Numerical aerodynamic optimization of helicopter rotors: multi-objective optimization in hover and forward flight conditions

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Abstract

A multi-objective procedure for helicopter rotor aerodynamic performance is presented. This optimization chain allows rotor blade shapes to be optimized by taking into account simultaneously hover flight performance and forward flight performance. It is built around two optimization algorithms, a gradient-based method CONMIN and a genetic algorithm GADO, which have been coupled to a 3D Navier-Stokes solver *elsA*, and a comprehensive rotor code HOST. Several multi-objective strategies have been considered and tested on the linear aerodynamic twist optimization of a rectangular blade rotor, the 7A rotor. An optimization run starting from the ERATO rotor and taking into account 3 objectives is then performed. Two designs, results of the optimization, are finally fully analyzed to demonstrate the efficiency of the method.

Notation

b	Number of blades
c	Local chord
R	Rotor radius
$S=\pi R^2$	Rotor disk surface
$\sigma = \dfrac{b.c*}{\pi R}$	Rotor solidity
$Zb = \dfrac{100.Fz}{\frac{1}{2}\rho_\infty S\sigma(R\Omega)^2}$	Rotor thrust coefficient
$Cb = \dfrac{100.C}{\frac{1}{2}\rho_\infty S\sigma R(R\Omega)^2}$	Rotor torque coefficient
$FM = \dfrac{T^{3/2}}{P\sqrt{2\rho_\infty S}}$, $FM = \dfrac{Zb^{3/2}}{20Cb}\sqrt{\sigma}$	Figure of Merit
τ	Linear aerodynamic twist
μ	Advance ratio

Introduction

Designing a helicopter rotor is a very complex task involving many disciplines strongly interacting one with another. The single aerodynamic considerations require taking into account a wide range of operating conditions. The helicopter rotor ensures indeed both the sustentation and the propulsion of the aircraft and should reach good efficiency for hover and forward flight conditions. A compromise has often to be found in the design of a rotor since a specific blade shape found to be efficient in hover may imply penalties in forward flight conditions and vice-versa. As CFD methods are now widely used to compute helicopter rotor aerodynamics, especially in hover, an optimization procedure based on a gradient-based method, CONMIN and a Navier-Stokes solver, *elsA* was successfully developed and applied in hover at ONERA [1].

This paper describes the extension of the application field of the optimization procedure named MORPHIA (acronym for Multi-objective Optimized Rotor Program for Helicopter Improved Aerodynamics) towards forward flight conditions and multi-objective optimization.

Multi-objective optimization is indeed a powerful answer to many design problems that aims at finding the best compromise between different objectives. Many strategies and algorithms have been considered in the literature and applied to aerospace engineering problems, in particular to design airfoils shape [2], [7]. Two types of methods are generally considered: deterministic methods, that are often based on the analytical construction of a single objective with several objectives [2], [3], [4]; and indeterministic methods, often based on genetic algorithms which allow several objectives to be taken into account simultaneously [5][6], [7].

These two types of methods are in the present paper considered and applied to helicopter rotor aerodynamic performance for several flight conditions. After a description of the optimization chain MORPHIA and of the multi-objectives strategies, a validation case on the linear aerodynamic twist of a rectangular blade rotor is presented. Then a more complex optimization, starting from a modern shape rotor (ERATO) is performed and a selection of results is fully analyzed.

Description of the optimization chain

The optimization chain for helicopter rotor aerodynamics, MORPHIA, was initially build to design blades with improved hover performance [1]. This optimization chain has been extended towards forward flight performance optimization and multi-objective optimization and is now centered around several flow solvers and optimization algorithms as shown in Figure 1:

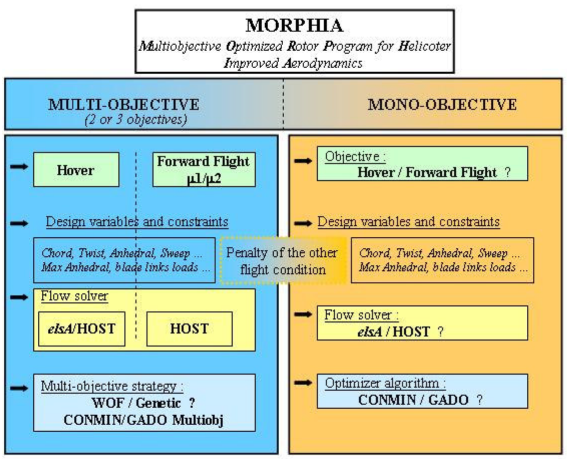

Figure 1: Global flowchart of the optimization chain MORPHIA

MORPHIA is made of two flow solvers: *elsA* a CFD code that solves the Reynolds Averaged Navier-Stokes equations and HOST [9], a comprehensive code in which the aerodynamics is modeled using a lifting-line theory. Moreover, two optimization algorithms can be used: a gradient-based method, CONMIN [10], and a genetic algorithm, GADO [11]. Depending on the association of these elements, optimizations of hover or forward flight performance, either mono-objective or multi-objective optimizations can be run. The optimization algorithm after an initialization phase creates a set of design variables that are used to build rotor blade geometry during a pre-processing phase. The performance evaluation of this rotor blade is then performed to compute the objective function in a post-processing phase, which is returned to the optimization algorithm. The process is continued until an optimum is reached.

Each element of MORPHIA are briefly described in the next paragraphs.

Optimization algorithm

Both deterministic and non-deterministic optimization algorithm are considered. The first one reaches only the nearest local optimum but within a limited number of evaluations. The second one ensures to reach the global optimum of the research space but requires a very large number of evaluations.

CONMIN – a gradient-based algorithm

CONMIN [10] is a gradient-based algorithm widely used in numerous optimizations studies [1], [12], [13]. Gradients are evaluated by finite differences at each optimization iteration. Three descent steps are performed per iteration to search for the objective function minimum with respect to the constraints by a feasible direction method (projection of the design vector). By this way, for N_{it} CONMIN iterations, the flow solver is called $N_{it}.(N_v+3)$ times, where N_v is the number of design variables.

GADO – a genetic algorithm

GADO (Genetic Algorithm for Design Optimization) was developed at the Rutgers University by K. Rasheed [11]. GADO is a steady genetic algorithm (the working population is constant over the optimization process in opposition to generational genetic algorithms), and works with real continuous design variables. GADO is based on the usual steps of a genetic algorithm: a random phase to generate a random population and evaluate each individual, a selection phase during which the individuals are ordered, a crossover phase to build a new individual from 2 selected individuals, a mutation phase during which a random perturbation is applied on the new individual, an evaluation phase to evaluate the new individuals and an insertion phase to decide if the new individual is injected in the working population or not. The process is continued until the optimum is reached.

Several innovative mutation and crossover operators have been developed in order to make the search process faster and more accurate. Depending on the number of evaluations allowed for the search, the stage of the optimization process is taken into account: the exploration of the search space is privileged at the beginning of the optimization process; the exploitation of the area near the optimum found is privileged at the end of the optimization process. If an early convergence is detected during the optimization process, a part of the population is randomized again (reseeding) in order to avoid local optimum.

Pre-processing phase

Design variables

The rotor blade shape is defining by a chord, a sweep, an anhedral, a twist and an airfoils distribution. Each of these parameters distribution can be optimized separately or combined one with another, all along the blade span or on a specific area of the blade. Only optimization with given airfoils can be performed (the airfoils are not modified through the optimization process), but the starting and ending position along the blade span of each airfoil can be optimized. For other parameters (chord, sweep, anhedral, twist), the design variables are control points of Bézier curves that define each distribution law.

When hover computation is considered, the collective pitch is also added as a design variable. By this way the thrust is not fixed during the optimization process, allowing the maximum of Figure of Merit to be reached.

Grid generation

When the *elsA* Navier-Stokes solver is used in the optimization, a grid has to be built at each new geometry evaluation. An in-house analytical grid generator is used for that purpose. All the grids have a C-H topology with 169 points in the chordwise direction, 49 points in the spanwise direction (with 28 sections on the blade) and 49 points in the direction orthogonal to the blade surface, which makes a total of 405769 points. The grid is splitted into 4 blocks in the spanwise direction in order to use parallel capability of the *elsA* software. Periodicity conditions allow the computational domain to be limited to an azimuthal sector around one single blade, as shown on Figure 2 for the 7A rotor. The grid extension in the vertical direction is equal to +/-1.4R and to 2R in the spanwise direction. The size of the first cells on the blade surface is chosen to have y^+ values below 1.

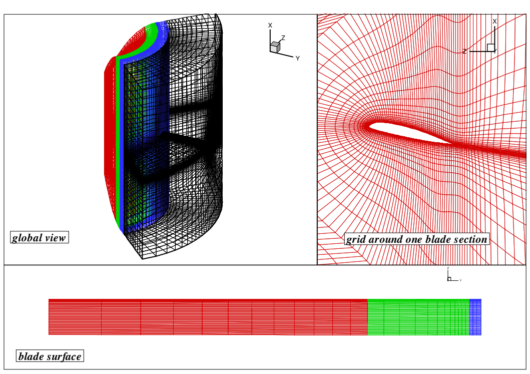

Figure 2: View of a typical optimization grid

Flow solvers

elsA

The *elsA* software, developed by ONERA, solves the Reynolds Averaged Navier-Stokes equations, written in a rotating Cartesian coordinate system (for the present application) in a cell-centered finite volume formulation. A classical Jameson 2nd order scheme discretization in space is used, with the addition of artificial viscosity. The time integration is ensured by an implicit LU-SSOR algorithm used with a backward Euler scheme. The convergence is improved by a 3-levels V-cycles multigrid method. Specific boundary conditions are imposed on the inflow/outflow boundaries, based on the 1D momentum theory. The turbulence is modeled with a k-ω (Kok) model with the addition of the SST correction. In the optimization process, each computation is initialized by the previous one to benefit from a more suitable initialization. 500 cycles are then necessary to obtain a satisfactory convergence of the integrated parameters. One hover computation requires finally 3440s (user time) in parallel mode on a dec_alpha platform using 4 processors and 680s in sequential mode on a NEC SX-6. However, *elsA* is only used for hover evaluations since the CPU time for a forward flight computations remains very important. In addition, forward flight performance evaluation with CFD would required a coupling with a comprehensive code to provide the rotor trim [8], which is not possible to use within an optimization loop.

HOST

The HOST code (Helicopter Overall Simulation Tool) [9] was developed by Eurocopter France in order to simulate and analyze the behavior of an isolated rotor or a complete helicopter in various flight conditions. HOST may be used as a dynamic code or as in the present study as an aerodynamic code. In the present study, HOST is used to compute both hover performance and forward flight performance for different advance ratios. The aerodynamic model used is based on the lifting-line theory. Given the trim (collective pitch in hover, flight conditions in forward flight) by the optimizer, the sectional Mach numbers and angles of attack are calculated, in order to determine aerodynamic coefficients from 2D airfoils tables. In hover, the induced velocity is then computed using a 1D momentum theory with a vortex ring model. In forward flight a prescribed wake model is used. In both cases, the soft blade model is activated.

Post-processing phase

Convergence

The convergence of each evaluation computation is carefully checked to ensure that the optimizer works with reliable data. In particular, comprehensive code like HOST may be very sensitive when very complex blades shapes are involved, which is frequent with GADO which is based on a random generation blade shape. To avoid any robustess problem, each time the convergence is not reached, a very poor objective function is affected to the design. By this way, the optimizer is forced to work within the evaluation capability of the codes *elsA* and HOST, without disturbing the optimization process.

Objective functions

In hover, the objective function is the maximum Figure of Merit (FM) which represents the rotor efficiency. In forward flight, the objective function is the rotor torque coefficient (Cb) which is directly linked with the total power consumed by the rotor.

Note that forward flight calculations are done to match given rotor lift and propulsive force coefficients in order to have a fair power evaluation, whatever the blade shape is.

Multi-objective strategies

Different solutions have been considered in order to take into account simultaneously several flight conditions in the optimization process. These strategies implemented in MORPHIA are detailed in the next paragraphs. The first ones are based on the gradient based algorithm CONMIN, the last one is based on the genetic algorithm GADO.

Through optimization constraints

The first solution is to use the existing optimization algorithm and to use constraints in the optimization. The idea is to minimize the power for one flight condition, while not allowing a power increase by more than a given percentage (*dopt* parameter) for the other flight condition. More precisely, one flight condition is the objective of the optimization process: maximize the Figure of merit at the maximum rotor thrust coefficient in hover or minimization of the consumed power at given rotor thrust and advance ratio in forward flight. The performance of the design rotor is also evaluated at each step for the other flight condition. This second evaluation is used as a constraint: in comparison with the performance of the reference rotor, the performance of the new design should not be more than *dopt*.

The constraint is written as follows:

$$g = 100.\left(\frac{Perf_{new} - Perf_{ref}}{Perf_{ref}}\right) - dopt$$

dopt is a parameter to be defined by the user (it is reminded that in CONMIN the constraint g is violated when $g<0$).

In MORPHIA, this strategy has been implemented for an optimization of hover performance with the forward flight as constraint and an optimization of forward flight performance with the hover flight as constraint. For the clarity of this paper this multi-objective method will be called *Constraint method.*

Weighting of objective functions

The second multi-objective strategy is based on the optimizer CONMIN. The gradient-based method can take into account one single objective. The idea is to build an objective function with several objectives; the objective function is a composition of several functions computed for several flight conditions:

$$F_{obj} = \sum_i \lambda_i F_{obj(i)} \text{ with } \sum_i \lambda_i = 1$$

Each single objective $\boldsymbol{F_{obj}(i)}$ is weighted by the λ_i coefficients, allowing the user to give more importance to some specific operating conditions. In practice this strategy has been implemented for different combinations of flight conditions (hover/forward flight) and evaluation code (*elsA*/HOST) in MORPHIA.

This multi-objective strategy will be used in this report with the name *WOF method*, WOF being an acronym for Weighting Of Functions (terminology often used in the literature).

Genetic algorithm

In its standard version, GADO can only be used to perform single objective optimization. However genetic algorithms are particularly well suited to perform true multi-objective optimizations, i.e. to treat simultaneously 2 or more objective functions. A lot of techniques have been considered to use genetic algorithm for multi-objective optimization as the work of Chafeka [14][15] who proposes two techniques to transform GADO into a multi-objective optimizer.

Among others, one way to perform multi-objective optimization is to stop working with individuals but working with groups of individuals, and to order the groups instead of the individuals. The rank is then determined taking into account the individuals with best values of the different objectives and the number of these best objectives. The ordering is performed iteratively as follows:

The first group is the group of non-dominated individuals with respect to all the objectives considered; they represent the whole best compromises between the different objectives, which is usually called the Pareto front. The individuals of this group are taken apart from the population. Inside the remaining population, a second group is defined with all non-dominated individuals, which are also taken apart from the population. And the ordering into group is so continued until all the individuals in the population have been ordered.

The purpose is so to have the most individuals in the first group i.e on the Pareto front at the end of the optimization process; the maximum number of individuals on this Pareto front is obviously the population size.

A multi-objective version of GADO has been coded at ONERA by G. Carrier [16][17] using the group techniques described above, that can take into account up to 3 objectives.

Validation on the 7A rotor aerodynamic twist

The multi-objective strategies are first tested, validated and compared on the simple case of the optimization of the linear aerodynamic twist rate of a rectangular blade. This optimization case, using only one design variable is very simple in hover: higher the linear aerodynamic twist rate is, higher is the maximum of Figure of Merit. On the other hand, the aerodynamic twist rate has to be limited to have good forward flight performance. A compromise has so to be found when designing a rotor blade.

Description of the test case

The optimization runs have been performed on the 7A rotor, a rectangular model blade (rotor radius=2.1m), designed and tested at ONERA. The reference linear aerodynamic twist rate of the 7A rotor is $-8^o/R$.

Table 1 presents all the optimization cases performed and some results that are commented in the next paragraphs. The cases Hover1, Hover2, FFlight1 and FFlight2 are single objective optimization runs respectively for hover and forward flight conditions (μ=0.4 and Zb=12.56), which results are used as reference results for multi-objective optimization runs.

The cases Cont1, Cont2, WOF1 and Gado1 are the multi-objective cases performed in order to evaluate the efficiency of the multi-objective strategies. In Cont1 and Cont2 cases, the objective is the hover performance and the constraint is the deterioration of the forward flight performance that should not exceed 0.5%.

For the case WOF1, several optimization runs have been performed for different sets of the weight parameters λ_1 and λ_2: the 310 evaluations correspond to the sum of the evaluations needed in the 10 optimization runs. The Gado1 case has been run using a population of 25 individuals and with 500 evaluations of each of the two objective functions (1000 HOST computations in total).

Single objective results

The hover cases were discussed in a previous study [1]. It was shown that the optimization process led to an important aerodynamic linear twist rate and even reached the geometric bound $\tau=-18^o/R$. In forward flight, the optimization process led to a very limited increase of the aerodynamic twist. A compromise is so expected when both flight conditions are taken into account.

Multi-objective results

Constraint method results

As expected, the results of the multi-objective optimization runs with the constraint method show that a compromise is reached: the value of the final linear aerodynamic twist $\tau=-15.1^o/R$ is between the optimal twist in hover $\tau_{optH}=-18^o/R$ and the optimal twist in forward flight $\tau_{optFF}=-11^o/R$. The results are very similar whatever the code used for hover performance evaluation is, showing that in the simple case of the linear aerodynamic twist optimization, the use of costly CFD codes may not be necessary. The compromise design reached is associated with an important improvement of the hover performance and a slight penalty for forward flight (+0.5% of power required, upper bound of the constraint). Indeed, the effect of the blade twist is known to be much more important in hover than in forward flight: the compromise appears logical.

In forward flight, the power decomposition of the optimized rotor gives an increase of the induced power (Pi=+12%), and a reduction of the profile power (Pp=-3%). The distributions of profile and induced power are plotted on Figure 3. It appears that the induced power penalty is mainly located on the advancing blade side near the blade root, where the increase of the linear aerodynamic twist leads to high angles of attack. Moreover, this figure shows also that the gain on the profile power is very limited.

Case	Type	Multi-objective Strategy	Optimizer	Code	τ (°/R)	gain FM (%)	gain Cb (%)	# Evals
Hover1	Hover		CONMIN	HOST	-18	**5.21**		31
Hover2	Hover		CONMIN	*elsA*	-18	**7.27**		50
FFlight1	Forward Flight		CONMIN	HOST	-11.07		-0.59	39
FFlight2	Forward Flight		GADO	HOST	-11.04		-0.59	200
Cont1	Multi obj	Constraint	CONMIN	HOST/HOST	-15.14	**5.50**	+0.5	69
Cont2	Multi obj	Constraint	CONMIN	*elsA*/HOST	-15.07	**6.30**	+0.47	51
WOF1	Multi obj	WOF	CONMIN	HOST/HOST	*see Figures*			310*
Gado1	Multi obj	Genetic	GADO	HOST/HOST	*see Figures*			500

Table 1: 7A linear aerodynamic twist optimization results (negative gain in Cb means power reduction)

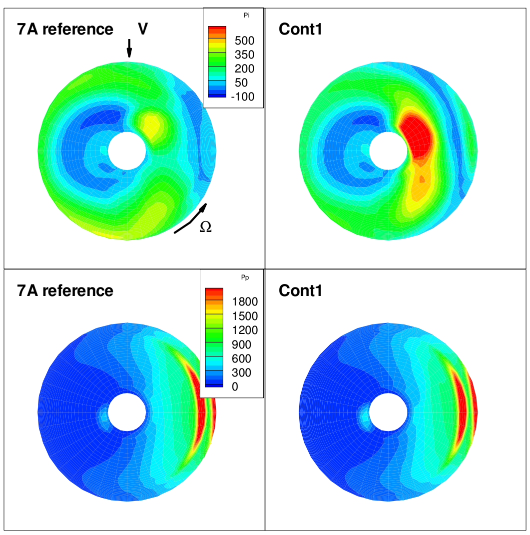

Figure 3: Comparison of induced and profile power distributions of reference and optimized twist 7A rotor in forward flight

WOF results

The results of the WOF optimization runs for different weighting parameters are presented on Figure 4. Each black triangle is an optimized design reached for a given set of the λ_1 and λ_2 weighting parameters.

$$F_{obj} = \lambda_1 \frac{FM}{FM_{ref}} + \lambda_2 \frac{Cb}{Cb_{ref}}$$

It should be added that the black triangles are ordered in accordance with the values of the weighting parameters:

- the design for which the forward flight power is minimum corresponds to λ_1=0.1, λ_2=0.9,
- the design for which the FM in hover is maximum corresponds to λ_1=0.9, λ_2=0.1.

Genetic results

The Gado1 run has been performed using a population of 25 individuals (i.e the maximum number of results on the Pareto front is 25), and 500 evaluations are requested.

The results of the Gado1 case, for which the genetic method has been used, are plotted in Figure 5, represented by the coloured squares. Each square corresponds to a design and the colour is the value of the linear aerodynamic twist. The group of the best individuals represented by this set of design is the group of the best compromises between hover and forward flight performance, considering the value of the aerodynamic twist. The curve that links all these best compromises is the Pareto front. One can notice that the values of the linear aerodynamic twist vary continuously when describing the Pareto front. As discussed many times, higher the linear aerodynamic twist is, better the hover performance is and stronger the penalty on the consumed power in forward flight is, and the inverse for lower twist.

Synthesis

The superposition of all the results of the different cases on Figure 5 leads to the following observations and statements:

- there is a very good agreement between the results obtained with the different methods for this simple case of the linear aerodynamic twist optimization (1 design variable)
- the hover optimization results are at the boundary of the Pareto front, and as mentioned previously the WOF results are ordered in accordance with the values of the weighting parameters
- In the simple case of the linear aerodynamic twist, *elsA* computations are not required to have a precise evaluation of the rotor performance (HOST returns good evaluations of the twist effect)
- Even if the results are very similar, GADO allows to have the whole set of best

compromise designs in one single optimization run with an equivalent number of evaluations in comparison to CONMIN and the WOF method.

This first case shows that the genetic method is more suitable to treat multi-objective optimization problems and the use of GADO will be privileged in the continuation of the study. Nevertheless the main weakness of the genetic method is the high number of objectives evaluations required which is at the present time incompatible with the use of CFD. And even if in the present case, no different results are observed between *elsA* and HOST evaluations, it may not always be the case when complex shape is involved [1].

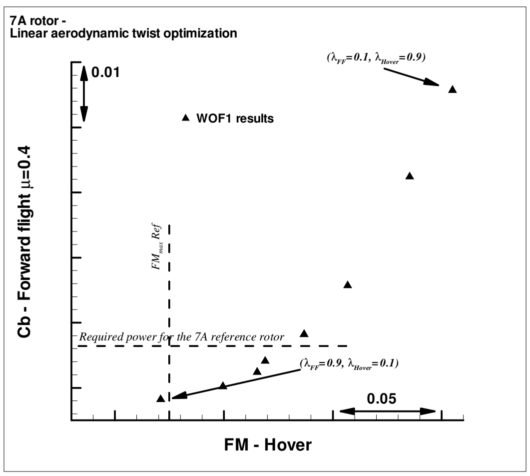

Figure 4: Optimization of the 7A rotor linear aerodynamic twist - WOF results

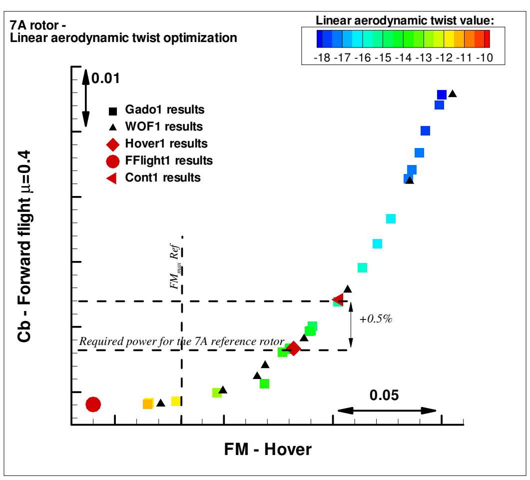

Figure 5: Comparison of the results of linear aerodynamic twist optimization of the 7A rotor with the different multi-objective strategies

Application on the ERATO rotor

Case presentation

One multi-objective optimization case is treated in this section using 8 design variables:

- chord distribution at r/R=1 (unchanged for r/R<0.9)
- anhedral distribution at r/R=1 (unchanged for r/R<09)
- sweep distribution at r/R=0.8 and 1
- twist distribution at r/R=0.57; 0.83; 0.9; 1.

The starting point is the ERATO rotor, initially designed in the framework of a cooperative program between ONERA, DLR and Eurocopter [18]. The purpose was to understand and reduce the noise generation of rotor blades, which has led to a forward/backward sweep planform (Figure 6). The ERATO rotor is a model rotor; its radius is 2.1 m for a Mach tip number equal to 0.617.

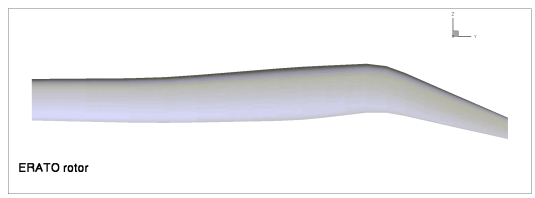

Figure 6: ERATO rotor planform

Three objectives are here considered simultaneously (illustrated in Figure 7):

1/ Maximum of Figure of Merit in hovering flight (flight condition that requires the maximal local power; this design point is obviously important for maximum take-off weight capability)

2/ Required power in forward flight at μ=0.2 for a medium rotor thrust Zb=12.5: at this advance ratio the required power is minimum; this design point is important for safety procedures

3/ Required power in forward flight at μ=0.4 for a medium rotor thrust Zb=12.5, that corresponds to a high speed cruise: this design point is important for maximum speed capability.

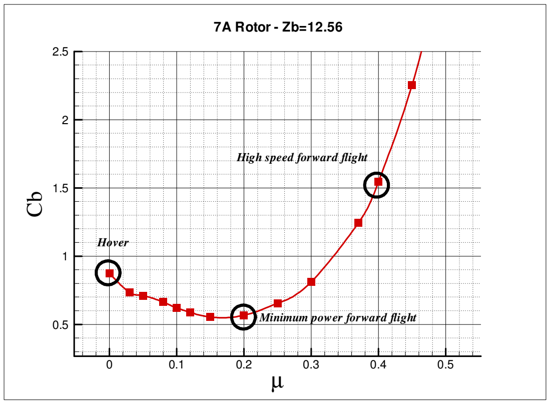

Figure 7: Choice of the design points for the multi-objective optimization

The genetic method is here applied and thus the 3 objectives are evaluated through HOST computations. Considering the number of design variables, a population of 50 individuals is used and 1000 evaluations are requested (consequently 3000 HOST computations are performed).

Results

The results of this multi-objective optimization run are presented on the Pareto front plotted in Figure 8, in which are represented all the "best compromise" designs within their performance in forward flight and colored by the gain in maximum of Figure of Merit.

In this case, even if most optimized designs have a better value of the maximum of Figure of Merit, only a few designs present important gain on the consumed power for both advance ratios. In particular, when important gains in hover are achieved, the power in forward flight for μ=0.2 is strongly increased. In the same way for big improvement on the forward flight performance at μ=0.2, important penalties are observed at μ=0.4. The compromise between the 3 objectives is difficult to reach in this case.

Figure 9 shows the values of the design variables that define the sweep distribution and the distribution of the optimized design on the Pareto front depending on these design variables. The second part of Figure 9 shows the value of the sweep at r/R=0.85, positive values indicating a forward sweep and negative values backward sweep. The design with important improvement of hover performance are characterized by a backward sweep distribution, and the design with important improvement of the performance in forward flight at μ=0.2 by important forward sweep distribution. The designs that show an improvement for the 3 objectives present a compromise between these extreme sweep distributions. These graphs show the complexity of the multi-objective optimization especially when hover flight and forward flight performance are together involved.

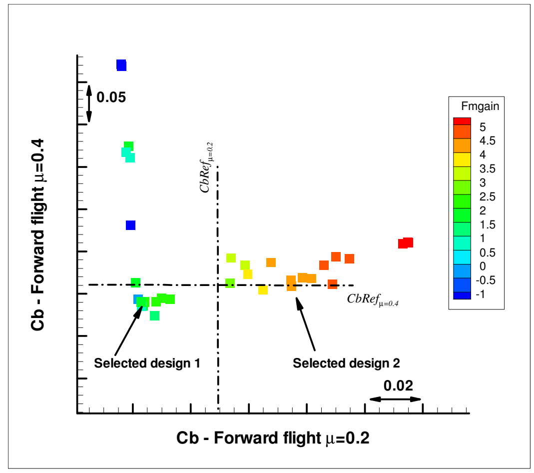

Figure 8: Results of the multi-objective optimization of the ERATO rotor using the genetic method - projection of the Pareto front

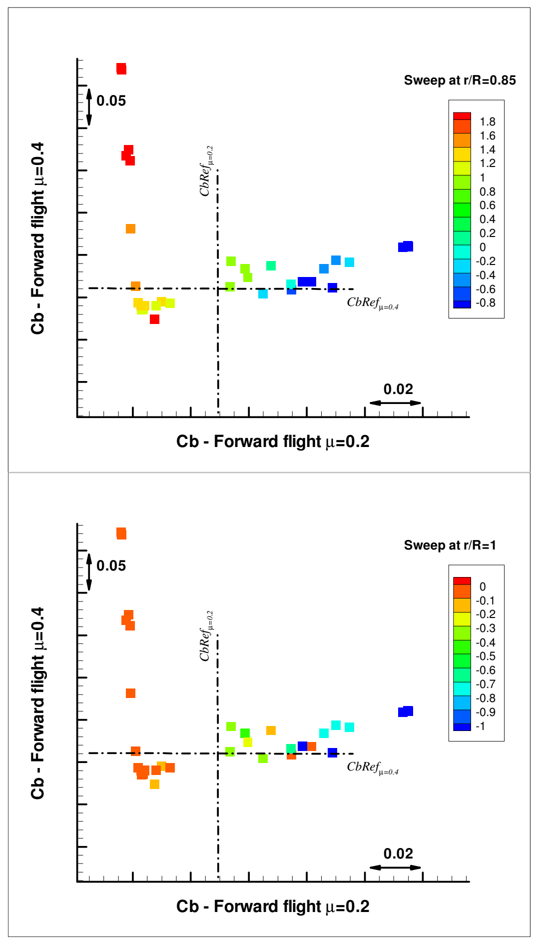

Figure 9: Position of the optimized designs on the Pareto front depending on the sweep design variables

Among the optimized designs with significant improvement that have been reached, two designs have been chosen to be analyzed in more details:

- one design that is a good compromise between the improvement of the three objectives: the forward flight performance are significantly improved but the hover performance is only slightly improved
- one design with significant hover performance improvement even if the forward flight performance is slightly lowered

Forward flight compromise – design 1

The planform of the selected design is presented in Figure 10. Its location on the Pareto front is shown in Figure 8. In comparison to the reference ERATO rotor, this rotor has a straight sweep distribution. The chord length is reduced at the blade tip and there is also a small anhedral of 3° at the blade tip. The twist distribution that was defined by 4 design variables is presented in Figure 11. Globally the optimized rotor is less twisted than the ERATO rotor.

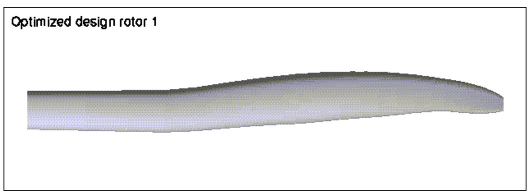

Figure 10: Optimized rotor design 1 planform

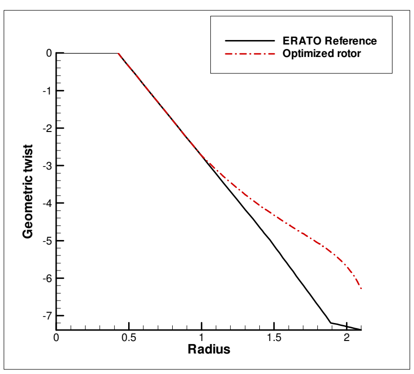

Figure 11: Comparison of reference and optimized design1 twist distribution

The FM/Zb curves of the optimized and ERATO rotors, computed with *elsA* on the medium grids using the k-ω (Kok) model and the SST correction are plotted and compared in Figure 12. Only a small improvement of the Figure of Merit can be observed for all thrust coefficients in comparison to the reference, but the maximum of Figure of Merit is not significantly increased (only +0.2 pts). CFD computations with *elsA* give thus a different result than HOST in the optimization process (+2 pts of FM_{max} predicted). Indeed the HOST computations were already shown to be not very accurate to evaluate the ERATO performance in hover. Hopefully the final optimized rotor has equal or slightly increased performance, in particular at high thrust coefficients for which 1 point of Figure of Merit is gained. This improvement at high lift coefficient is probably due to the small anhedral angle [1].

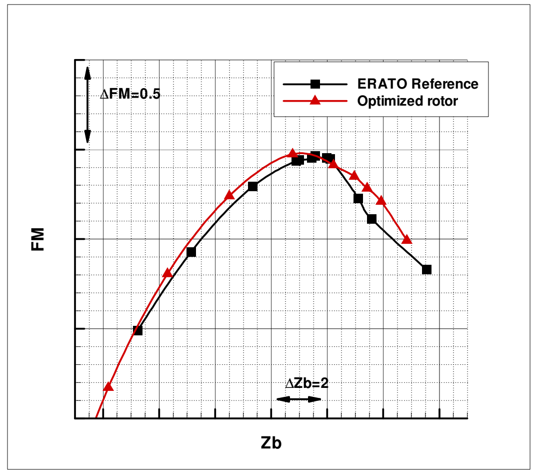

Figure 12: Comparison of reference and optimized design1 FM/Zb curve in hover

The Zb/Cb curves for different advance ratios are plotted in Figure 13 for both rotors. First, at the rotor thrust for which the optimization process is performed (Zb=12.56), the optimized rotor shows a power reduction for advance ratios up to 0.4. At μ=0.2, 0.3 and 0.4 the reduction of the consumed power is respectively of 4.6%, 6.5% and 1.45%, which are good improvements in comparison to the ERATO rotor performance. However at the highest advance ratio tested, μ=0.45, the power is strongly increased by 9.4%: the optimized rotor has important penalties at very high speed. On the other hand, at high thrust coefficient the gains on the consumed power of the optimized rotor seem to be higher.

In order to explore the origin of the improvements or penalties of forward flight performance, 3 forward flight conditions have been chosen: at μ=0.3 for two rotor thrust coefficients, Zb=12.5 and Zb=20 and at Zb=12.5 for two advance ratios μ=0.3 and μ=0.45. The decomposition of the consumed power is presented in Table 2 for the optimized rotor in comparison to the ERATO rotor:

Conditions	Pt gain (%)	Pi gain (%)	Pp gain (%)
μ=0.3 Zb=12.5	-4.60	-21.70	0.10
μ=0.3 Zb=20	-11.15	-21.67	-10.81
μ=0.45 Zb=12.5	9.40	22.92	**18.36**

Table 2: Decomposition of consumed power for different flight conditions

First, at μ=0.3 and Zb=12.5, the main improvement is due to an important reduction of the induced power. This reduction of the induced power is probably due to the optimized twist distribution which leads to lower angles of attack near the blade tip in the case of the optimized rotor. The difference of induced power distribution between the optimized rotor and ERATO rotor is plotted on Figure 14. The main reduction of the induced power is located in the inner blade area as an important increase is noticed in the outer blade area, especially near the fore and aft blade. This may be due to the anhedral distribution of the optimized rotor.

At a higher thrust coefficient Zb=20, the improvement on the induced power are quite the same as the one observed at Zb=12.5, but the profile power is also reduced by 10%. The poor forward flight performance at high thrust coefficient of the ERATO rotor were already detected in comparison to the 7AD rotor [18] and were demonstrated to be due to a consequence of incoming stall on the retreating side near the tip. The gain of the optimized rotor at high lift coefficient may be due to the chord distribution at the blade tip which has been thinned, since the airfoils distributions along the blade span are identical for the two rotors, and mostly due to the smaller twist distribution

At very high speed and for example at an advance ratio μ=0.45, both induced and profile powers are increased in comparison to the ERATO rotor. As shown in Figure 15, the induced power consumption increase is located on the advancing blade side and on the retreating blade side, especially in the outer blade area. This increase may be due to the anhedral distribution at the blade tip, even if the anhedral value is small.

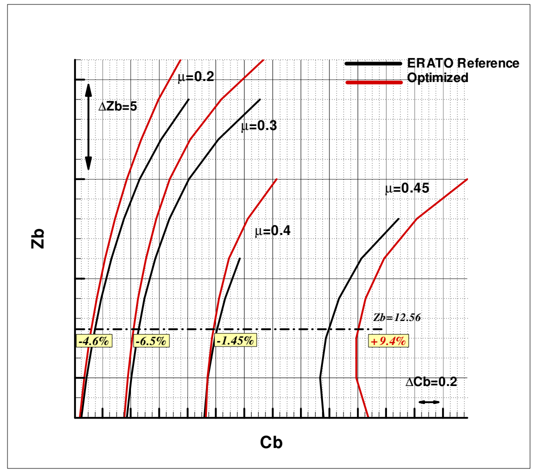

Figure 13: Reference and optimized design1 Cb/Zb curvesin forward flight at several advance ratios

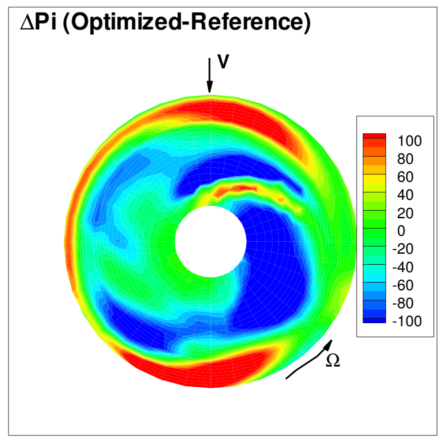

Figure 14: Induced power distribution difference at μ=0.3 and for a rotor thrust coefficient Zb=12.5

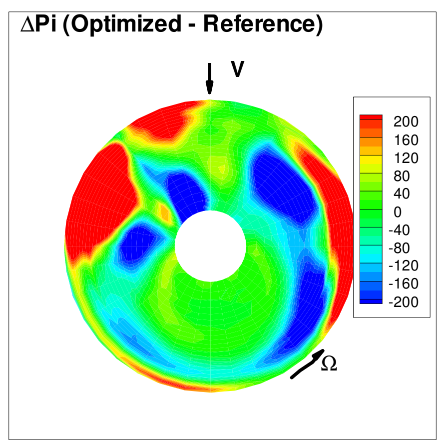

Figure 15: Induced power distribution difference at μ=0.45 and for a rotor thrust coefficient Zb=12.5

In conclusion the selected design among the Pareto front obtained thanks to the genetic multi-objective optimization shows improvement of the aerodynamic performance for all the flight conditions. In hover, the efficiency gains are very limited, except at high thrust coefficients where the Figure of Merit is increased by 1 point, even if the HOST predictions were more optimistic. This shows the lack of accuracy in hover flight performance evaluation with lifting-line method.

In forward flight, the final optimized performance is more impressive: the consumed power is reduced for all advance ratios except for very high speeds, for which the optimized rotor has much lower performance. However, at high thrust coefficients, large reduction of the consumed power is observed, especially at low advance ratios.

Globally, the optimization succeeds in reaching a design with improvement of the 3 objectives, but it remains always uncertainty on the off-design conditions were improvement are sometimes observed (high rotor thrust here) or strong penalties (very high forward speed here).

Hover compromise – design 2

The design presented here has mainly been chosen because of its hover performance. The design analyzed in this paragraph is presented in Figure 16. This design has a straight sweep distribution with a thinned tip with a small anhedral of 4°. Its main particularity is the twist distribution presented in Figure 17 which has been strongly increased.

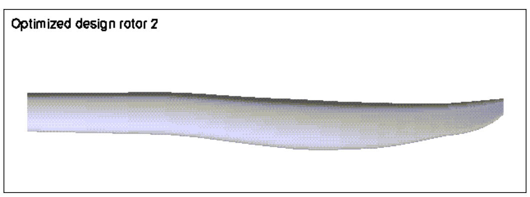

Figure 16: Optimized design2 planform

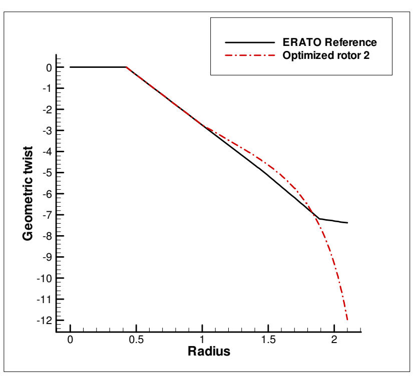

Figure 17: Comparison of reference and optimized design2 twist distribution

The FM/Zb curve (Figure 18) is computed with *elsA* using the optimization grids and the k-ω (Kok) + SST turbulence model. The maximum of Figure of Merit is strongly increased by 5.1 points and this maximum is reached at a much higher thrust coefficient Zb=19.6 instead of Zb=15.5. This spectacular improvement of the hover efficiency is mainly due to the optimized twist distribution. The twist at the tip has thus been increased by around 4°. The improvement observed here is similar to the one reached in [1] when optimizing the hover performance. However the main improvements were achieved thanks to the very strong anhedral distribution at tip.

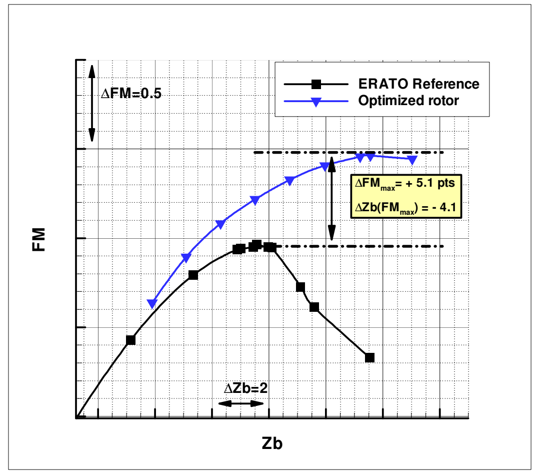

Figure 18: Comparison of reference and optimized design2 FM/Zb cuve in hover

The chosen design, when looking at the Pareto front on Figure 8, presents for Zb=12.56 an increase of the consumed power at μ=0.2 and a similar consumed power to the ERATO rotor at μ=0.384. The Figure 19 shows the Cb/Zb curve for several advance ratios to evaluate the case 2 optimized rotor performances at off-design forward flight conditions.

If the consumed power is increased at low speed and at low rotor thrust, the optimized rotor is better than the ERATO rotor for some flight conditions:

- at very high speed (μ=0.45), the optimized rotor has a power consumption reduced by ~1 % for all thrust coefficients,
- at high thrust coefficients, the optimized rotor has also a power consumption reduced in comparison to the ERATO rotor. The shift towards high thrust of the occurrence of the stall observed in hover seems to be effective in forward flight too.

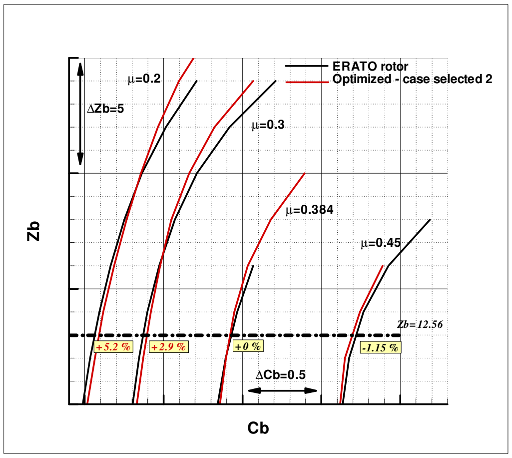

Figure 19: Reference and optimized design2 Cb/Zb curves in forward flight at several advance ratios

This second selected case confirms the success of the optimization chain in finding designs with improved performance. In this case, the hover flight was voluntary privileged and finally the optimized rotor chosen presents a very important increase of the maximum Figure of Merit. Moreover the forward flight performance penalties are limited. For some flight conditions the optimized rotor has even a reduced consumed power. In conclusion, this shows that the multi-objective optimization using genetic algorithm provides several designs defined as "best compromise" that all have advantages.

Conclusion

An optimization chain for helicopter rotor aerodynamic performance, MORPHIA, has been presented. The optimization procedure is articulated around 2 optimizers, a gradient-based algorithm CONMIN and a genetic algorithm GADO, and 2 aerodynamic codes, a Navier-Stokes solver *elsA* and a comprehensive code HOST. MORPHIA has been developed to perform multi-objective optimization using different strategies that are presented and tested. Two strategies rely on the use of CONMIN, the last strategy is based on GADO and allows up to 3 objectives to be treated simultaneously. These strategies have been first evaluated on the simple optimization of the 7A rotor linear aerodynamic twist. This validation case shows the efficiency and the coherence of the methods involved. The advantages of the use of genetic algorithm in multi-objective optimization are also demonstrated. In one single optimization run, the whole "best compromise" designs between the several objectives are obtained.

MORPHIA is then applied to treat an optimization case starting from the ERATO rotor and using several design variables on chord, sweep, twist and anhedral distributions to maximize rotor efficiency in hover and minimize consumed power in forward flight at two advance ratios. Among the compromise results given by the optimization, two rotor designs are deeply investigated: the first one is chosen for its performance in hover flight, the second one is chosen for its performance in forward flight. Off-design point performance are computed and each case. It is demonstrated that the optimization procedure succeeds in providing rotor and giving reliable performance evaluation. Finally, this application on the ERATO rotor demonstrates the applicability of the optimization chain in an industrial context to design new rotor blades.

Nevertheless, only the aerodynamic part of the design of a rotor blade is here taken into account. The future development of MORPHIA will be performed towards multi-disciplinary optimization. Much of the element of a multi-disciplinary are already ready to use since HOST is an aeromechanical code, that can evaluate for example vibratory properties of the blade or pitch link loads.

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