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Aerodynamic Design of a Tilt-Rotor Blade (*)

by

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Abstract

The EUROFAR (**Euro**pean **F**uture **A**dvanced **R**otorccraft) project is a cooperative program to study an advanced tilt rotor aircraft for a primary civil application. ONERA is in charge of the aerodynamic definition of the rotor.

After a preliminary code validation and selection of suitable airfoils, the RC3 rotor has been designed, achieving a good compromise between cruise efficiency ($\eta = 0.83$) and hover figure of merit (F.M. = 0.80). In parallel, a higher performance RC4 rotor with reduced airfoil thickness at the blade root has been designed; the RC4 rotor will be wind-tunnel tested in order to check the ambitious goals of the design, and to ensure the validation of the definition methods.

Some sensitivity studies have been performed around these basic rotors taking into account additional design constraints and new airfoils benefits. They will be accounted for the EUROFAR rotor final definition.

Notations

c : chord (m)

C_D : drag coefficient

C_L : lift coefficient

C_P : proprotor power coefficient

$$C_P = \frac{P}{\rho_0\, U^3\, S} = \frac{4\chi}{\pi^4}$$

C_T : proprotor thrust coefficient

$$C_T = \frac{T}{\rho_0\, U^2\, S} = \frac{4\tau}{\pi^3}$$

$F.M.$: Figure of Merit

$$F.M. = \frac{T^{3/2}}{P\sqrt{2\rho S}} = \frac{\sqrt{2}}{\sqrt{\pi}}\,\frac{\tau^{3/2}}{\chi}$$

L/D : lift to drag ratio ($= C_L/C_D$)

M : Mach number

N : number of blades

P : power (W)

R : radius (m)

S : disk area (m^2)

T : thrust (N)

$U = \Omega R$: tip speed (m/s)

V_0 : air speed (m/s)

α : angle of attack (^{0})

γ : propeller advance ratio

$$\gamma = \frac{\pi\, V_0}{\Omega\, R}$$

η : propulsive efficiency

$$\eta = \frac{V\,T}{P} = \frac{\gamma\,\tau}{\chi}$$

Λ : advance ratio

$$\Lambda = \frac{V_0}{\Omega R} = \frac{\gamma}{\pi}$$

χ : propeller power coefficient

$$\chi = \frac{P\ \pi^3}{4\ \rho_0\ U^3\ R^2}$$

ϕ : twist angle (^{0})

ρ_0 : air density (kg/m^3)

σ : thrust weighted solidity

$$\sigma = \frac{3N}{\pi.\, R^4}\int_0^R c(r).\, r^2\, dr$$

τ : propeller thrust coefficient

$$\tau = \frac{T\ \pi^2}{4\ \rho_0\ U^2\ R^2}$$

Ω : rotational speed (rad/s)

Ω_C : rotational speed in cruise

Ω_H : rotational speed in hover

Introduction

In spite of the extended capabilities of future helicopters, a gap will remain between helicopters and fixed wing aircraft. Today, the tilt-rotor aircraft seems to be the most attractive way to obtain vertical and short take-off and landing (V/STOL), both capabilities associated with high speed in cruise. The tilt-rotor consists of an airplane fuselage with a low-aspect ratio fixed-wing and wingtip-mounted contra-rotating rotors (Figure 1). A tilting system allows the aircraft to take off like an helicopter, with the rotor disk being horizontal, and to fly like a propeller airplane, when the axis of rotation is turned through 90^0.

In the United States, the XV15 demonstrated the capabilities of tilt-rotor aircraft and the V22-Osprey performed its first flight in March 1989.

In Europe, Aérospatiale, Agusta, CASA, MBB and Westland decided to join and study the common EUROFAR (EUROpean Future Advanced Rotorcraft) project. This research and development program has been launched in 1987 [1]. In the preliminary three year feasability phase, Aérospatiale, in charge of the aerodynamics of the rotor, asked ONERA for the aerodynamic definition of the blade.

(*) Study sponsored by the DRET agency of the French Ministry of Defence.

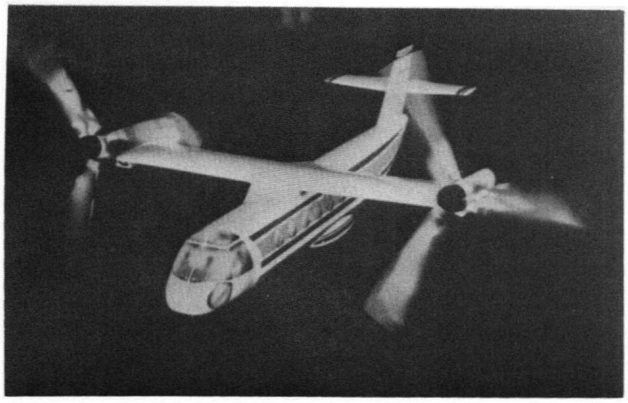

Figure 1 : Model of the EUROFAR tilt-rotor aircraft.

The aim of this study is to draw an advanced rotor for a primary civil application, which would have good performance both in hover and in cruise flight (M = 0.50), with 30% thrust margin in hover.

To satisfy these objectives, a twofold analysis is performed. Starting with current design methods and available airfoils, a reference rotor has been designed to be manufactured and tested at the end of 1990. In parallel, different layout studies, including new airfoil designs and method development, are performed in order to refine the design. At the end, the design methods, validated by comparison with wind-tunnel results, will be used to draw the final rotor design.

In the first part of this paper, the aerodynamic design methods will be presented, and a first validation of the codes on the X910 and V22 proprotors will be shown.

Then, the general specifications will be recalled, and we will describe the different iterations of the design phase which led to the RC3 rotor definition (current EUROFAR reference rotor) and to the RC4 rotor designed for performance tests.

The last part will be devoted to the analysis of the possible evolutions of the design taking into account new constraints and/or modified specifications together with the benefits of new airfoils.

Computation Methods

The basic method used for the EUROFAR proprotor design is a curved lifting line method (**LPC** code). It was developed during the **CHARME** operation [2-3] for definition and performance computation of the HT3 transonic propeller with twelve swept blades.

The aim of lifting line methods is to calculate the velocities induced on the blades by the bound vortices (representation of the blades) and by the trailing vortices (representation of the blade wakes). These induced velocities are used to modify the geometrical angle of attack of the airfoils by an induced angle of attack correction, and to compute the real local relative Mach number. As the analysis is performed on two-dimensional airfoils, only the axial and tangential components of the induced velocities are considered. When the angle of attack and Mach number are known, the local lift and drag are interpolated in an experimental 2D airfoils data base. This procedure allows the compressibility and viscous effects to be taken into account in the basical incompressible inviscid method.

The originality of the LPC method is that the pitch λ of each trailing vortex is iteratively adjusted in order to match the local velocity direction at its origin on the bound vortex. This technique results in a set of two approximations of the local circulation Γ, one depending upon the wake geometry and the other upon the interpolated lift coefficient. An iterative method (Newton method) is used to determine the radial distribution of λ that gives the equality of the two approximations of the circulation.

In the past, the LPC code precision was assessed by numerous cases of validation on propellers both on the overall performance coefficients (χ,τ,η) and on the radial lift distribution on the blades. The application of the LPC code to cruise configurations, during which the proprotors operate as propellers, did not raise any particular problem.

The application of the LPC code to the hover performance computations was more difficult. Several difficulties had to be overcome including :

- initialization of the computations at high thrust coefficients.
- interpolation of airfoil polars in the neighborhood of and beyond C_{Lmax}, associated with difficulties of convergence of the method.
- validity of the use of 2D polars at high lift.

The first problem is due to the fact that the iterative process is initialized with a constant wake pitch λ distribution. For high thrust in hover, this initial distribution is too far from the solution and the code diverges. A better initialization was found by using the λ distribution of a converged calculation made at a lower thrust coefficient. This operating mode allows the code to converge in many cases up to the maximum thrust coefficient and requires less computational time when the complete performance curve is needed.

The LPC convergence process was strengthened and the interpolation routines were modified to avoid problems in the neighborhood of the C_{Lmax} of the airfoils. However, the use of 2D airfoil polars at high lift is not validated. Several types of polars were used for hover computations (see Figure 2). For all types, the polars are the real experimental polars up to the 2D C_{Lmax}. For angles of attacks higher than the C_{Lmax} angle of attack, different types of extrapolation were studied :

- Type 1 : a constant slope of $C_L(\alpha)$ curves.
- Type 2 : a constant C_L equal to the C_{Lmax}
- Type 3 : the 2D stall behaviour and a prescribed curve for high angles of attack.

For the three cases, the drag $C_D(\alpha)$ remains unchanged.

The type 1 polars were only used with the initial code for convergence convenience. It was obvious that it led to a significant overestimation of the performance of the rotor for high thrusts and is now disused. The use of type 2 and type 3 polars will be discussed further.

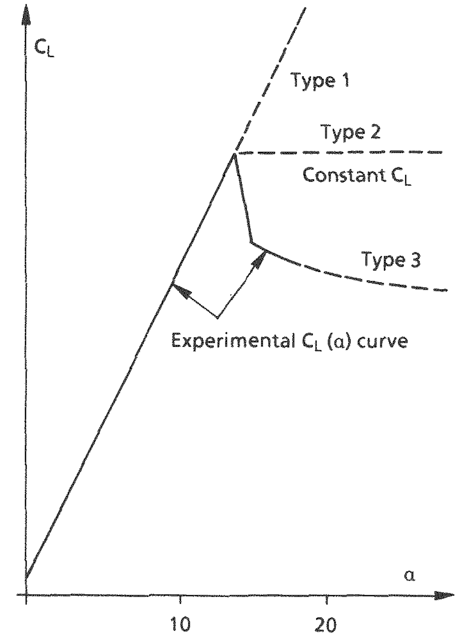

Figure 2 : Polars extrapolations used for LPC calculations.

Rotor hover performance may also be analyzed by using a blade element/momentum theory rotor analysis program (R85/HEL code from Aérospatiale). For cruise configurations, the EULER 3D code [2] may be used, mainly to check the definition.

Validation of LPC code

In 1975 and 1976, Aérospatiale conducted wind-tunnel tests in S1MA on the X910 proprotor [4]. These tests included cruise performance measurements (for various advance ratios Λ from 0.29 to 0.81) and pseudo-hover (with the test section obstructed or not by a tarpaulin). The X910 test results have shown that this rotor equiped with classical NACA64 airfoils had good performance in cruise, but rather poor performance in hover.

To investigate the case of proprotors fitted with advanced airfoils, the ATB and V22 proprotors were considered [5-6]. Due to the lack of data on the aerodynamic characteristics of the airfoils used on the ATB rotor, it was not taken into account. The requirements and performance of XN airfoils [7-8] were used to estimate their complete characteristics. The data available in references [5-6] were used to draw an approximate geometry of V22 rotor. Despite the uncertainties on geometry and airfoils data, the V22 rotor constitutes an interesting and important validation case on a modern proprotor.

X910 Proprotor

Cruise

Figure 3 shows the measured and computed performance for cruise (advance ratio Λ = 0.81) and at a low forward speed (Λ = 0.29). The measurements from the 1976 test campaign are presented with and without spinner drag corrections. It can be noticed that the correction is very large for Λ =0.81 (approximately 10 to 15 percent of the blade thrust).

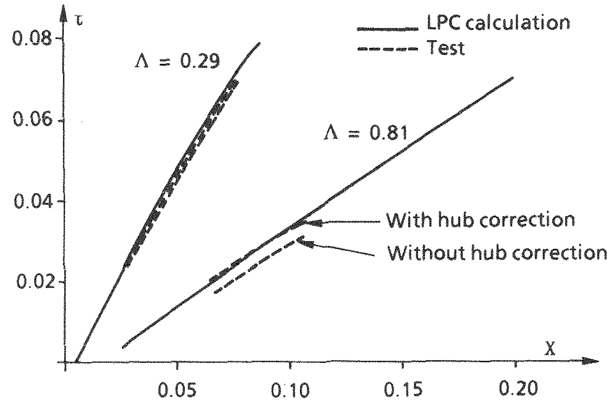

Figure 3 : X910 proprotor in advance flight - thrust coefficient versus power coefficient.

The LPC computations give correctly the variation of the thrust coefficient τ versus the power coefficient χ for both advance ratios. For the advance ratio Λ =0.81, the differences between computation and experiment are very small compared with the spinner drag corrections. In terms of efficiency, a slight overestimation of the performance can be seen at Λ = 0.29 (Figure 4).

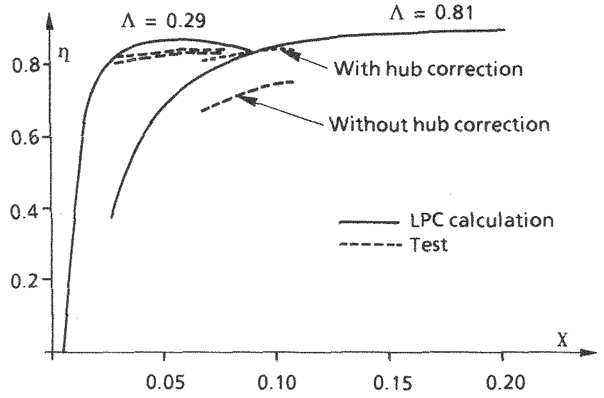

Figure 4 : X910 proprotor propulsive efficiency versus power coefficient.

Hover

Figure 5 compares the computation results (type 2 polars) with the 1975 test results with a complete tarpaulin ($V_0 \le 5$ m/s). The comparisons are qualitatively good in spite of a slight overestimation of the power coefficient χ required for a given thrust coefficient τ at the higher thrust levels (τ ≥ 0.10). Figure 6 shows the results expressed in terms of figure of merit F.M. as a function of the thrust coefficient τ. We can see that the maximum hover figure of merit is correctly estimated, but there are some minor discrepancies :

- the performance is underestimated at low thrust (τ ≤ 0.07)
- the rotor stall occurs earlier in the computation than in the test (τ ≥ 0.10).

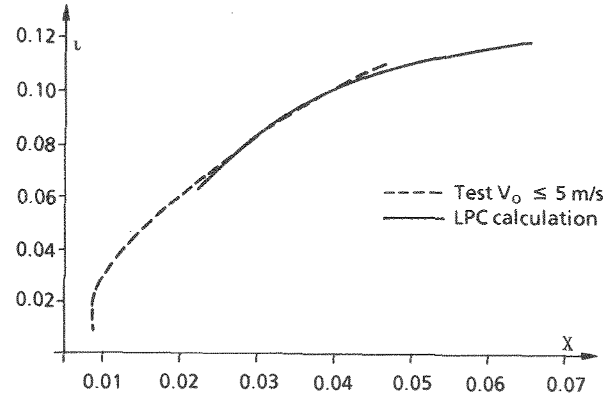

Figure 5 : X910 proprotor in hover - thrust coefficient versus power coefficient.

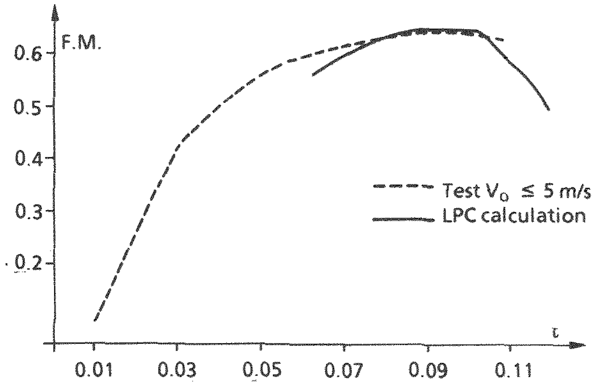

Figure 6 : X910 proprotor in hover - Figure of Merit versus thrust coefficient.

V22 Proprotor

Cruise

Calculations were made with the LPC code for three different advance ratios. They are compared in figure 7 to experimental data and Bell analysis [9]. The LPC results are for the three cases lower than the experimental data. However, it must be pointed out that the test Mach numbers are not known. The LPC calculations were run with Mach numbers ($M = 0.42$ for $\Lambda = 2.10$) which may be higher than the test values. Taking into account the uncertainties on geometry, airfoil data and tests conditions, the calculated efficiencies seem satisfactory.

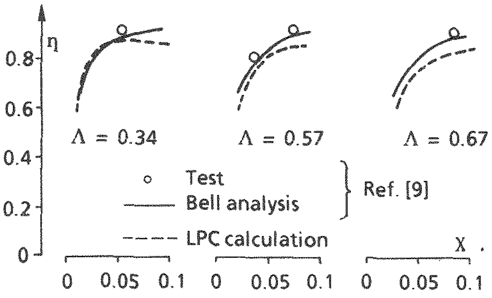

Figure 7 : V22 proprotor in advance flight - Propulsive efficiency versus power coefficient.

Hover

The hover performance was computed with the two types of polars (types 2 and 3 of figure 2). Figure 8 shows that the computed figure of merit obtained with the limited polars (type 2) is in rather good agreement with the experimental data for the range of operational thrust. As for X910 rotor, the performance is underestimated at low thrust coefficients. The use of type 3 polars leads to an underestimation of the performance for all the thrust coefficients.

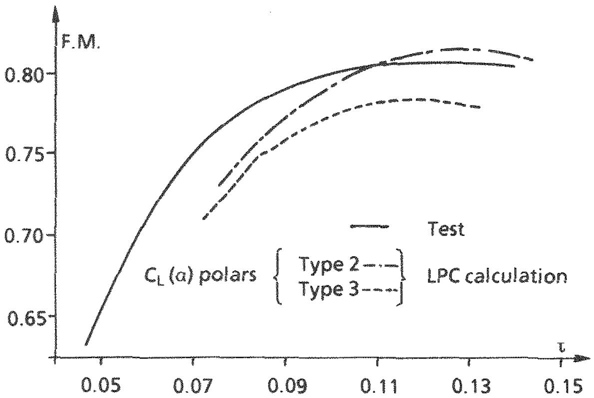

Figure 8 : V22 proprotor in hover - Figure of Merit versus thrust coefficient.

Code validity

The LPC code developed for the definition of propellers also appears well suited for the computation of proprotors propulsive efficiencies when operating in airplane mode.

Despite some differences between experiments and computations on the hover figure of merit curves, the agreement is rather good for hover operational conditions. It has been noted that for low thrust level, the figure of merit is lower in the LPC calculation than in the experiment; this general tendancy should not affect the EUROFAR rotor design as these conditions are not considered in the optimization. For high thrust levels, the simplicity of the LPC code is certainly insufficient to describe accurately the blade stall. It is known that these conditions are very difficult to compute. Recent Navier-Stokes analysis on the V22 blade [10] has confirmed that the separation of the flow on the inner part of the blade appears later than predicted by a lifting surface code using 2D airfoil data. In our case, the simple extrapolation techniques used for 2D aerodynamic characteristics (type 2 or type 3) seem to be precise enough for the estimation of the maximum thrust coefficient.

The good sensitivity of LPC code for all design parameters (chord and twist laws, airfoil distribution ...) associated with the low-cost computing times (less than 0.5 second on a Cray XMP computer) makes it a good tool for proprotor design. For confidence, the final designs are verified with other codes of EUROFAR partners. In particular, the R85/HEL helicopter code of Aérospatiale is used for hover performance computations, and an EULER 3D code from ONERA for cruise performance analysis.

EUROFAR Rotor Specifications

The three design objectives of EUROFAR proprotor are a high propulsive efficiency $\eta > 0.83$ in cruise, a hover figure of merit of 0.78 and 30% thrust reserve in hover.

Based on the design objectives and in conjunction with operational constraints, the main characteristics were selected (diameter, tip speed, thickness constraints ...). The specifications for the EUROFAR tilt-rotor aircraft led to optimize the rotor under the following conditions :

Cruise

Altitude	: 7500 m ISA
Mach number	: 0.50
Tip speed	: 176 m/s
Advance ratio Λ	: 0.876
Nominal thrust coefficient τ	: 0.032

Hover

Altitude	: 500 m ISA T+20^0
Tip speed	: 220 m/s
Blade tip Mach number	: 0.63
Nominal thrust coefficient τ	: 0.108

The specifications given at ONERA by EUROFAR Rotor Team are presented in Table 1. Some constraints exist on the thickness in the inner part of the blade which are highly dependent on hub technology ; these constraints have changed during this preliminary design phase.

The number of blades, initially an optimization parameter, was set at four.

Diameter	11,21 m
Number of blades	3 or 4
Stacking of airfoils	25 % on the chord
Pitch axis	25 % on the chord
Airfoils	Existing families (to be defined)
Thickness Law	To be optimized
Chord Law	To be optimized
Twist Law	To be optimized
Spinner Diameter	1 m

Table 1 : EUROFAR proprotor specifications.

Choice of Airfoils

Considering the limited time available for the definition of the rotor for wind-tunnel performance tests, the choice of airfoils had to be limited to existing ones. Helicopter and propeller airfoils as well as NACA64 airfoils with thickness to chord ratio between 8% and 30% were considered. Their characteristics were examined after determining a proprotor airfoil specification based on the preliminary rotor design made by MBB. It appeared that the performance of NACA 64 airfoils was clearly insufficient for a high performance rotor.

The OA3xx and DMHx helicopter airfoils are well suited for the outboard part of the blade. As the use OA312 airfoil starting at 0.50R was possible, the OA3xx family was chosen.

As the existing 20% thick airfoil had too high a drag coefficient C_D for cruise, ONERA has quickly developed the OH120 airfoil. The preliminary specifications set for the design of this airfoil were used at the beginning of the rotor study. The OH120 tests, performed in CEAT Toulouse wind-tunnel, have confirmed that the aerodynamic characteristics are better than the specifications. In cruise conditions (M ~ 0.50 at the blade root), the drag coefficient is maintained at a reasonable level ($C_D \approx 0.008$). For low Mach numbers, the OH120 airfoil has a high lift coefficient ($C_{Lmax} > 1.85$) with a maximum lift-to-drag ratio of 110.

For the inner part of the blade, airfoils with thickness to chord ratios higher than 25% are necessary. The overview of available airfoils has shown that none was satisfactory for EUROFAR application. At the request of MBB, the DLR has defined the KRx airfoils, with relative thicknesses from 25% to 28%. As the development was not achieved when most of the present studies were done, we used a 28% thick airfoil with the same aerodynamic characteristics as the XN28 airfoil used on V22 proprotor (see Validation of LPC Code). In future studies, the use of advanced thick airfoils will be considered.

Rotor Aerodynamic Definition

Historical Evolutions

The first geometry (RC1 rotor) was aimed at identifying the performance level which could be obtained from the selected airfoils. This three-blade rotor defined with OH120, OA 312 and OA309 airfoils, had a propulsive efficiency $\eta = 0.856$ for cruise and a hover figure of merit higher than 0.80. The thrust reserve in hover was only 15% with respect to the nominal thrust. As this rotor did not fully satisfy the aerodynamic specifications, it was abandoned. However, the main geometric characteristics of the RCx family (chord law, airfoils distribution) were determined during this first stage.

The RC2 geometry was defined with new geometric constraints. The selection of the possible hub technologies led to increase the blade root thickness and to set the number of blades at four. A 28% thick airfoil was used at the blade root to fit the thickness requirements and the rotor solidity σ was increased to rise the 30% thrust margin. The twist law was adapted to keep the cruise performance to a good level (η = 0.836). For hover, the figure of merit calculated with LPC code, F.M. $\approx$ 0.76, was lower than the design objective F.M. = 0.78. In contrary, the helicopter R85/HEL code indicated that the figure of merit could be better (F.M. $\approx$ 0.78).

As the hover performance of the RC2 rotor was considered insufficient, additional work was required to improve the figure of merit without giving up the good propulsive efficiency in cruise. For that, inboard chord was reduced and the twist was optimized in a different way. With the RC3 geometry, the hover performance was improved with a figure of merit F.M. $\approx$ 0.80 higher than the objective (Figure 9). The propulsive efficiency was preserved to a very satisfactory level η = 0.83. This geometry was chosen for the reference EUROFAR proprotor.

As the definition of an airfoil with a thickness to chord ratio of 28% was not completed early enough to allow the RC3 rotor to be built for the S1MA wind-tunnel tests, ONERA defined the RC4 rotor, mainly differing from the RC3 rotor by the use of a 20% thick airfoil section at the blade root. The performance of this rotor are superior to those of the RC3 rotor ($\eta \approx 0.84$ and F.M. ≈ 0.81).

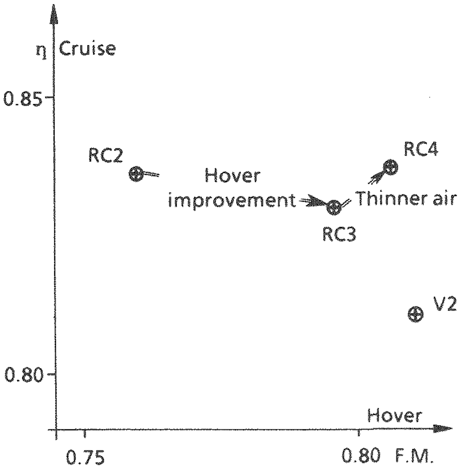

Figure 9 : Cruise efficiency and hover Figure of Merit of successive RCx rotor designs.

Description of RC3 and RC4 Rotors

In order to achieve a satisfactory cruise performance, it was decided to use the lowest possible thickness in all points of the blade. The optimized twist law implies low lift coefficients in the inner part of the blade during cruise. Consequently, an increase of the chord in this part of the blade mainly causes an increase of the blade drag. For this reason, the chord was set to the minimum value giving with a 28% thick airfoil the absolute thickness required. In the outer part of the blade, the chord was ajusted so that the airfoils operate during hover as close as possible to their maximum L/D ratio without excessive penalty in cruise flight. The resulting geometry does not have a constant taper, but a rapid variation of the chord around mid span (Figure 10).

The trade-off between cruise and hover is achieved by modifying the twist law. As it can be seen from Figure 11, the optimized twist is more important and more regular for cruise than for hover. In hover, the twist varies quickly near the root of the blade and there is a very slow variation between 0.4R and 0.9R; this kind of twist law gives very low propulsive efficiency in cruise. As a simple interpolation of the twist between cruise optimum and hover optimum resulted in low cruise efficiency for the desired hover figure of merit, an other approach was selected to find the 'best compromise'.

The hover performance was obtained by the decrease of twist evolution around 0.7R keeping the global twist law as close as possible to the cruise optimum (in particular in the inner part of the blade). Further improvement is obtained by a decrease of the tip twist.

Figure 12 compares the twist of RC3 and V22 rotors. The twist variations between 0.4R and R are about the same for the two rotors. This is due to the decrease of the twist at the tip of the RC3 blade, but we can see that in the outer part of the blade, the twist variation is more important on RC3 rotor than on V22 rotor, inducing a better cruise adaptation.

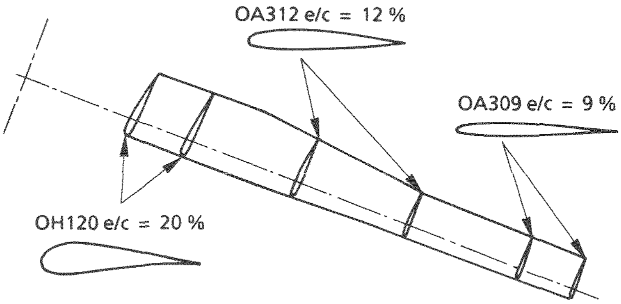

Figure 10 : Geometry of the EUROFAR RC4 blade.

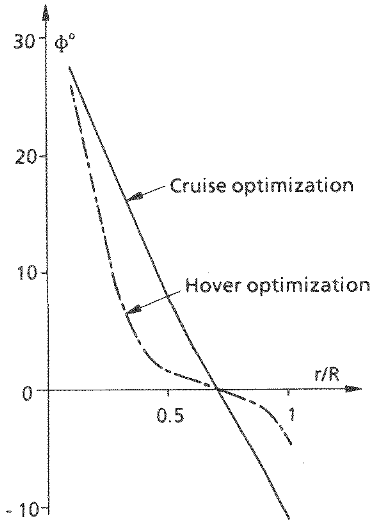

Figure 11 : Twist law optimization examples.

Twist variation		
Δr/R	RC3	V22
0.1 to 1	35.35°	~ 40.5°
0.4 to 1	18.40°	~ 18.5°

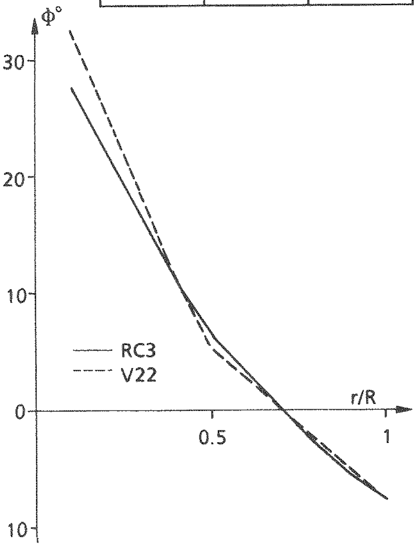

Figure 12 : Comparison of RC3 and V22 twist laws.

The twist law of the RC4 rotor is about the same as the one of the RC3 rotor. It was adjusted to take into account the change of root airfoil section and to distribute the performance gains between cruise flight and hover.

In cruise conditions ($M = 0.50$, $\Lambda = 0.876$), the RC3 and RC4 rotors have a propulsive efficiency higher than 0.83 at nominal thrust (Figure 13). According to our computations, they would be better than V22 rotor in the same conditions. In hover (Figure 14), their figure of merit would be slightly lower or equivalent to V22 one (F.M. = 0.81). This good compromise is obtained with a maximum thrust coefficient much lower than V22 one.

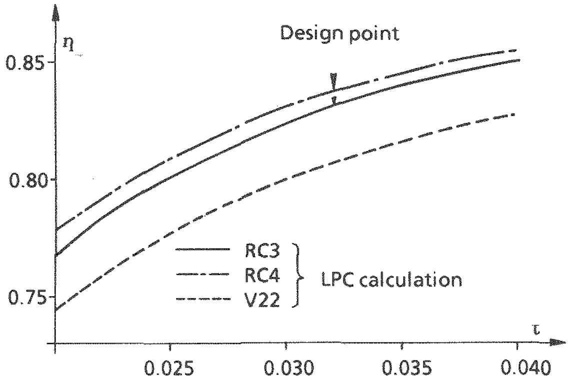

Figure 13 : V22, RC3 and RC4 proprotors in cruise ($M = 0.50$, $\Lambda = 0.876$) - Propulsive efficiency versus thrust coefficient.

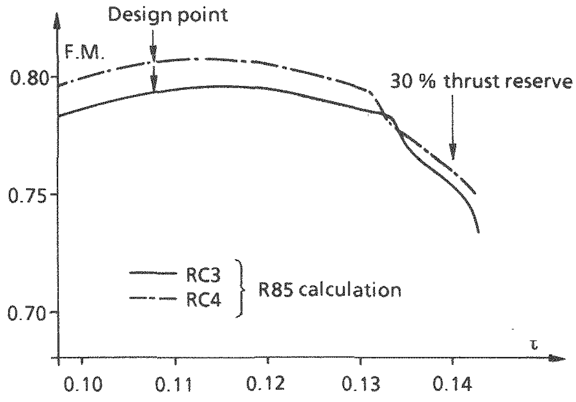

Figure 14 : RC3 and RC4 proprotors in hover - Figure of Merit versus thrust coefficient.

Figure 15 shows the evolution of cruise performance of the RC4 rotor versus the cruise Mach number at nominal rotational speed. We can see that the RC4 rotor is perfectly well adapted at the design point ($M = 0.50$, $\Lambda = 0.876$) for which it reaches the maximum efficiency $\eta = 0.837$. Further, the propulsive efficiency of the rotor remains higher than 0.80 for Mach numbers up to 0.60.

Figure 16 shows that the propulsive efficiency could be improved by an increase of the advance ratio Λ which means a reduction in helical tip Mach number at the fixed cruise Mach number ($M = 0.50$). If the ratio Ω_C/Ω_H decreases from 0.80 to 0.70 (from $\Lambda = 0.876$ to $\Lambda = 1.00$), the efficiency is increased from $\eta = 0.837$ to the maximum value $\eta = 0.857$; in this case the hover figure of merit remains equal to 0.806. If the ratio of rotational speed in cruise and in hover Ω_C/Ω_H remains constant ($\Omega_H = \Omega_C/0.8$), the hover thrust reserve becomes lower than the required 30% (dotted part of the F.M. curve in Figure 17). Consequently, the RC4 rotor design helical tip Mach number is the optimum value to satisfy the objectives for the prescribed value of the ratio $\Omega_C/\Omega_H = 0.80$.

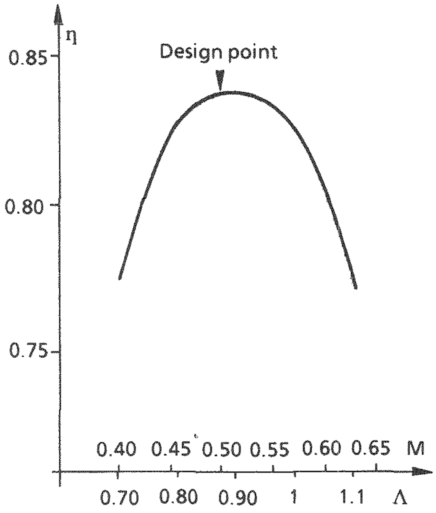

Figure 15 : Evolution of the RC4 proprotor propulsive efficiency with advance Mach number (Ω_C = Cst, Thrust/M^2 = Cst).

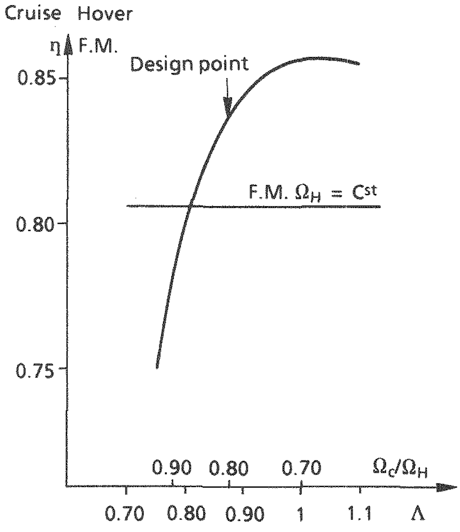

Figure 16 : RC4 proprotor - Influence of rotational speed Ω_C variation on cruise efficiency ($M = 0.50$, nominal thrust).

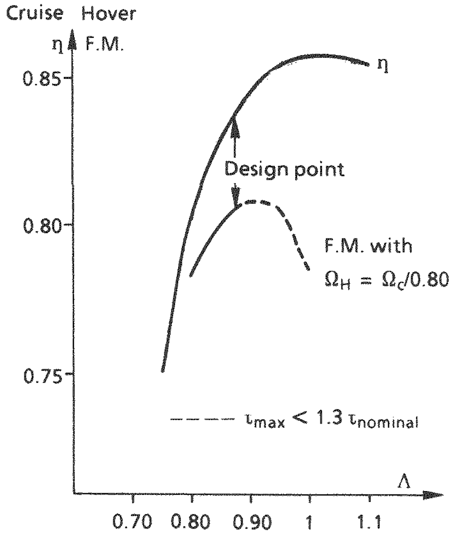

Figure 17 : RC4 proprotor - Influence of rotational speed variation on cruise efficiency (M = 0.50, nominal thrust) and hover Figure of Merit (Ω_C/Ω_H = 0.80).

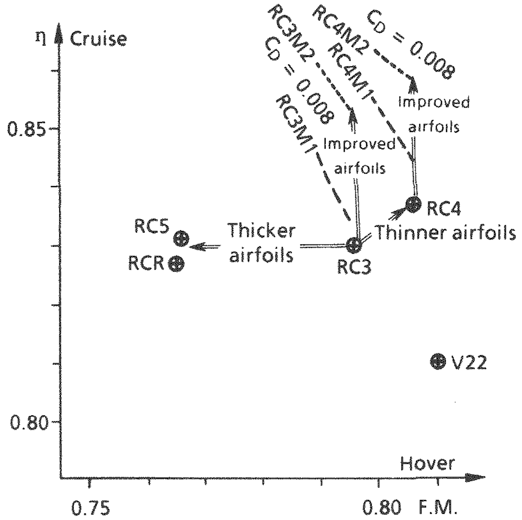

Figure 18 : Sensitivity analysis - Cruise efficiency and hover Figure of Merit.

In conclusion, the RC3 and RC4 rotors have high cruise efficiency associated with a good hover performance. Better cruise efficiency can be obtained by a tip speed reduction , but may result in drive system weight and in the engine working further from its optimum. A complete trade-off study should be performed, including blade twist refinements, to evaluate the real benefits.

Parametric studies

Many parametric studies were done to prepare the future evolutions of the EUROFAR rotor :

- increased thicknesses at blade root for a flexbeam application on a composite gimbal rotor
- rectangular blade studies for parametric investigation on rotor behaviour (H-forces, autorotation)
- possible improvements and changes of trade-off.

Figure 18 gives the propulsive efficiency in cruise (M = 0.50 Λ = 0.876 at EUROFAR nominal thrust) versus the hover figure of merit. It compares all these parametric investigations to RC3, RC4 and V22 results.

The RC5 rotor was designed for the flexbeam application in order to have the same propulsive efficiency as the RC3 rotor. The use of thick airfoils on an important part of the blade results in an important decrease in hover figure of merit (ΔF.M. = 0.03).

The RCR rotor with rectangular blades, having the same thickness-law and the same solidity as the RC4 rotor, also shows an important loss of performance in the trade-off diagram (ΔF.M. = 0.04). These two studies clearly show that there is a great sensitivity on the hover figure of merit. A better figure of merit could be obtained with thick airfoils having a higher maximum lift.

Recent studies have been performed taking into account the experimental characteristics of OH120 airfoil. Figure 18 shows that we can possibly expect an 0.5% increase in propulsive efficiency with the same hover figure of merit, or 2% increase of cruise efficiency with less than 1% figure of merit in hover (dashed lines corresponding to RC3M1 and RC4M1).

As we said previously, all these studies were done using mainly existing airfoils. For this reason, during cruise, the drag coefficient C_D is higher than 0.0085 on the main part of the blade. To show the interest of new airfoils adapted to proprotor application, some computations were done with a constant drag fixed at C_D = 0.008 all over the blade. It can be seen on Figure 18 that this leads to a further improvement in cruise efficiency between 1% and 2% (dotted lines corresponding to RC3M2 and RC4M2).

These examples show that there are still considerable gains to be made with well adapted airfoils. Their development would allow the design of rotors with high cruise efficiency (η > 0.85) in conjunction with the hover objectives (F.M. > 0.78 and 30% thrust reserve).

To show the influence of baseline geometry on parametric investigations, we have compared the influence of helical tip speed on propulsive efficiency of the RC4 rotor (η = 0.837, F.M. = 0.806) and of an improved RC4M2 design (η = 0.854, F.M. = 0.800). On Figure 19, we can see that there is less improvement to expect from a tip speed reduction for the rotor having the best cruise adaptation. On the other hand, the maximum efficiency is obtained with a ratio Ω_C/Ω_H = 0.74 for the improved design instead of Ω_C/Ω_H = 0.70 for RC4 rotor.

In conclusion, these parametric studies have shown the general trends on rotor performance resulting from constraints modifications in the rotor optimization. They will be accounted for the next design of EUROFAR rotors.

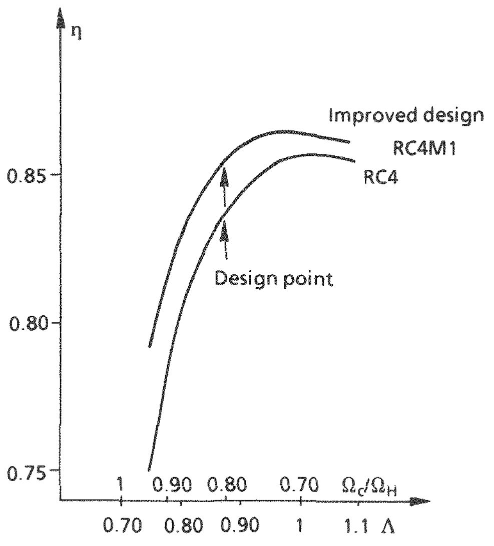

Figure 19 : Influence of helical tip speed on the RC4 and RC4M1 proprotors propulsive efficiency in cruise (M = 0.50, nominal thrust).

Conclusions

As the preliminary validation on the X910 and V22 proprotors had shown that the LPC Curved Lifting Line method was a well adapted tool for the aerodynamic analysis, this code was selected for the design of the EUROFAR proprotor blade.

In order to achieve a high level cruise efficiency suitable for the EUROFAR primary civil application, the best available airfoils have been selected to tailor the blade design accounting for good hover performance.

The resulting RC3 rotor performance is high with a cruise efficiency $\eta = 0.83$ at Mach number $M = 0.50$, a hover figure of merit F.M. = 0.80 and a 30% thrust reserve in hover flight.

In parallel, a model RC4 rotor has been designed to be tested in hover on Aérospatiale test rig and in cruise in the ONERA S1MA wind-tunnel. The test results will be used to check the ambitious goals of the design, and to ensure the validation of the definition methods.

Some sensitivity studies have shown that a significant loss of performance could happen in the case of a blade root thickening for technological reasons. On the contrary, major gains are to be envisaged by using advanced airfoils currently under development among the EUROFAR partners.

The future studies will integrate the informations from the the wind-tunnel results and the benefits of new airfoils, to draw a new reference rotor by the end of the EUROFAR preliminary phase.

References

[1] **J. Andres, G. Monti**
EUROFAR. Status of the European Tilt Rotor Project
14th European Rotorcraft Forum, 20-23 September 1988, Milano, Italy

[2] **J.M. Bousquet**
Méthodes aérodynamiques utilisées en France pour l'étude des hélices pour avions rapides
AGARD CP366, Toronto 1984
(English translation in La Recherche Aérospatiale N^0 1985-1)

[3] **J.M. Bousquet**
Theoritical and Experimental Analysis of Highspeed Propeller Aerodynamics
AIAA-86-1549, AIAA/ASME/SAE/ASSE 22nd Joint Propulsion Conference (june 16-18,1986/Huntsville, Alabama)

[4] **G. Beziac**
Composite Blade for a 5m Diameter Tilt Rotor
Vertica Vol. 3 p155-176 (1979)

[5] **F.F. Felker, M.D. Maisel, M.D. Betzina**
Full-scale Tilt-Rotor Hover Performance
41st Annual Forum of the American Helicopter Society, Ft. Worth, TX, May 1985

[6] **H. Rosenstein, R. Clark**
Aerodynamic Development of the V-22 Tilt Rotor
AIAA/AHS/ASEE, Dayton, Ohio, Octobre 1986

[7] **J.C. Narramore**
Advanced Technology Airfoil Development for the XV-15 Tilt-Rotor Vehicule
AIAA/NASA Ames VSTOL Conference, Palo Alto, Ca., December 1981

[8] **J.C. Narramore**
Airfoil Design, Test, and Evaluation for the V22 Tilt Rotor Vehicle
43rd Annual Forum of the American Helicopter Society, St Louis, Mo., May 1987

[9] **M. K. Farrell**
Aerodynamic Design of the V-22 Osprey Proprotor
45th Annual Forum of the American Helicopter Society, Boston, MA, May 22-24, 1989

[10] **J.C. Narramore and R. Vermeland**
Use of Navier-Stockes Code to Predict Flow Phenomena near Stall as Measured on a 0.658-Scale V-22 Tilrotor Blade
AIAA 89-1814 (AIAA 20th Fluid Dynamics, Plasma Dynamics and Lasers Conference, Buffalo, New-York / June 12-14, 1989)