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# **Recent Advances in Rotor Aerodynamic Optimization, Including Structural Data Update**

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### **Abstract**

This study summarizes a rotor blade shape optimization exercise with an emphasis on the risk of off-design performance degradation. After optimizing by comprehensive analysis twist and anhedral with respect to rotor shaft power in a high speed, high-load forward flight condition, benchmarks against the reference blade were performed on vibratory levels, acoustics in descent flight and aerodynamic performance. Performance in forward flight and in hover is validated by coupling comprehensive analysis with CFD. In forward flight the coupled evaluations confirm the moderate comprehensive code predictions of shaft power reduction. In hover, the optimized-for-forward-flight rotor

underperforms the reference. Also, higher blade-vortex interaction noise levels occur in descent flight. Next, as a step to evolve towards increasingly feasible optimized designs, a method to update blade structural properties as a function of variations in blade shape is proposed. The method is first evaluated between two real blades of known properties. Secondly the method is implemented in a shape optimization loop and assessed for two optimization cases. It is shown that accounting for structural data modifications smoothes the optimal shape and produces more realistic designs, albeit at a cost of smaller margin in power reduction.

### Nomenclature

$C_T$	rotor thrust coefficient
$(C_x S)_f$	fuselage drag coefficient
FM	figure of merit
$M^2 C_n$	sectional normal force coefficient
$P_{ind}$	induced power, kW
$P_{prof}$	profile power, kW
$P_{tot}$	total (shaft) power, kW
R	rotor radius, m
S	rotor disk surface, m <sup>2</sup>
$V_h$	advancing velocity, kts
$\alpha_d$	descent angle, deg
$\mu$	advance ratio

$\sigma$  rotor solidity $\Omega$  rotor rotational speed, rpm

### Introduction

The design of helicopter rotor blades has significantly evolved during these last decades, especially due to the improvement of optimization algorithms, the advances in simulation methods, and the increase of computational capabilities, in all the disciplines in which the helicopter is concerned. The helicopter rotor design process is multidisciplinary in nature and involves a merging of several disciplines including aerodynamics, dynamics, acoustics and structures. The quality of the new designs of helicopter rotor blades largely depends on the accuracy of the codes used to simulate the helicopter behavior, the efficiency of the sensitivity analysis techniques, and the availability of suitable approximate analysis (Ref. 1).

The search of new designs by passive optimization of blade planform and/or airfoils can be carried out to improve one single objective function (performance improvement, reduction of vibration, reduction of blade-vortex interaction noise level) or multi-objective optimization. A major difficulty for designers is to find the best compromise solution, without degrading the performance of the optimized rotor on other disciplines, and/or other flight conditions than those chosen for the optimization point, while observing realistic technological constraints.

The design of new industrial optimized rotors follows this approach. Since the early 1990's, ONERA has performed several design studies, in the framework of single optimization programs, such as the ORPHEE and B2005 for aerodynamics (Refs. 2-4)

and for dynamics (Ref. 5) and ERATO for acoustics (Ref. 6). These efforts contributed to the new Airbus Helicopters' Blue Edge<sup>TM</sup> blade, based on a double-swept blade planform (Ref. 7).

In the same way, since 1975, the different phases of the British Experimental Rotor Programme (BERP (Refs. 8, 9)) led to the design of an optimized rotor blade (especially the blade tip) with increased hover and forward flight performance and reduced vibration. Successive technologies based on materials selection and structural and manufacturing constraints were successfully demonstrated on AgustaWestland helicopters.

Several works on optimization methodologies for helicopter rotor blade planforms have been performed at NASA since the 1980's, dealing with multi-objective optimization procedures, relative to the aerodynamics, dynamics, and structure disciplines (Ref. 10). For instance, an integrated aerodynamic/dynamic/structural procedure (Ref. 11) has been developed, split into two level analysis, with the upper level concerning the blade design on performance, dynamic and global structural measures, and the lower level concerning the structure optimization through the required stiffness. This procedure provided better design than a single-level optimization, as a consistent set of structural properties was found.

The quality of the optimized design depends on the accuracy of the numerical optimizers. Some of the optimizers require the calculation of the gradients (or even the Hessian) of objective functions and constraints when they exist (for example, the Kuhn-Tucker conditions are used for the feasible direction methods). Many of the studies mentioned above used the CONMIN optimizer (Ref. 12), a gradient-based method based on the feasible direction, for which the gradients are obtained numerically. Sensitivities

can also be obtained analytically, because of the linearization of the differential equations (Euler, Navier-Stokes) modeling the flow. The formulation of the discrete steady adjoint of the Reynolds-Averaged Navier-Stokes (RANS) equations has allowed efficient use of gradient based algorithms and high fidelity models to obtain an aerodynamic shape design of a helicopter rotor blade in hover (Ref. 13). In the field of civil aircraft wing optimization, an aero-structural adjoint method has been developed, allowing the improvement of both aerodynamic (planform parameters) and structural functions (internal structural element thicknesses and structural characteristics flexibility) in the same design space (Ref. 14). The adjoint formulations become more complex for optimization in forward flight. These formulations require either considering the problem as periodic, or solving the unsteady adjoint equation backwards in time. Moreover, aerodynamics and structural dynamics are largely coupled in forward flight, and fluid-structure interactions need to be taken into account (Ref. 15).

The gradient-based methods can not always be ensured to reach the global optimum. An alternative to these methods is the use of stochastic or genetic algorithms, which began to be used during the 90's. These algorithms require a large number of evaluations of the objective function (and eventually the constraints). The computational cost should be as limited as possible, by performing either low fidelity simulations, or by using surrogate based optimization methods (SBO). Recent studies show the effectiveness of surrogate models used in an optimization procedure to evaluate the objective function, in order to reduce vibration levels (Ref. 16) or to improve the aerodynamic performance of a helicopter blade (Refs. 17-19). These methods have the advantage of reducing the CPU cost of complex numerical simulations (such as loose CFD/CSD coupling), and offer a

global search of the design space. Concerning vibration level reductions in forward flight, it has been shown that a Kriging surrogate model is very efficient to determine an optimal design, despite some local errors. The same conclusions are drawn in a recent multi-point optimization (for hover and forward flight configurations) using the Nash game theory, to improve the performance of a helicopter rotor blade (Ref. 19).

Some of the above references clearly show that an optimum solution found from an aerodynamic design can present some unrealistic shape when additional structural and/or flight mechanics constraints are not taken into account in the optimization procedure. Modifying the structural data consistently with complex geometry blade planforms becomes an important step. In Ref. 20, structural data is scaled following the variation in size of the cross-section. In Ref. 21, updates to the blade structural properties (using parametric equations) in the design variables allow accurate evaluation of performance objectives and realistic structural constraints.

This paper is composed of two parts. The first one summarizes a recent rotor blade shape optimization exercise with an emphasis on the risk of off-design performance degradation. The optimization procedure is based on the coupling between a low fidelity comprehensive analysis (HOST code based on lifting line theory, Ref. 22) and an evolutionary optimizer (CMA-ES; Refs. 23, 24), chosen to avoid the risk to obtain a local optimum. After optimizing the blade shape with respect to rotor power in a high speed and high-load forward flight condition, benchmarks against the reference blade were performed on acoustics in descent flight and aerodynamic performance in hover.

Then, in the second part, as a step to evolve towards increasingly feasible optimized designs, a method to update blade structural properties within a shape optimization loop



is proposed and evaluated. The primary contribution of this article is the proposal, implementation and evaluation of a method to update the structural properties of a blade as a function of variations in its shape that prevents the aerodynamic optimization from producing unrealistic designs.

### **Blade Shape Optimization**

In the framework of the European CleanSky Green Rotorcraft project, DLR (Ref. 25) and ONERA (Ref. 26) conducted optimization studies in order to deliver to Airbus Helicopters Deutschland characteristics of an optimized full-scale rotor blade for performance improvement, which is planned to be tested in a whirl-tower. More specifically, ONERA worked on the twist distribution and anhedral of a reference blade, at a single-point condition at high speed ( $V_h=140\text{kts}$ ,  $\mu=0.36$ ), and high load ( $C_T/\sigma=0.09$ ).

### **Reference Rotor Definition**

The reference rotor is 5-bladed and full scale, with an aspect ratio of 18.6. The blade planform is presented in Fig. 1.

The blade is rectangular on a large extent of the span, and then, at the blade tip, the leading edge follows a parabolic evolution. The blade is equipped with the two airfoils OA312 and OA309. Linear interpolation is performed in the area between these airfoils. A linear geometric twist is defined, and no anhedral is applied at the blade tip.

### **Optimization Procedure**

The objective of this study is to define an optimized static twist law, and then an anhedral law to reduce the shaft power consumed by the main rotor. The optimization

procedure is driven by the open-source optimization tool DAKOTA (Design Analysis Kit for Optimization and Terascale Applications; Ref. 27), using a Covariance Matrix Adaptation Evolution Strategy (CMA-ES) algorithm. The CMA-ES (Refs. 23-24) is an evolutionary algorithm for difficult non-linear non-convex optimization problems in the continuous domain. It is typically applied to unconstrained or bounded constraint optimization problems. It has been shown that this method can be reliable for global optimization when derivative based methods fail due to rugged searched domains (discontinuities, noise, local optima, outliers ...).

The objective function is the minimization of the main rotor shaft power. The design variables are firstly the twist law, discretized on 9 Bezier poles distributed along the blade span, and then the anhedral law, discretized on 2 Bezier poles, on the outboard 5% of the span. No constraint is applied on the objective function. The design variables are bounded between  $-10^\circ$  and  $+10^\circ$  for the twist angle, and between  $-2^\circ$  and  $+2^\circ$  for the anhedral angle. 950 evaluations were performed to reach convergence of the optimization procedure. Since the comprehensive code used in this study uses a lifting-line approach which is not time consuming, the large number of optimizer calls is not prejudicial.

## **Numerical Tools**

The objective function is the minimization of the power consumed by the main rotor. The goal function is evaluated with the HOST comprehensive analysis (CA) (Ref. 22), developed by Airbus Helicopters. The aerodynamics of HOST is based on a lifting line approach based on airfoil look-up tables. Different options and corrections (sweep effect, stall correction, unsteady Theodorsen pitching moment coefficient, curvature effect ...) can be activated to improve the aerodynamic calculation. Different inflow velocities

models are available in the HOST code. In particular, the METAR code (Ref. 28) consists of taking into account a prescribed wake helical geometry.

HOST modeling of blade dynamics is achieved through a simple beam model with 3 degrees of freedom, which are the chordwise and flapwise bendings, and the torsion angle. In order to reduce the number of unknowns, each degree of freedom is projected on a modal basis. The blade is represented as an assembly of rigid segments connected by virtual joints and distributed along a straight axis, assumed to be collinear with the pitch axis. Center of gravity and elastic axis offsets are enabled.

The effects of the optimized twist and anhedral laws are analyzed in forward flight and in hover by a CA/CFD loose coupling method, which is more accurate than pure comprehensive analysis for the evaluation of three-dimensional effects of the flowfield. The CFD *elsA* code (Ref. 29), developed at ONERA, solves the three-dimensional URANS (Unsteady Reynolds-Averaged Navier-Stokes) equations for both background Cartesian grids and blade curvilinear grids. The spatial discretization of the equations is performed with Jameson's cell-centered second order scheme, using 2<sup>nd</sup> and 4<sup>th</sup> order coefficients of artificial viscosity. The unsteady algorithm corresponds to a backward Euler scheme, with an implicit Gear scheme for the 2<sup>nd</sup>-order time integration. The time step is equivalent to 1.2° of blade rotation. Turbulence is taken into account by the Kok  $k-\omega$  model, with SST corrections (Ref. 30) and Zheng limiter (Ref. 31). The flow is modeled as be fully turbulent.

In the 1990's, ONERA developed an aeroacoustic computational chain, called HMMAP, to predict the radiation noise emitted by a helicopter, especially in descent flight, for Blade Vortex Interaction (BVI) noise prediction. This tool has been

successfully used for the definition of an optimized aero-acoustic rotor, in the ERATO program (Ref. 6), and validated by wind-tunnel experimental data. In this study, the HMMAP chain is used to analyze the effects, in descent flight, of the optimized twist and anhedral laws (designed for a level flight condition) on the prediction of blade-vortex interaction noise level. This computational chain is divided into 5 steps (Ref. 32). After the trim calculation by HOST, a full-span free-wake model developed in the MESIR code (Ref. 33) is used to compute the velocities induced by all trailed and shed vortex lattices at each discretisation point of the wake using the Biot - Savart law. Then, the following acoustic steps are performed with the roll-up model performed by the MENTHE code (Ref. 34), the blade pressure computed by the unsteady singularity-based potential theory method ARHIS (Ref. 35), and the noise radiation performed by the PARIS code (Ref. 36) based on the Ffowcs Williams and Hawkings equations.

Table 1 summarizes the different numerical tools used in this study, on the one hand for the optimization procedures and on the other hand for the aerodynamic and acoustic analysis of the optimization results.

### **Optimization results**

The search of optimized twist and anhedral laws is performed for the following forward flight configuration, at rather high values of thrust and velocity:  $C_T/\sigma=0.09$ ,  $V_h=140\text{kts}$ ,  $\Omega=347.21\text{ rpm}$  ( $\mu=0.36$ ),  $(C_xS)_f/S\sigma=0.15$ . The isolated rotor is trimmed by the HOST comprehensive code, following a 3-variables law, prescribing these values for the rotor thrust ( $C_T/\sigma$ ), the propulsive force  $(C_xS)_f/S\sigma$ , and the rolling moment  $M_x$  (at 0

Nm). Prescribing the propulsive force allows a constant value of the fuselage power for the reference and the optimized rotors to be simulated.

The radial evolutions of the optimized twist and anhedral laws, obtained by the optimization procedure to improve the aerodynamic performance of the main rotor, are plotted in Fig. 2.

The optimization procedure provides a moderate decrease of the twist angle in the inner part of the blade, and then an increase of the twist in the outer part of the blade. Concerning the anhedral optimization, the best compromise leads to a negative linear deflection, corresponding to an angle of  $-4.7^\circ$  at the blade tip.

The effect of these two optimized laws is analyzed in detail from the aerodynamic, vibration and acoustic points of view.

### **Aerodynamic evaluation in forward flight by comprehensive analysis**

Comprehensive analysis with the HOST code has shown its capability to correctly predict the hierarchy between different rotors (ORPHEE, ERATO, B2005 programs). Comparisons with numerical results from other comprehensive analyses performed in the framework of international cooperations (HART-II; Ref. 37) are largely satisfactory.

The power reductions predicted by HOST comprehensive analysis, at the nominal optimization point, for the twist optimized rotor on one hand, and the optimized twist and anhedral rotor on the other hand, with respect to the reference are summarized in Table 2. It is reminded that shaft power can be split into different terms: induced power (linked to the lifting loads), profile power (linked to the drag of the airfoils), and parasite power (linked to the drag of the fuselage). Since trim is done to ensure a constant propulsive force, only induced and profile power are addressed next.

Significant reduction of the shaft power is predicted by the comprehensive computations (about 4%), mainly due to a decrease of the induced power. The main origin of the shaft power reduction comes from the optimized twist law. The addition of the optimized anhedral law on the optimized twisted rotor provides a further power reduction of only 0.1%.

The rotor disk distributions of the difference of the induced power and the profile power between the optimized twist and anhedral rotor and the reference are plotted in Fig. 3.

The decrease of the induced power for the optimized rotor is located in the inner part of the advancing side of the rotor (blue area). This reduction of the induced power is directly linked to the decrease of the optimized twist law in the inner part of the blade, leading to smaller values of incidence angles, and consequently of aerodynamic loads. A limited increase in profile power is generated at the retreating blade tip. This effect of the optimized twist law on the profile power (and so on the drag coefficient) can lead to predict a behavior more sensitive to stall. Actually, the flight domain for an advancing speed of 140 kts, predicted by comprehensive computations for the reference and the two optimized rotors, shown in Fig. 4, illustrates this trend for the highest thrust coefficients. For instance, for the thrust coefficient of  $C_T/\sigma$  of 0.1, the power reduction falls to 2%. The slope of the curve of the thrust coefficient versus the total power becomes lower for the twist optimized rotor at the highest loads. It can be noticed that the effect of the anhedral law is more important for low thrust levels.

**Aerodynamic analysis in forward flight by CSD/CFD loose coupling**

The power consumed by the main rotor is evaluated by a comprehensive analysis during the optimization procedure as the large number of evaluations (~1000) to determine the optimized point requires a fast evaluation. It is now interesting to check a posteriori the power prediction of the reference and the optimized rotors by a higher fidelity computational tool, taking into account the three-dimensional effects of the flow. This is achieved by a loose coupling between the HOST comprehensive code and the *elsA* CFD code (Ref. 29).

The CFD simulations are based on a structured, overset grids approach composed of a fixed Cartesian background grid and rotating, deformable, near-body blade grids (Ref. 38). The near-body multiblock curvilinear O-grids are built around each blade.. The total number of cells is equal to 1.7 million per blade. A Cartesian grid is automatically generated around the near-body grids with 5 levels of refinement. The finest grid extent is 3R in the radial and in the normal directions. The grid size of the finest grid is equal to 14% of chord length. The Cartesian grid contains a total of 13 million cells. Chimera technique is then involved in order to interpolate the solution between blade and Cartesian overlapping grids.

The performance of the reference and the twist optimized rotors are evaluated with the HOST and the coupled HOST/*elsA* codes, for the following flight configuration:  $C_T/\sigma=0.075$ ,  $V_h=140\text{kts}$ ,  $\Omega=347.21\text{ rpm}$  ( $\mu=0.36$ ),  $(C_x S)_f/S\sigma=0.15$ .

Both low and high fidelity simulations (respectively by HOST and HOST/*elsA* codes) predict significant power reduction for the optimized rotor with respect to the reference, respectively of -3.8% and -2.7%. Even if the flow is assumed to be fully turbulent in the

CFD calculations, the local aerodynamic loadings are more accurately predicted by high fidelity simulations than by comprehensive analysis, as it can be shown in previous studies (Ref. 39). The positive effects of the optimized twist law on the lift coefficient occur in the two types of calculations (Fig. 5): vanishing of the negative peak at the tip of the advancing blade (between  $90^\circ$  and  $180^\circ$  of azimuth) while reducing the lift in the inner part of the blade. As previously explained, these effects are directly associated to the reduction of the optimized twist in the inner part of the blade, leading to smaller values of angle of incidence, and so reducing the lifting loads. These effects are beneficial for the induced power level.

The reduction of the lift on the advancing side of the optimized rotor is balanced by an increase of the lift on the aft part of the rotor ( $\psi=0^\circ$ ), to ensure the same total rotor thrust. This trend is particularly pronounced with the HOST/*elsA* loose coupling calculation. This over-loaded area is supposed to be partly responsible for an increase of the (induced) power consumed by the optimized rotor in this area, predicted by the loose coupling calculations, leading to a moderation of the total power reduction with respect to comprehensive simulations.

### **Aerodynamics analysis in hover**

In hover, performance of the reference and the optimized rotors is predicted using the loose coupling methodology between the HOST comprehensive code and the *elsA* CFD code. The multi-block grid generated for the reference blade is deformed with respect to the optimized twist and anhedral laws (following Bezier curves deformations). The near-body grids are then immersed in a cylindrical background grid, using the Chimera



technique. Only one sector of the 5-bladed rotor is modeled and periodicity boundary conditions are applied on the azimuthal boundaries of the computation domain.

The evolution of the figure of merit with respect to the rotor thrust is plotted in Fig. 6 for the reference and the two optimized rotors. The plotted points confirm the expectations, namely that optimization in forward flight tends to degrade hover performance.

At the highest thrust coefficient solved ( $C_T/\sigma=0.095$ ), figure of merit is decreased by 2.7 points for the optimized twist rotor, and by 1.8 points for the optimized twist and anhedral rotor with respect to the reference, which is quite significant. Like in forward flight, the optimized rotors' performance declines faster than the reference at the higher loadings. The effect of anhedral is noticeable, with an improvement of the figure of merit, when the thrust is increased. This improvement can be explained by a reduction of the lifting airloads at the blade tip. This reduction of the loads is directly linked to the reduction of the intensity of the tip vortex. This anhedral effect is illustrated in Fig. 7 by comparing, without (Optim Twist) and with anhedral (Optim Twist + Optim Anhedral), a vorticity contour on a vertical plane upstream of a blade revealing the vortex shed by the previous blade tip.

### **Acoustic analysis in descent flight**

Even though the main objective of this study is to improve the aerodynamic performance of the reference rotor by optimizing its twist and anhedral laws, it is interesting to evaluate a posteriori the blade-vortex interaction (BVI) noise levels of the resulting aerodynamically optimized rotors.

The aero-acoustic computational chain HMMAP is used to evaluate the BVI noise. The flight configurations are the following:  $C_T/\sigma=0.0845$ ,  $V_h=65\text{kts}$ ,  $\Omega=347.21\text{ rpm}$  ( $\mu=0.17$ ), the descent angle  $\alpha_d$  varying from 0 to  $12^\circ$ .

The isolated rotor is trimmed with the no-flapping law. The thrust and the propulsive loads to be reached are determined with respect to the value of the descent angle. The maximum BVI noise levels (determined 115m beneath the rotor disk, and filtered between the 6<sup>th</sup> and 40<sup>th</sup> blade passage frequencies) detected on the advancing side of the rotor are plotted in Fig. 8. It clearly appears that the optimized rotors are noisier than the reference, especially when the descent angle is steeper. The anhedral tends to slightly increase the BVI noise level with respect to the optimized twisted rotor, especially provided by a decrease of the downwards convection of the wake, which moves closer to the blade tip (Ref. 21).

### **Updating blade structural data during a shape optimization loop**

The main idea of this investigation is to develop a fast method to estimate the variations in structural properties of a blade following a change in its shape. The objective is to include this new structural update capability in an aerodynamic shape optimization loop. Thus, the potential performance gain of any new blade shape will be more realistically assessed, provided the aerodynamic cost function is evaluated through a coupled aeromechanic approach.

This section is structured in four parts: first it presents the beam structural model in the comprehensive rotorcraft code HOST, because the developed method for structural update was adapted to HOST, although it should be valid for any general beam

representation. Then the approach for developing the structural update is described. Thirdly, a validation exercise is carried out comparing against real blades of known properties. Finally, the method is assessed through two optimization exercises.

### **Development of a method for estimation of structural properties**

In the current study, structural data estimations are inferred from a parametric study based on finite element computations, as described next. The approach for developing this innovative method was based on two steps. A set of polynomial functions for sectional mechanical properties such as flap bending stiffness, lag bending stiffness, torsion stiffness, mass, etc were produced by conducting a parametric study with a finite element model of a typical blade cross-section structure and varying its chord and thickness. The selected approach assumes an internal structure of the cross-section of the blade, representative of a typical sandwich construction of rotor blade. While the structural layout of the cross-section remains constant, it is its scaling (e.g., chord variations, which will also affect thickness if the airfoil relative thickness is to be maintained) that will modify the mechanical properties.

In the shape optimization loop, for each new shape to evaluate, blade structural properties are modified accordingly before evaluating the rotor power through an aeromechanic simulation. These data modifications include both spanwise stiffness information and geometrical information concerning the location of the centre of gravity with respect to the blade pitch axis. Blade planform variations, like sweep, will not modify the stiffness of the blade, but will change the offsets of the elastic axis and sectional centre of gravity with respect to the blade pitch axis, so they are taken into account as well. The update of stiffness, mass and inertia data relies on the functions

obtained in the first step. Geometrical data on offsets between the different airfoil centres (gravity, shear, tension) and the blade pitch axis are estimated analytically from the above mentioned assumption that the internal structure of the blade cross-sections remains constant (i.e., the position of the centres relative to the chord and thickness of the cross-section does not vary).

The method needs three inputs: (1) the structural properties of the original blade; (2) the shape of the original blade; and (3) the new shape. The output is a modified set of structural data according to the variations between the original and the new geometries.

Stiffness, linear mass and inertia are updated as follows:

$$\text{New value} = \text{original value} \times (\text{new estimated value}) / (\text{original estimated value})$$

where '*estimated*' means that the structural value has been recomputed, with the polynomial functions, from the cross-section chord and thickness. In addition, polar inertia must be corrected by the Steiner parallel axis theorem whenever a change in sweep or dihedral translates the cross-section with respect to the rotation axis for polar inertia, which in this study is the blade pitch axis. This is achieved by adding to the above expression the term  $md^2$ , where  $m$  is the section linear mass (freshly updated) and  $d$  the distance between the two parallel axes.

### **Validation by comparison against two real blades of known properties**

This validation stands on two real blades of known properties. These blades are ONERA's 7A and 7AD scale model blades, tested in ONERA's S1MA wind tunnel in 1991. They only differ in the outboard 5% of the blade: 7A has a rectangular blade tip, whereas 7AD has a parabolically swept leading edge, as schematized in Fig. 9. Although

not apparent in the figure, 7AD tip features also some anhedral. In the actual model both tips could be clipped on a common truncated blade.

The structural update method is used to estimate 7AD's structural properties, having as input the geometry of both blades and the structural properties of the 7A blade.

Fig. 10 compares some of 7AD's actual structural properties (labelled 'Data 7AD') against those predicted by the new method (labelled 'Estimated 7AD'). Figures include relative error between data and estimation at the blade tip. Estimations are most accurate for flap bending stiffness, with a relative error of -6.3%. The highest error is on the linear mass, which is overestimated by 127% at the blade tip. This in turn increases the error in the polar inertia due to the Steiner term  $md^2$ . If the actual 7AD linear mass is imposed in the polar inertia estimation, then polar inertia relative error is reduced from current 64.3% to -27.3%.

Although relative errors in this validation exercise are often double-digit, the error would be much larger if structural data were not updated at all, as can be seen by looking at the original 7A data.

To validate further this estimation of 7AD structural properties, three comprehensive analyses of the 7AD rotor in forward flight, at advance ratio 0.4 and  $C_T/\sigma=0.080$ , were carried out, the first one with the actual 7AD properties, the second one with 7A properties and the third one, with the estimated 7AD properties. Total power differences are negligible, probably because only the 5% outboard blade structural properties differ. However, maximal blade elastic torsion (which happens at the advancing blade tip, azimuth=90 deg) is more revealing. The 7AD comprehensive analysis with original 7AD data predicts a nose-down twist equal to -2.83 deg. With 7A structural data, nose-down

twist is smaller, -2.59 deg, consistently with a larger tip chord and thus greater torsional stiffness. With estimated 7AD data, elastic twist is -2.87 deg, which is much closer to the true 7AD results. Had the structural properties differed over a greater outboard span, differences in elastic twist would have likely had an impact on rotor performance.

The least accurate assumption in the new method probably lies in the estimation of the position of the tension center (where axial forces can be applied without inducing any bending, and which is assumed to be colinear with the elastic center (where shear forces can be applied without inducing any torsion)). The method simply shifts the position of the tension center by as much as the variation in sweep and/or anhedral. While this is known to be inaccurate, an accurate estimation of the tension center position would require an effort beyond the fast and computationally inexpensive capability of this method.

### **Assessing the influence of the structural update on two aerodynamic shape optimization exercises**

The new tool for structural data update has been tested on two optimization cases: an optimization of chord distribution and an optimization of sweep distribution. Twist is not tested because the method of estimation of structural properties does not model the effect of twist variations on blade stiffness (e.g. transfer of flapping stiffness into lag stiffness and vice versa). That is why the twist optimization performed in the first part of this investigation would not benefit from the structural data update.

The two examples compare the outputs of optimizations in forward flight ( $V_h=140\text{kts}$ ,  $C_T/\sigma=0.09$ ) using an evolutionary algorithm (CMA-ES) and evaluating the cost function (shaft power) through comprehensive analysis, with and without the structural update

option. Comprehensive analysis takes into account the elasticity of the blade and therefore, the aerodynamic performance depends on the mechanical properties of the blade.

### *Chord optimization with structural data update*

The parametrization is defined by 10 Bezier poles spread from  $r/R=0.30$  to  $r/R=1.0$ . Thrust-weighted iso-solidity is maintained. Fig. 11 shows a planform view of the reference blade and the optimized blades with and without updating the structural properties. The optimization without structural update reduces rotor power by 1.56% and features a 40% chord reduction around  $r/R=0.50$ . If structural stiffness update is considered for such a chord reduction, the result is a decrease of torsional stiffness  $GJ$  as shown in Fig. 12. A torsionally softer than designed blade turns into greater elastic twist than intended, which in turn drives aerodynamic angles of attack off-design. As a result, aerodynamic performance is degraded. When the optimized-without-update blade is evaluated with an updated structure, rotor power increases by 11.8% with respect to reference. Maximum elastic twist of this rotor surges to  $-14.7\text{deg}$  (nose down) at azimuth  $225\text{deg}$ , whereas the rotor without structural update had a maximum elastic twist of  $-4.88\text{deg}$  at azimuth  $175\text{deg}$ . This explains why, when the structural update is activated in the optimization, the optimal chord distribution (Fig. 11) is closer to the reference chord than when not considering structural update. However, the reduction in rotor power of the chord optimization with structural update is smaller: 0.22%, compared to the 1.56% of the optimization without structural update.

Rigid blade comprehensive calculations predict a rotor power reduction of +1.3% for both optimized rotors with respect to the reference rotor in rigid blade modelling. This shows that a part of the power reduction is exclusively due to aerodynamic shape.

An alternative solution could be to optimize the blade twist simultaneously with the chord distribution, which is actually a means to link the blade deflected shape to its jig shape. This would allow investigating a larger design space for chord distribution while using the structural data update.

### *Sweep optimization with structural data update*

The parametrization is defined by 6 Spline<sup>1</sup> control points spread from  $r/R=0.50$  to  $r/R=1.0$ . Fig. 13 compares the obtained blade planforms depending on whether the structural update was activated or not during the evolutionary optimization. Like in the case of the chord optimization, the update of the structural data has resulted in an optimal planform which has a smoother shape than the optimal planform without structural update. In terms of power, the optimization without structural update reduces power by 4.2%, whereas with structural update power is reduced by 3.3%.

It was attempted to evaluate by comprehensive analysis the sweep distribution obtained after an optimization without structural update, although estimating the structural properties corresponding to the new optimum shape. The comprehensive code

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<sup>1</sup> Splines are here preferred to Bezier because, as opposed to chord parametrisation where chord variations are defined as positive fractions of a reference chord, sweep may combine positive and negative values. In that case, Bezier control points may take large values (which must be then allowed in the design space), whereas splines pass through the control points that are the optimization parameters.



failed to converge for the soft blade computation. However, rigid blade computations predicted identical power for the reference rotor and optimum without structural update rotor. This reveals that the reductions in rotor power are not achieved due to compressible flow alleviation by sweep, but rather to aeroelastic effects; displacing the blade forward contributes to displacing the aerodynamic lift forward of the pitch axis, which contributes to cancelling the nose-down elastic twist. Thus, both optimized planforms undergo smaller torsion amplitudes than the reference blade, which allows them to keep an actual twist distribution closer to the reference geometric twist.

An aeroelastic stability analysis would have probably ruled out forward-swept blades because forward sweep favors static divergence, but stability has not been considered here.

### **Conclusions**

Recent optimization work performed at ONERA, in the framework of the European Research Program Clean Sky, as part of the Integrated Technology Demonstrator "Green Rotorcraft 1 - Innovative Rotor Blades", has been presented in this paper. The first topic concerns the aerodynamic and aero-acoustic evaluations of the reference and shape optimized rotors in twist and anhedral. The objective is the minimization of the shaft power consumed by the main rotor, evaluated during the optimization procedure by a comprehensive code (low CPU cost), at a single-point forward flight configuration. Significant power reduction is predicted in forward flight, at the end of the optimization procedure and by a posteriori computations: (a) around 4% predicted by comprehensive analysis and (b) around 3% predicted by CFD-CSD loose coupling.

In both types of computations, the main origin of the power reduction comes from a large reduction of the lifting loads in the inner part of the advancing part of the rotor. It would be interesting in future studies to take into account the effect of three-dimensional unsteady effects of the flow through multi-fidelity surrogate models.

Then, a posteriori computations have been conducted to predict the performance in hover, and the level of blade-vortex interaction noise in descent flight. It clearly appears that the twist law, optimized for a forward flight configuration, is not well adapted either to hover or to descent flight: (a) 2.7 points on the maximum figure of merit in hover and (b) up to +8 dB in descent flight.

This study clearly shows the interest to perform multi-point optimization procedures, to take into account different aerodynamic, and/or acoustic or aero-elastic behaviors of the blade.

As a step towards more feasible blade shape designs, a fast, low-cost, method for structural data update has been developed and implemented in a shape optimization procedure. This method is based on functions obtained by polynomial fitting on the results of a 2D finite-element model of a typical, sandwich technology, blade cross-section, which was solved for several relative thicknesses. Accounting for changes in structural properties helps eliminate those optimization specimens that are structurally unrealistic. Optimal shapes tend to be smoothed compared to the optimal shapes obtained without structural update.

The method has proved its capacity to provide useful estimations of structural properties on a validation exercise using two real blades of known properties. Future

shape optimizations at ONERA will continue exploiting the advantages of structural data update.

### Acknowledgments

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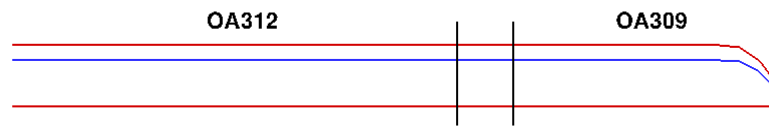
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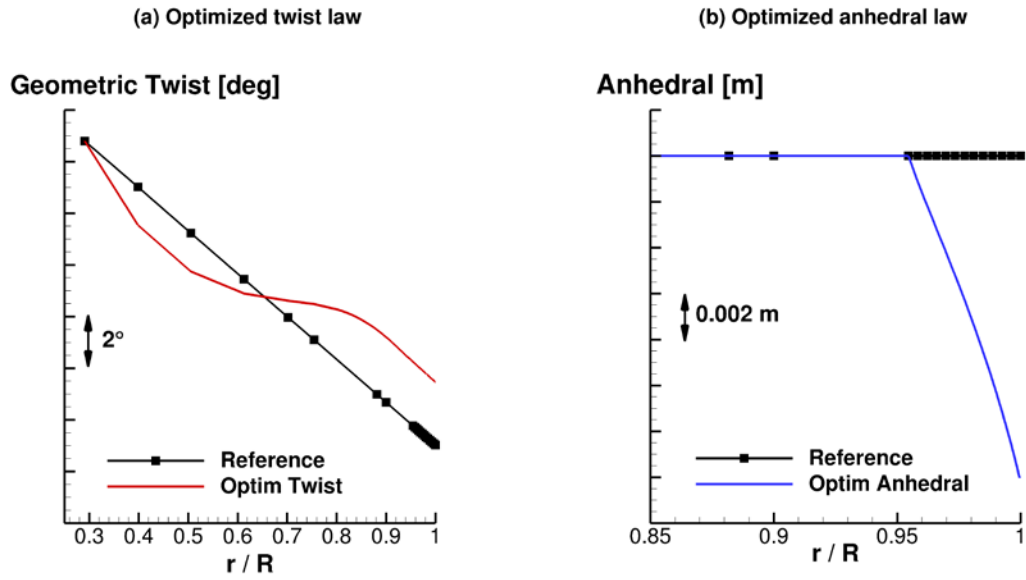


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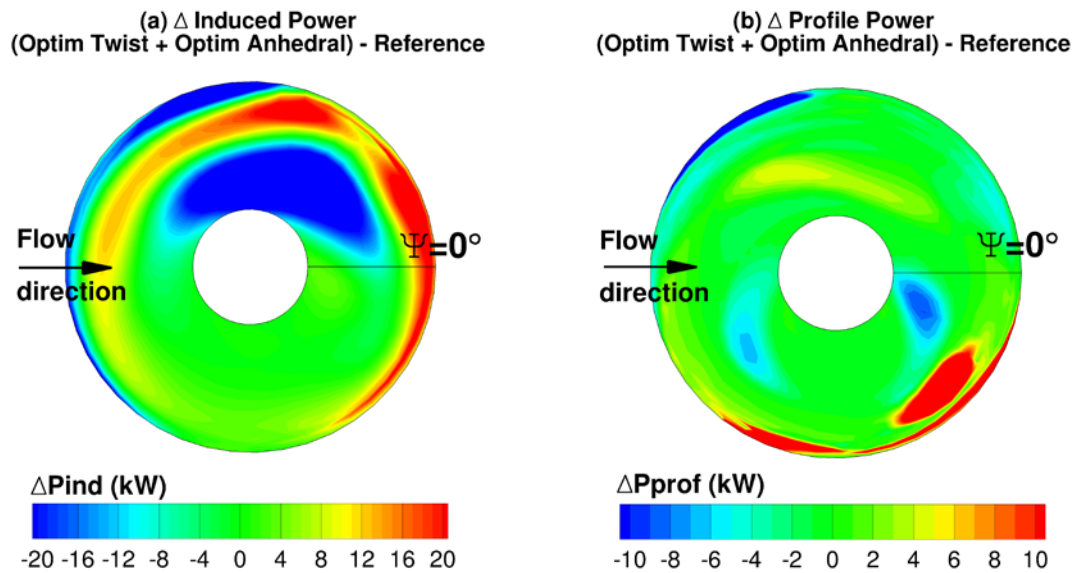
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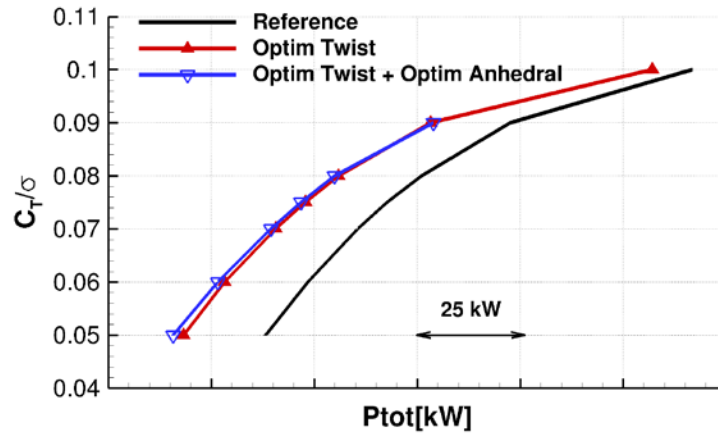
**Fig. 1.** Planform of the reference blade



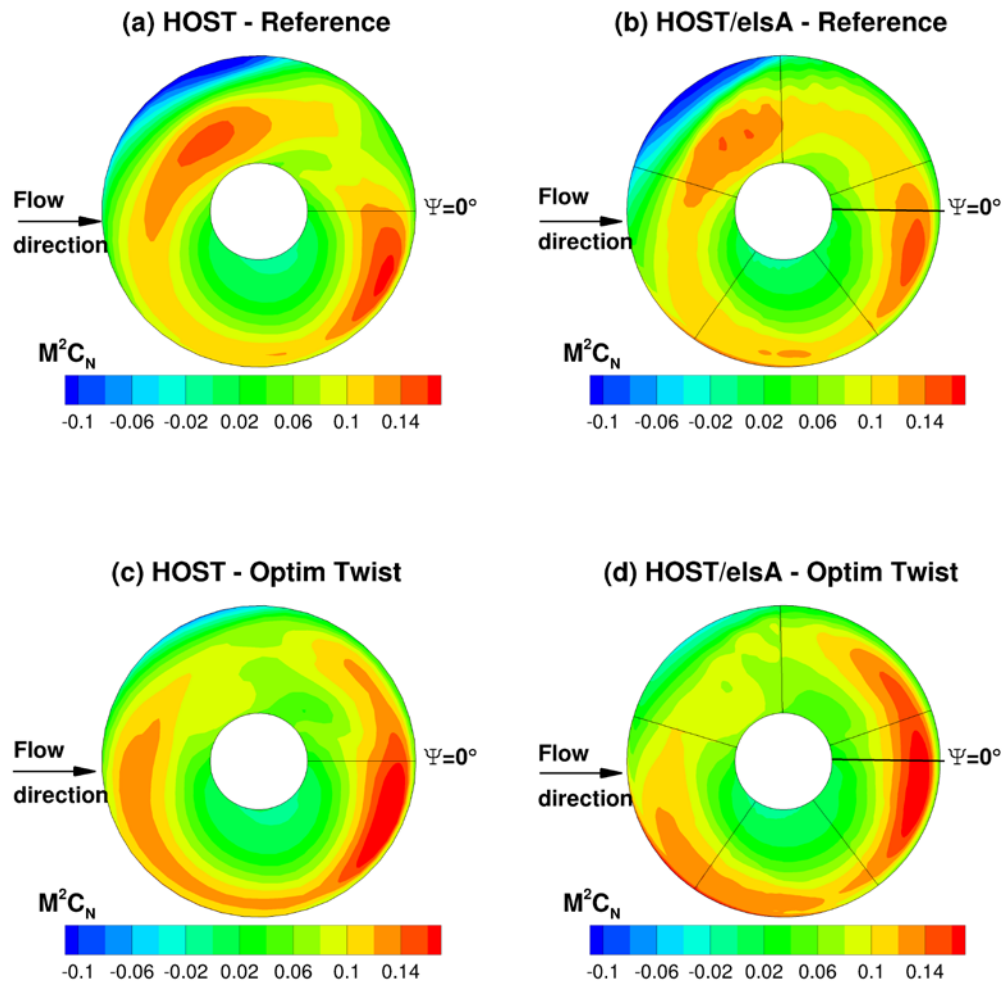
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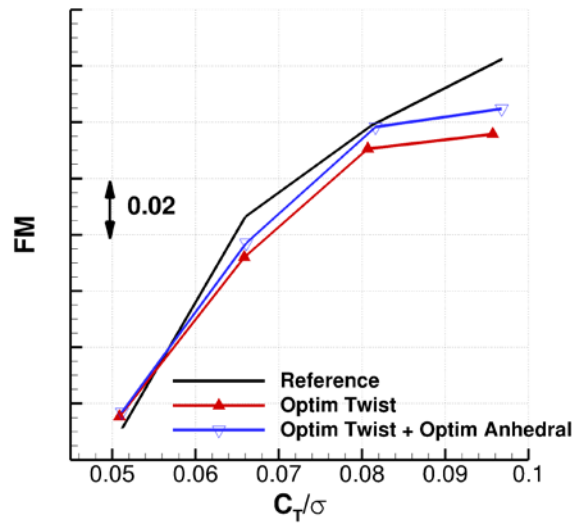
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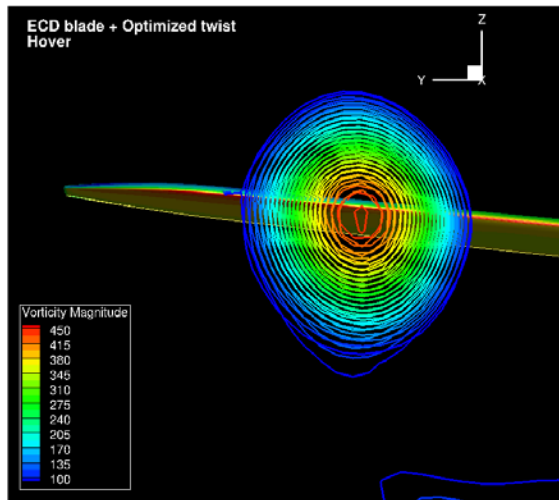


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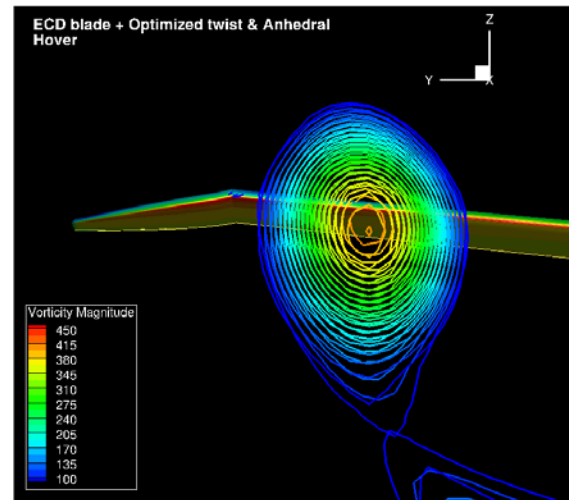


**Fig. 6.** Hover performance of the reference and the rotors optimized for forward flight

(a) Optim Twist

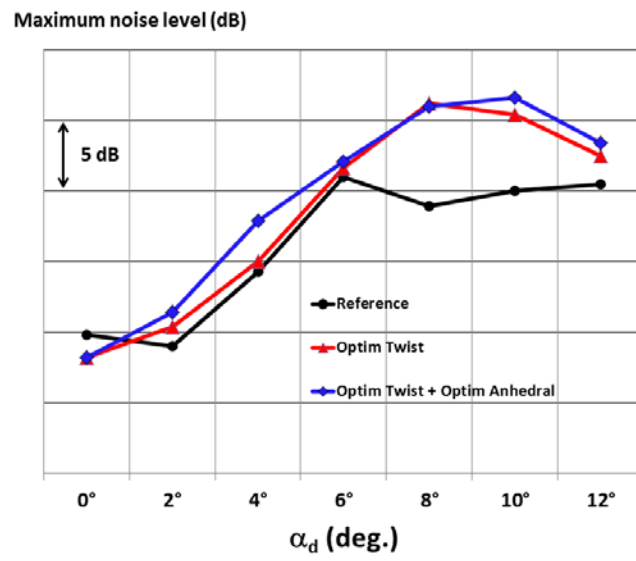


(b) Optim Twist + Optim Anhedral

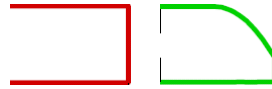


**Fig. 7.** Effect of anhedral on tip vortex vorticity magnitude (in  $s^{-1}$ ) of the optimized rotors, at  $C_T/\sigma=0.095$

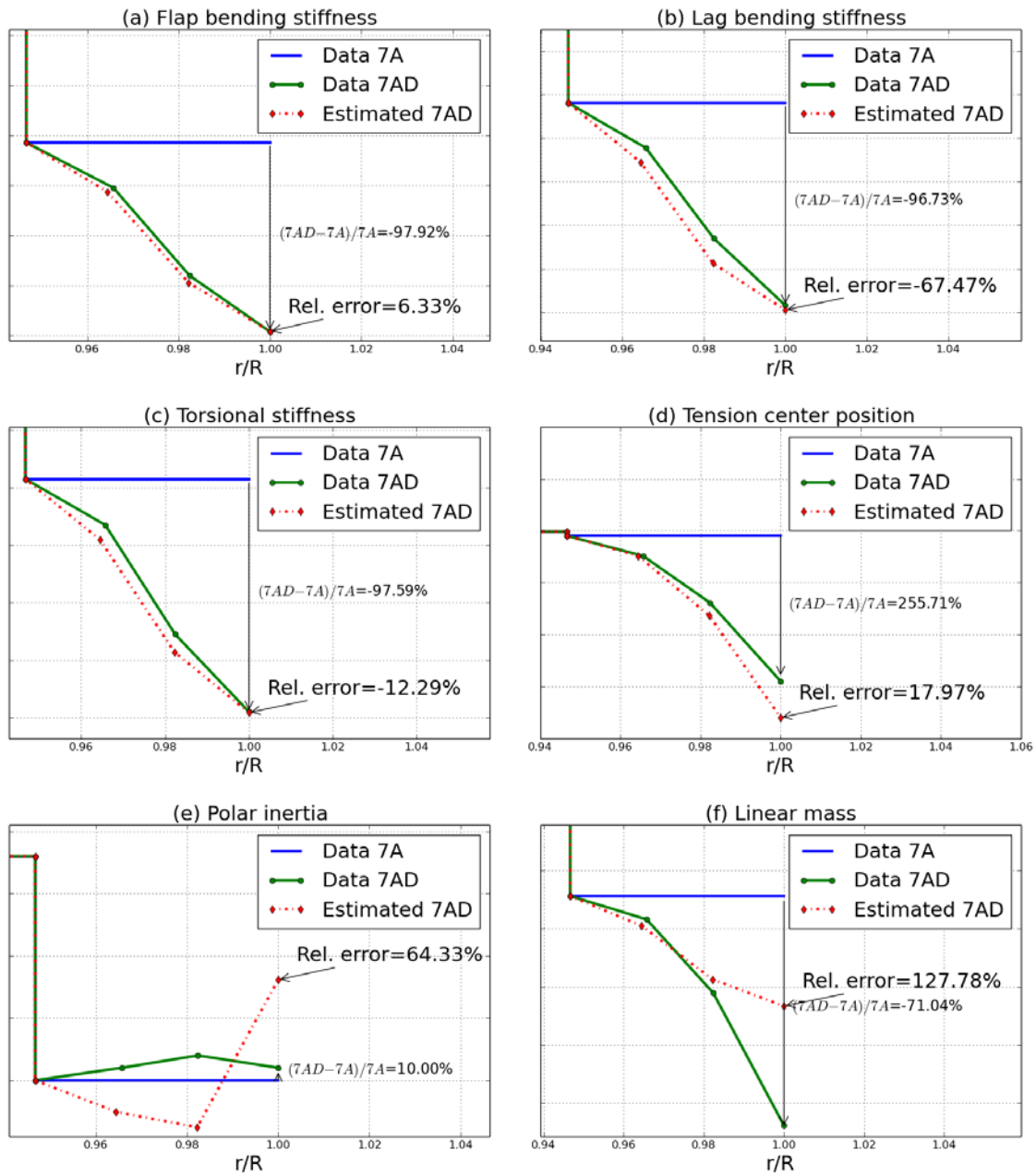




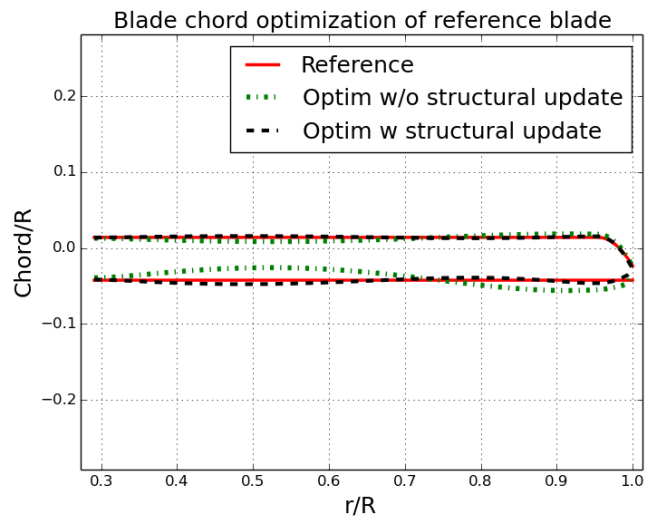
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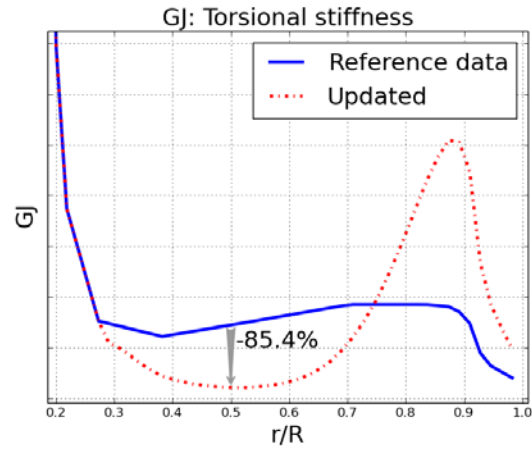
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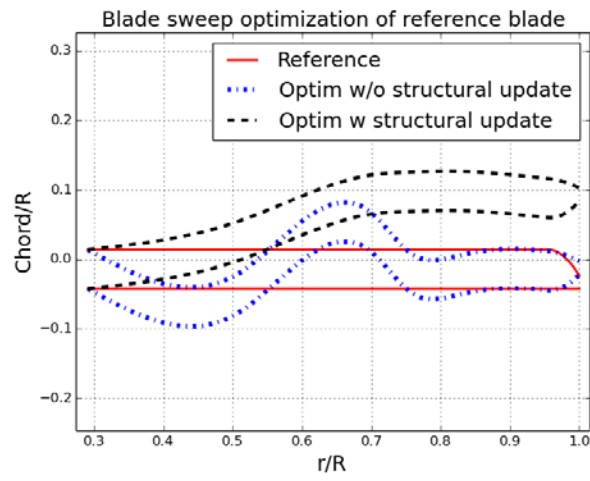
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**Fig. 11.** Comparison of the output of a chord distribution optimization when the structural update is considered.



**Fig. 12.** Blade torsional stiffness. Blue solid line: original blade property. Red dotted line: torsional stiffness that would be deduced from the chord obtained in the optimization without structural update.



**Fig. 13.** Comparison of the output of a sweep distribution optimization when the structural update is considered.

Methods used for blade shape optimization	Methods used for analysis of optimization results
Rotorcraft comprehensive analysis with prescribed wake (HOST/METAR) Covariance matrix adaptation evolution strategy (CMA-ES)	CFD RANS for hover aerodynamics ( <i>elsA</i> ) CFD URANS loosely coupled to comprehensive analysis (for trim and blade deformation) for level flight aerodynamics (HOST/ <i>elsA</i> )
Update of blade structural properties as function of blade shape	Rotorcraft comprehensive analysis with free wake plus Ffowcs Williams and Hawkings acoustic analysis (HMMAAP)

**Table 1.** Summary of numerical methods used in this study

Power Gain (%)	Shaft Power	Induced Power	Profile Power
Optim Twist	-4.1 %	-18.4 %	+0.1 %
Optim twist + Optim Anhedral	-4.2 %	-18.8 %	+0.3 %

**Table 2.** Prediction of power gain for optimized rotors vs. reference by HOST

comprehensive computations