered. The main driver for the efficiency improvement at TOC conditions here was found to be the change in shock strength and its position on both propellers as shown in Figure 3 (left). An additional sweep in the tip region of the front propeller was introduced for the optimized individual Memb25652 to obtain an almost shock free diffusion (see Figure 2, right). When assessing the gain in overall efficiency for Memb2652 compared with the initial version (as shown in Figure 2), it needs to be considered that few geometric constraints concerning the manufacturability of the blades were introduced during the optimization since the material specifications and stress limits were not known prior to starting this first optimization. As a consequence, most of the optimized blade geometries including the optimized Memb2652 did not meet all geometric requirements (such as keeping a minimum chord length in the tip region) and basic mechanical criteria e.g. with respect to the expected flutter behavior. In order to come up with with a design that actually could be built and tested, Snecma re-designed version Memb2652 to comply with the torque split limits allowed and applied all necessary geometric constraints in order to ensure a mechanically valid setup. The focus of Snecmas re-design was to transfer as many of the main geometric features as possible from the optimized Memb2652 (such as 2D profiling, leading edge contour etc.), in particular in order to retain the improved acoustic characteristics. This redesign resulted in blade version V2.0, results of which are also shown in the Pareto front with DLR’s own numerical setup and evaluation methods applied.

The key driver for the improvement in terms of the acoustic cost function (second optimization objective) is summarized in Figure 3 (right): shown are the wake structures downstream of the front propeller for the initial (INI) and the modified (COMBI) designs.
propeller in terms of the entropy contours. It can be seen in the figure that for the optimized version V2.0 the wake velocity deficit up to approximately 80% span was significantly reduced compared with V1.1, which was expected to improve the noise interaction characteristics when impinging on the aft propeller. In the blade tip region of the front propeller additional loading was placed by the optimizer resulting in a more pronounced tip vortex. However, this was one of the objectives since the clipping of the aft propeller was aiming at preventing the tip vortex to interact with the aft propeller.

In a last and final step of phase 2 all configurations, namely the baseline V1.1, the optimized Memb2652 and the re-designed final geometry V2.0 were evaluated by Snecma independently. The remaining gains between V2.0 and the reference V1.1 showed an improvement in terms of efficiency by +0.5% at TOC conditions and an improvement in terms of the acoustic cost function by -10 dB, which correlated with +2.6% in TO efficiency. Although the given changes are not directly comparable with the shown results in the Pareto front (Figure 2) for several reasons (different numerical setup, solver, implementation of the acoustic cost function, etc.), the main trends and improvements from the phase 2 optimization could be preserved and were confirmed, resulting in a configuration that is expected to provide aerodynamic and acoustic benefit and also forms the basis for the next optimization phase, results of which are presented in the following Section.

2.3 Design and Lessons Learnt from Phase 3

The DoE generated for the complete aero-mechanical design phase by Cenaero held about 430 fully converged individuals. Focus was set on the acoustic cost function chosen as the single objective, while a constraint with an ambitious minimum bound, inspired by the efficiency gains obtained during phase 2 without mechanical constraints, was progressively imposed on the efficiency at TOC. Over 80 aerodynamic, mechanical and geometric constraints were handled by Minamo. The reference V2.0 did not allow reverse mode operation for the front propeller and did still violate the aft propeller maximum stress value chosen as constraint for the phase 3 optimization by a factor 2. Within less than a 100 additional function calls, the design did point out the following aerodynamic/acoustic trade-offs to be achievable at the extremes of the Pareto front with all aerodynamic, mechanical and geometric constraints fully satisfied: about 0.7% efficiency gain could be achieved at TOC regime without degrading the acoustic performance or an additional gain of about 2.5 dB (according to the pseudo-acoustic cost function definition) could be obtained with no degradation of aerodynamic performance.
Figure 3: Efficiency maximization at TOC by shock strength reduction and relocation (left: pressure distribution at 50% span for both propellers) and minimization of the acoustic cost function by radial loading re-distribution resulting in a stronger tip-vortex core and a lower wake deficit over the rest of the span for the optimized version V2.0 in comparison with V1.1 baseline.)

at TOC. As Cenaero also employed the elsA code, these numbers directly compare with the evaluations of V1.1 and V2.0 performed by Snecma, with a similar numerical setup and grid refinement level.

Figure 4 displays for the pseudo-acoustic cost function at TO vs the propulsive efficiency at TOC the superposition of

- the CFD results (DoE points in dark yellow circles, optimized experiments in red circles, the reference V2.0 in green hexagon, the optimized A and B individuals described hereafter in purple and orange hexagons respectively),
- the constrained Pareto front extrapolated from the surrogate models (in turquoise triangles),
- the Pareto front extrapolated from the surrogate models but with stress constraints relaxed to 600MPa (in pink triangles),
- the Pareto front extrapolated from the surrogate models only accounting for aerodynamic constraints (in green triangles),
- the Pareto front extrapolated from the surrogate models if all constraints are disregarded (in dark blue triangles).

The maximum von Mises stress constraints appeared by far the most stringent and active along the design process. This is clearly visible in the evolution of the extrapolated Pareto front when diminishing the allowed upper bound by a hundred MPa (from the pink to the turquoise triangles). It is
worth underlining that in terms of number of function calls, only 5 times the number of parameters were used in this very high (102) dimensional space. While the surrogates quantitatively overpredict aerodynamic performances, it is interesting to note that the quantification of aerodynamic/acoustic trade-offs is accurate.

The geometry trends of the optimized individuals appeared stabilized. In order to analyze their gain and features in more details, two experiments have been selected for the compromise they offer in terms of aerodynamic and acoustic gain. The optimized experiment A (following 30 design iterates) increases the global efficiency by 0.3% with respect to the reference case at TOC while decreasing the interaction noise by 0.8 dB at TO. After stabilization of convergence, the optimized experiment B almost further doubles both the efficiency improvement at TOC (0.5%) and the interaction noise gain at TO (1.5 dB) with respect to the reference. These two individuals are hereafter compared with respect to their values of the acoustics cost function at TO vs propulsive efficiency at TOC.

Figure 4: Phase 3 Pareto front: Acoustic cost function at TO vs propulsive efficiency at TOC.

The aerodynamic, geometrical and mechanical constraints could be fully satisfied, essentially through stacking and slight thickness modifications as far as mechanical constraints are concerned, and the main trends in terms of blade geometries as well as flow improvements appear similar. A closer look at global values of the efficiency and thrust for each propeller separately shows that it is essentially the first propeller performances that are markedly improved, both at TO and TOC conditions. This appears logical with respect to the optimization specification enforced since the minimization of the pseudo-acoustic cost function goes hand in hand with a weakening of the front propeller wake up to the aft propeller height. The comparison of the radial distribution of the efficiency of the front propeller for the two optimized experiments with respect to the reference one shows that there is a significant improvement of the efficiency between 20-70% span for both
Figure 5: Non dimensional static pressure along SS, close-up in the LE region above 25% span (front propeller - TOC)

(a) Optimized
(b) Reference V2.0

Figure 6: Spanwise efficiency distribution and non dimensional blade static pressure distribution (front propeller - TOC)

(a) Efficiency
(b) Close to midspan
(c) Close to tip

optimized experiments (see Figure 6(a)). This efficiency increase appears mainly due to the decrease of the losses resulting from the reacceleration downstream the shock (see Figure 5). The static pressure distribution around the blade around 50% span also clearly exhibits the smoothing of the Mach number evolution downstream the shock (see Figure 6(b)). In addition, both optimized experiments reduce the shock strength compared to the reference case, which further decreases the losses (see
Figure 6(b)). Between 70% and 90% span, a similar slight degradation of the efficiency distribution is to be noted for both optimized experiments while the flow appears improved in the tip region (see Figure 5). In this region, thanks to a fine tuning of the parameterized sections stagger angles, it is essentially the shock strength that appears markedly decreased for both optimized experiments compared to the reference case (see Figure 6(c)). Front propeller loading redistribution results from the optimization. Both optimized cases enhance the work extraction and reach the required minimum thrust despite the forced downscaling of the hub chord to comply with reverse mode thanks to adequate increased chord scaling, which is clearly visible in Figures 6(b) and 6(c). Regarding the improvement in terms of the acoustic cost function, the key driver showed similar to phase 2 results, with a wake harmonic content of the front propeller reduced up to approximately 75% span while its tip vortex core appears strengthened, taking advantage of the clipping of the aft propeller. Experiment A, hereafter termed V2.1.a was finally selected as best optimized geometry following Snecma reevaluation which confirmed its aero-acoustic potential while a more detailed mechanical assessment showed that this geometry was directly manufacturable for the rig tests.

3 AERODYNAMIC AND ACOUSTIC ANALYSIS

3.1 Tools and Methodologies

The acoustic analysis of several selected individuals from the optimization was made based on time-accurate RANS computations. As within the optimization, DLR’s turbomachinery code TRACE was applied, here taking advantage of efficient phase-lagged boundary conditions in order to reduce the overall computational effort (Schnell 2004). The results in terms of time-dependent pressure and flow fields, either on the blade surfaces or along an integration surface covering both propellers, were then fed into an acoustic method in order to carry out the acoustic far field extrapolation with the corresponding polar directivities as the main results. The acoustic method applied was the APSIM code which has been developed at the DLR Institute of Aerodynamics and Flow Techniques for the prediction of rotor or propeller noise radiated in the free far-field (Stuermer and Yin 2009; Yin and Delfs 2003). In principle two approaches were feasible: one using blade pressure data (also referred to as the non-permeable method), as well as the approach based on a permeable (or porous) integration surface which covers both propellers and was placed at a radial distance of approximately half a blade height above the propeller tip. A comparison of both approaches for the given configuration, including a discussion of their advantages and drawbacks, can be found in (Schnell et al. 2010). The acoustic results in the near and the far field were not only used in order to assess the acoustic characteristics of the optimized version, but also allowed for an assessment of the effectiveness of the acoustic cost function definition as used within the optimization loop.

Onera has exploited the KIM code (Rahier and Prieur 1997; Prieur and Rahier 2001) for the evaluations of open rotor noise. As DLR’s APSIM code, the KIM code is based on acoustic integral methods and can solve the Ffowcs Williams Hawkings (FW-H) solid or porous surfaces equation (Ffowcs Williams and Hawkings 1969) as well as provide a solution to the Kirchhoff formulations (Di Francescantonio and Giles 1997; Brentner and Farassat 1998). Using the permeable formulation of the FW-H equation allows to take into account quadrupole sources between the front and aft propellers, but also for non linear propagation in the near field, reflection/scattering and masking effects. Still, the use of the FW-H equation together with permeable surface in the context of the unsteady resolution of the Navier-Stokes equations gives also birth to some other difficulties related to boundary conditions, interpolation techniques and mesh quality used both in the aerodynamic and aeroacoustic computations. The solid surface formulation of the FW-H equation cannot take into account all the phenomena discussed above but, since each propeller noise is computed separately and then summed up, it allows analyzing the contribution of each propeller to the global radiated noise. Moreover, dealing with interaction noise related to blade pressure fluctuation, the solid surface for-
mulation can provide an interesting insight on which region of the blade has to be optimized to reduce the emitted noise.

### 3.2 Comparison of V2.0 Acoustic Data

Acoustic results in the far field of configuration V2.0 are here compared for two different methodologies. The results in Figure 7 summarize the sound pressure levels obtained in the farfield on a line of microphones parallel to the engine axis (see Figure 8) for both methods, the Onera one in comparison with the DLR approach. All results were obtained by coupling single-passage URANS results (Onera: elsA/DLR: TRACE) with a non-porous FW-H approach using blade pressure on both rotors. Concerning the CFD evaluation, both partners used their own setup in terms of grid generation and overall resolution, placement of the inlet and exit boundaries etc. as well as their individual FW-H method (Onera: KIM -dashed lines- / DLR: APSIM -solid lines-) for the far field analysis. The results shown were split into the contributions from the rotor-alone tones and the interaction tones at selected frequencies (Figure 7, left). The shown rotor-alone tones yield typical results with their maximum close to the propeller axis at $90^\circ$ and a strong attenuation of the intensity when moving up- and downstream, away from the rotational axis. The SPL values for these tones are identical for both methods applied, confirming the blade steady loading and thus the operating conditions were identical. The interaction tones show a very similar behavior for both methods in terms of the directivity at both shown frequencies. The differences between both methods are all within a few dB, which is remarkable considering the complexity of the numerical setup. In the right graph the results of the overall sound pressure level are compared against each other for both methods, again showing a very similar trend with respect to the location and the height of the maximum SPL values along the directivity. Here the results shown were also split into the contribution from the front and the aft rotor showing that the front rotor contribution to the interaction noise is almost negligible and the front rotor wake/aft rotor blade as well as the front rotor tip vortex/aft rotor interaction respectively is the dominant noise source for the interaction tones. Again, the overall sound pressure levels as well as the individual contributions from both rotors are in good agreement between both methods.

![Graph showing comparison of acoustic data](image)

(a) Individual interaction tones $\text{BPF1+2BPF2}$, (b) Overall sound pressure levels and contributions from $\text{BPF1+3BPF2}$ and rotor alone tones $\text{BPF1}$, $\text{BPF2}$ the front propeller and the aft propeller

Figure 7: Comparison of far field directivity between DLR (solid lines ——) and Onera results (dashed lines - - - -) for CROR version 2.0

### 3.3 Detailed Analysis of V2.0 vs V2.1.a

This Section is now dedicated to the comparison of the optimized designs resulting from phase 2 (V2.0) and phase 3 (V2.1.a), which were described in Sections 2.2 and 2.3 respectively. The flowfield of the single-passage URANS computation was stored over a chorochronic period of each propeller in
order to reconstruct the full flowfield around the propellers over a complete revolution. This flowfield was then interpolated on \( z = 0 \) plane at each time-step during a full revolution of both propellers. The time-depending evolution of the interpolated pressure fluctuation (filtered from mean value over one revolution) clearly shows the propagation in the nearfield emanating from the blades.

![Figure 8: Schematic view of the axis system with microphones and interpolation plane positions](image)

The Fourier analysis of the pressure fluctuation is compared on Figure 9 to the acoustic directivities computed with the solid surfaces approach on two microphone distribution: a 4 meters radius arc. Figures 9 (a) and (b) for the V2.0 design and (c) and (d) for the V2.1a design show the acoustic directivities of the first two interaction tones computed on the 4m radius arc. \( \theta = 180 \) corresponds to the upstream axis and \( \theta = 0 \) to the downstream. These plots are superimposed to one pressure amplitude contour level \((p/P_{inf} = 2.5 \times 10^{-5} Pa)\) for the mode corresponding to the plotted acoustic tone.

For the tone corresponding to the blade passing frequency (not shown here) of the front and aft propeller, the acoustic directivity is centered on the respective propeller. In the same manner, the pressure fluctuation amplitude of the corresponding mode also has a lobe centered on each propeller. The flow downstream the aft propeller blade tip and root exhibits also areas with pressure fluctuation of high amplitude, corresponding to the tip and root vortices shedding downstream. Since no high SPL level is found for these low \( \theta \) values, this high pressure fluctuations appear to be mostly hydrodynamic and do not radiate. For the first interaction tone ((a) and (c)), the acoustic prediction show some particular directivities consistent with the lobes of the pressure fluctuation amplitude. As mentioned in the preceding Section, the interaction tones are dominated by the rear propeller. It is to be noticed that all the lobes of pressure fluctuation amplitude are centered on the aft propeller. The arc of microphone being centered on the first propeller, this explains why the directivities do not match perfectly with the pressure lobes. For the second interaction tone considered ((b) and (d)), the acoustic predictions show again important levels in both upstream and downstream directivities, while the corresponding pressure amplitude mode has a large high level area in the downstream region only. The front directivities seem to be blocked by the front propeller. This masking effect, if present, does not appear to be taken into account by the solid surface approach.

Comparing V2.0 with V2.1a results, the BPF levels are identical since the two designs are operating at the same conditions with imposed thrust and balanced power split. The OASPL in the propeller plane is not dominated by any specific tones but is quite the same for both designs. The major difference between the pressure mode amplitudes is found for the first interaction tone. The lobe at \( \theta = 130^\circ \) is smaller for the V2.1a design, which can be linked to the 5dB difference for this directivity of the interaction tone. In the farfield, the corresponding difference is located at the \( x = -50m \) on the microphone line. If there is a shielding of the second interaction tone plotted (BPF1+2BPF2) by the front propeller, the gain in the direction of the \( x = -50m \) microphone could be obtained on the OASPL since the second interaction tone would not be dominant anymore. For most other directivities the V2.1a design is found to be 2-3dB less noisy than the V2.0 design in the
farfield.

Figure 9: Pressure mode contour levels and acoustic directivities for V2.0 (left) and V2.1a (right) designs. In red: pressure amplitude contour level $p/P_{\text{inf}} = 2.5 \times 10^{-5}$Pa

4 CONCLUSIONS

In the framework of DREAM WP3.2 Advanced concepts studies, major advances have been made by all partners to identify promising axes aiming at improving the aero-acoustic behavior of CROR in TO conditions while securing an ambitious level of efficiency at TOC. Efficient multi-objective 3D RANS-based surrogate-assisted optimizations strategies were developed and successfully applied by Cenaero and DLR in order to tackle a complete aero-mechanical design specification incorporating a simplified acoustic cost function, proposed by Snecma, aiming at minimization of interaction noise. It is worth underlining that Cenaero, DLR and Snecma closely worked together along the design phases. This work and the associated cross-checks clearly helped to improve the understanding of the key drivers, to refine the design specification and to confirm trends beyond the different tools used. The main drivers for the clear acoustic cost function and TOC efficiency gains obtained were found to be the optimization of the 3D blade leading and trailing edge contours as well as appropriate staggering, influencing and optimizing the shock structures on both propellers. More specifically, the acoustic cost function gain, with a minimization of the wake deficit of the front propeller over the entire span of the aft propeller, not only came from optimized 2D profiling and flow incidence decrease, but also essentially resulted from a relocation of the front rotor loading, implicitly taking advantage of the aft propeller clipping.

In order to assess the aerodynamic and acoustic characteristics of both baseline and optimized geometries, coupled URANS simulation and farfield prediction based on an integral Ffowcs-Williams-Hawkins approach were carried out. Both aerodynamic and acoustic computational methods used by DLR and ONERA have been cross-checked on a reference CROR geometry. The aerodynamic and acoustic solutions obtained by both partners are very close, building confidence in the trends observed. It is also worth noting that an assessment of ONERA aerodynamic and aero-acoustic tools for open rotors has been performed using an experimental database generated by TsAGI on a reference geometry and this assessment is to be presented at this ETC conference (Boisard et al. 2011). These tools have been used by ONERA to evaluate the optimized geometry V2.1a. The results clearly show a
decrease of the noise radiated by the final optimized geometry V2.1.a compared to the phase 3 reference, V2.0. Since both geometries generate the same thrust, the gain is only obtained on interaction noise which is dominant at TO condition. A deeper analysis of the near field pressure fluctuation however showed that some interaction tones could be overestimated by the acoustic prediction due to the shielding by the front propeller. The obtained results show that the acoustic cost function implemented and fine-tuned to drive the optimization studies may be regarded as a cost-effective way to incorporate noise-related aspects into the design intent. Several geometries incorporating innovative 3D shapes came out of WP3.2 studies and were judged mature enough to become candidates for rig tests in TsAGI T104 low speed facility. Both V2.0 and selected concept V2.1.a are hence to be tested at TsAGI end of 2010 and beginning of 2011 respectively.

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