RACER aero-acoustic propeller design and analysis

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Within the frame of the Clean Sky 2 NACOR project, ONERA has performed a detailed analysis of the Airbus Helicopters RACER propellers. Two main axis of improvement have been investigated, the first one was the propeller blade design, with airfoil optimization, blade design and optimization for aero-acoustic performance with respect to the internal structural and manufacturing constraints. The second axis of improvement was to take advantage of the strong and complex aerodynamic interactions that occurs when the RACER flies in cruise or hover conditions. Important improvements of this aircraft aero-acoustic performance have been proposed by ONERA thanks to the wide range of accuracy of the simulation methods that have been used during this project.

I. Introduction

The RACER propellers (Figure 1) correspond to a very specific design since they assume a part of the aircraft propulsion in cruise in addition to the anti-torque function in hover. The propellers are wing tip mounted on a nacelle, very close to the wings and the main rotor and they directly blow the tail unit. Such a complex integration problem has been studied by ONERA with different level of accuracy methods in order to propose a new blade design and to take advantage of all complex aerodynamic interactions.

In the following paper, we will first focus on the propeller blade design methodology used by ONERA to increase the performance while reducing the noise penalty. The second part of this paper will be dedicated to the major aerodynamic interactions comprehension that occurs while the RACER is flying.

Figure 1: Airbus Helicopters RACER.

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II. Propeller design

To meet the wide range of performance objectives from hover to cruise flight conditions, a specific airfoils family has been identified and optimized in order to allow the specific blade designed for the left and right propellers.

A. Airfoils optimization

Specific airfoil family has been designed for the Airbus Helicopters RACER propellers with ONERA in house optimization tools. An airfoil is considered to be the addition of a thickness and a camber laws along the chord and ONERA managed to modify those two laws with the help of Bezier control points. Many airfoils can be generated by this method and their performance quickly evaluated by a simple code considering Euler equations with a boundary layer development. Thus, the Bezier control points defining the airfoil are optimized maximizing the lift over drag ratio of the airfoil for 3 operating conditions, corresponding to a Mach number velocity and lift coefficient. Considering not only one operating condition but 3 allows ensuring high performance for a wide range of Mach numbers and lift coefficients.

This airfoil optimization exercise can be done for several relative thicknesses, but this could lead to relatively different camber laws while varying the relative thickness. Such different camber laws could lead to surface bumps along the blade span. That is the reason why we chose a single airfoil, for example located at 70% of the blade span, to be optimized for a wide range of operating conditions. Then, this optimized airfoil is distributed along the blade span conserving the same camber law and only scaling the thickness law. Each airfoil performance is also evaluated by the mean of 2D CFD simulations with the ***elsA*** software co-owned by AIRBUS, SAFRAN and ONERA for a wide range of Mach number and angle of attack (Figure 2).

Finally, 2 airfoil families have been optimized for both left and right propellers, since they assume the anti-torque function in hover. Thus, in hover a propeller is generating positive thrust while the other propeller operates in reverse mode. The camber law has been significantly reduced for the airfoil family operating in reverse mode in hover condition.

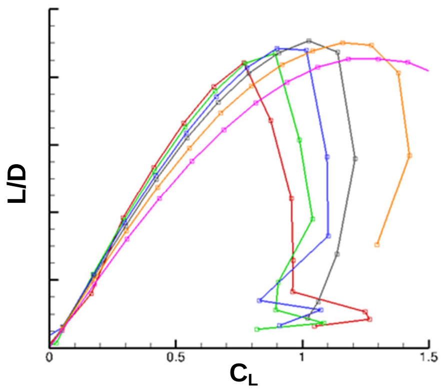

Figure 2 : CFD 2D lift-to-drag ratio for relative thickness from 4% to 12% airfoils at Mach number = 0.4.

B. Blade design

Blade design can be done considering the previously described airfoils families. We are dealing with the chord, twist, sweep, dihedral and thickness laws along the blade span. But the aerodynamic blade surface has to be designed with respect to the internal structural and manufacturing constraints. Within the frame of the Clean Sky 2 NACOR project, the preliminary design of the propeller blade relies on natural composite material, that is to say wooden propeller. Even if aerodynamic and acoustic considerations would lead to a thin blade, internal structural and manufacturing constraints were high and lead to a thick blade, especially in the root region, in order to avoid any flutter and guaranty the wooden blade to support the aerodynamic and inertia loads.

Nevertheless, ONERA respect those structural constraints and was able to define many blade laws. A blade performance can be quickly evaluated by the in house code PUMA, based on the lifting line theory with an unsteady wake method. The ONERA in-house unsteady free-wake plus lifting-line code PUMA uses the previously computed airfoil lookup tables and is able to take into account a flow field perturbation such as a wing tip vortex. In addition, the PUMA code gives access to physical quantities along the blade span in the aerodynamic reference frame, for example lift and drag coefficients. This allows the design to be adapted in order to present the best induced efficiency with the airfoils operating at their best lift-to-drag ratio.

A PUMA simulation result could be also used as an entry for acoustic analysis. The loads along the lifting line can be distributed in chord with different model in order to obtain a blade surface pressure coefficient distribution. This surface pressure coefficient is then analyzed with the ONERA in house KIM code based on integral methods (Kirchhoff or Ffowcs-Williams Hawkings) to produce noise levels and spectra.

When a blade candidate is identified with good performance in both hover and cruise, a blade surface geometry can be drawn and grided in order to perform 3D CFD simulations. Many blade shapes have been evaluated by the mean of CFD in cruise and hover (forward and reverse thrust) with a pitch variation, thus the Chimera technic was very helpful in saving time (Figure 3). CFD blade surface pressure distribution can also be used for a detailed acoustic analysis with the KIM code.

Finally, this design procedure allows about 2% power consumption reduction in cruise, more than 5% in hover and up to 3dBA in hover. It also allows showing the loss of efficiency due to the blade root thickness in addition to vortical structures coming from a blade root flow separation. A blade structure allowing a thickness reduction could provide more efficiency and less noise emissions.

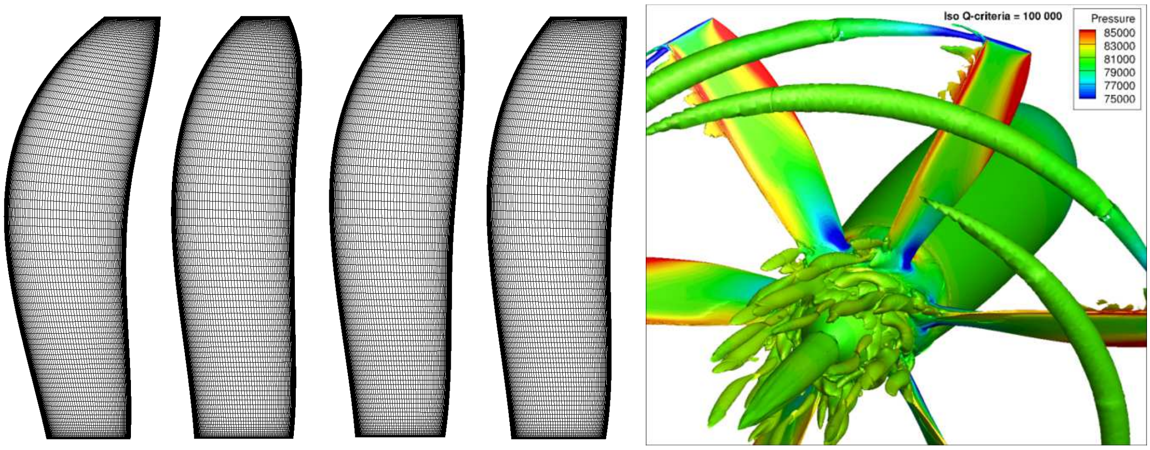

Figure 3 : Example of blade shapes evaluated by the mean of 3D CFD (left), vertical structures coming from a blade root flow separation (right).

C. Blade optimization

In parallel of the iterative designs method, an optimization method has been used in order to evaluate the possibility of improving the design based on PUMA multi-objective optimization. The PUMA code has been used for this optimization process since a simulation restitution time is far smaller than for a CFD simulation. Two main optimization platforms have been used in the framework of this study, DAKOTA and OTOOL.

DAKOTA is a commercial software, which contains among others the CONMIN gradient-based optimizer used for the Cruise configuration. This optimizer is based on the feasible directions method. The main advantage of this method is its low CPU time consumption, but the eventuality to reach a local optimum point is non negligible especially when the objective function is multi-modal. The CMA-ES evolutionary optimizer has been used for the Hover configuration. This optimizer is supposed to reach the global optimum, but a large number of evaluations is required (2500 for example).

OTOOL, is an ONERA in house optimization platform, which contains, among others, the KORRIGAN Kriging surrogate model (developed at ONERA), coupled with a conventional genetic algorithm optimizer.

The first step of this methodology consists in building the Design of Experiment (DoE). The research domain limited by the lower and upper values of the design variables is discretized using the Latin Hypercube Sampling (LHS) methodology, which allows a homogeneous sampling of the domain. Low Fidelity (LF) computations are performed with the PUMA code, on 128 sampler points. 126 points are correctly converged for the Cruise configuration, and 58 points for the (rather severe) Hover configuration.

The second step consists in the enrichment of the data base to update and improve the accuracy of the Kriging model. Two steps are performed, first to determine the minimum point of the model (thanks to a classical genetic algorithm), and then evaluate the real value of the objective function of this point by a PUMA simulation. Secondly, to determine the maximum Expected Improvement (EI) point, thanks to an Efficient Global Optimization (EGO) methodology, and then evaluate the real value of the objective function of this point by a PUMA simulation.

The research and the evaluation of the minimum point and the maximum EI point are performed 100 times twice (which is a choice of the user). Two objectives have been defined for this study, first to determine the design that will provide the best performance in Cruise and in Hover separately. Secondly to validate the optimization procedure using the Kriging surrogate models in Cruise and in Hover. Those models have been used in the framework of the multi-objective optimization procedure in a second part of this study, to define the Pareto front between the two flight configurations.

It has been concluded that the Kriging surrogate model for the Cruise configuration is expected to be as accurate as the PUMA code. But, for the Hover configuration, due to the difficulty to obtain PUMA converged results, some lack of accuracy can occur for the corresponding Kriging surrogate model. Nevertheless, these two surrogate models will be used in the multi-point optimization procedure, in order to replace the PUMA evaluations. More details will be given in the final paper on the multi-objective optimization procedure and results obtained.

III. Aerodynamic interactions analysis

Installation effects are fundamental to the aerodynamic and acoustic performance of the installed propellers of the RACER configuration. Many effects have been deeply investigated within the frame of the Clean Sky 2 project NACOR.

For example, in cruise conditions, the total power consumed by the two propellers varies by more than 10% depending on whether they rotate counter or co- with respect to the wing tip vortex (Figure 4). This trend has been confirmed by 3D CFD simulations.

In forward flight, the main rotor can increase the efficiency of the propellers under certain circumstances. This phenomenon has been investigated with PUMA free-wake simulations. Many simulations allow showing that propeller thrust is linked to the variations in axial velocity induced by the main rotor wake. Axial velocity is slowed beneath the main rotor wake and increased above it; decreases in axial velocity increase propeller thrust. Tangential velocities induced by the main rotor also affect propeller thrust; tangential velocity tends to have an outboard direction.

Trailing edge to propeller distance effect has also been investigated. The objective of this investigation was to quantify the noise mitigation that can be obtained by increasing the spacing between the wing trailing edge and the propeller. The interaction between the propeller and the viscous wake of the wing is a source of noise. The further aft the propeller is placed, the more the viscous wake of the wing is dissipated, thus reducing the strength of this source of noise.

The aerodynamic interaction of the main rotor, the propellers and the tail unit of the aircraft has also been deeply investigated. The propellers were modelled by body-force source terms through an ***elsA***-PUMA coupling and are trimmed in thrust according to the specifications given by Airbus Helicopters (Figure 5). Detailed acoustic analysis of these simulations have been done and main results will be presented in the final paper (Figure 6).

Finally, wind tunnel test have been performed by Airbus Helicopters, modeling the propeller with and without wings in order to quantify precisely these interactions and evaluate the impact on acoustic measurements. This configuration has been simulated by the mean of 3D CFD in order to make precise comparisons with the wind tunnel test results (Figure 5). More details will be given in the final paper.

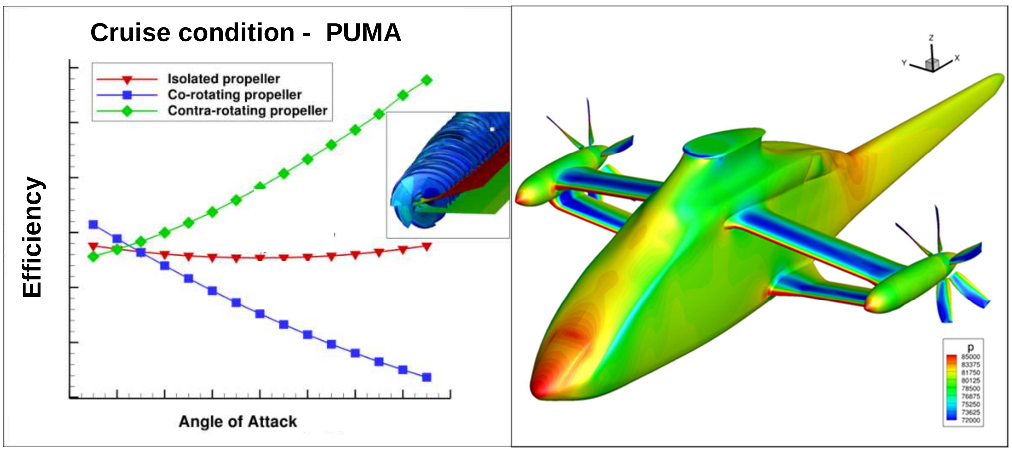

Figure 4 : Propeller rotation direction effect compared to the wing tip vortex in cruise by PUMA simulations (left) and 3D CFD simulations (right).

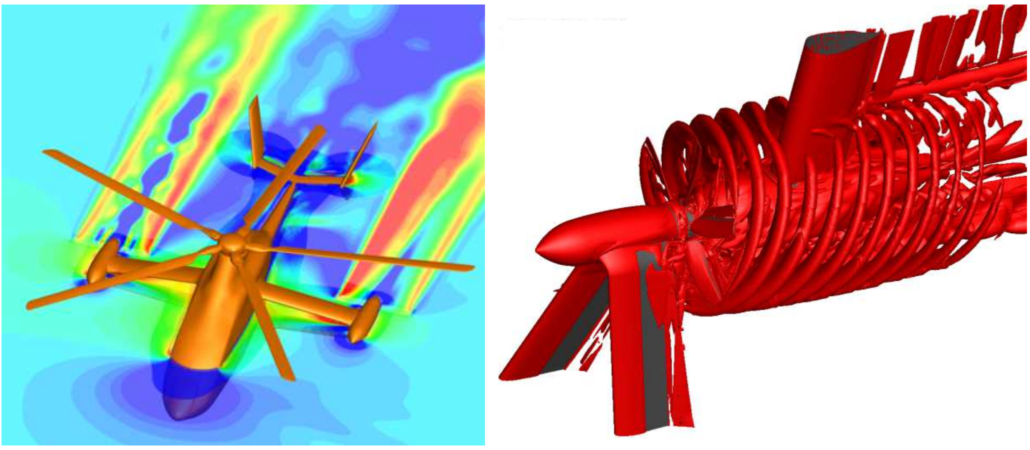

Figure 5 : Complete aircraft with main rotor CFD simulation coupled with propellers by Body-Force method (left), wing-propeller interactions wind tunnel measurements modeled by CFD (right).

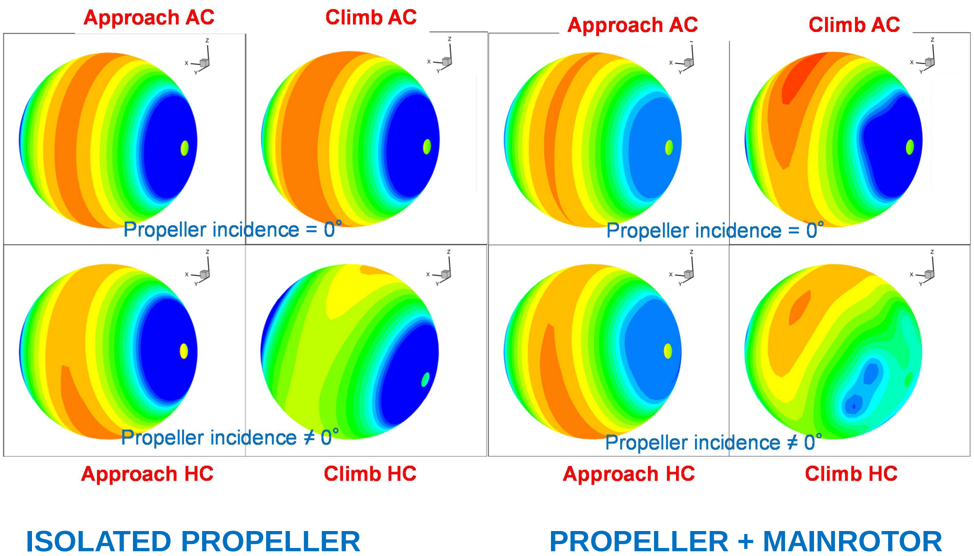

Figure 6 : Example of acoustic analysis, directivity of the isolated propeller (left) and in the presence of the main rotor (right) depending on the flight configuration. Sphere centered on the propeller, in the near field.

IV. Conclusion

The final paper will first present in detail the methodology used within the frame of the Clean Sky 2 project NACOR for blade design and aero-acoustic optimization. This design will lead to important improvements in terms of performance but also in terms of acoustic emissions for both cruise and hover flight conditions. A second part will detail complex aerodynamic interactions studied with different methods developed by ONERA. The final proposed design will takes advantage of these interactions. A far better understanding of the complex physical phenomenon happening while the RACER is flying will also be presented thanks to numerous simulations performed with different levels of accuracy.

V. Acknowledgments

These activities were carried out jointly with the DLR as part of a call for tender won in the ITD AIRFRAME of the CleanSky2 platform. The DLR was in charge of the aerodynamic performance of the wing, and of the horizontal stabilizers, as the acoustic analysis is done jointly with ONERA. The particularity of the project was to work on each component individually, taking into account the many aerodynamic interactions between wing/propeller, propeller wing, rotor/propeller/wing /tail parts, requiring numerous and frequent exchanges between the partners.