EIGHTEENTH EUROPEAN ROTORCRAFT FORUM

B.16

Paper No. 127

EUROFAR ROTOR AERODYNAMIC TESTS

by

Frederic BEROUL, *EUROCOPTER FRANCE*
Pascal BASSEZ, *EUROCOPTER FRANCE*
Patrick GARDAREIN, *ONERA OA*

September 15-18, 1992

Avignon, FRANCE

ASSOCIATION AERONAUTIQUE ET ASTRONAUTIQUE DE FRANCE

EUROFAR ROTOR AERODYNAMIC TESTS

by

Frederic BEROUL, *EUROCOPTER FRANCE*
Pascal BASSEZ, *EUROCOPTER FRANCE*
Patrick GARDAREIN, *ONERA OA*

ABSTRACT

Within the framework of the Eurofar Program Phase 1, an isolated rotor model has been designed, manufactured and tested, in hover on a whirl tower at EUROCOPTER FRANCE (ECF), and in conversion/cruise in the ONERA Modane S1 Wind-Tunnel.

The rotor aerodynamic design has been achieved by ONERA, according to the «Eurofar Baseline Aircrafr» specifications using a curved lifting line computational model. The design process is recalled.

The model design and manufacturing was shared between ECF (Hub, controls, rig/W.T. adaptation) and Agusta (model blades). The rotor test facilities & measurements are described.

The main aerodynamic test results are analysed, and compared with theoretical predictions.

In conclusion, recommendations are made concerning the optimization of the design.

NOTATIONS

R : radius (m)
D : diameter (m)
S : Disk area (m^2) $S = \pi R^2$
P : Power (W)
T : Thrust (N)
ρ : Air density (kg/m^3)
Ω : Rotational speed (rad/s)
n : Rotational speed (rps)
V : Air speed (m/s)
U : Tip speed (m/s) $U = \Omega R$
a : Sound velocity (m/s)
M : Mach number $M = V/a$
Mp : Tip Mach number $Mp = U/a$
Mh : Helical Mach number $Mh = \sqrt{M^2 + M^2p}$
Λ : Advance ratio $\Lambda = \frac{U}{V}$
τ : Thrust coefficient : $\tau = \frac{T}{\rho n^2 D^4}$ $\tau = \frac{\pi^3}{4} Ct$
χ: Power coefficient: $\chi = \frac{P}{\rho n^3 D^5}$ $\chi = \frac{\pi^4}{4} Cp$
η : Efficiency: $\eta = \frac{TV}{P}$
FM : Figure of merit $FM = \frac{T^{3/2}}{P\sqrt{2\rho S}}$
e/c: Relative thickness of the airfoil

1 INTRODUCTION

For many years helicopter performance have been improved as far as handling qualities, vibrations, noise levels and speed in cruise were concerned.
New concepts of rotor associated with active control technology have extended the flight envelope of rotary wing aircraft.
In spite of these extended capabilities a gap will remain between advanced helicopters and fixed wing aircraft as far as the cruise speed is concerned.

Therefore new concepts of V/STOL aircraft (Vertical and Short Take Off and Landing) have been studied like compound and tilt rotor.

The latter system consists in taking off like a helicopter and tilting the two rotors to fly like a propeller airplane at relatively high speed (around Mach 0.5 compared with 0.3 for an advanced helicopter).

Its feasability has been demonstrated in the U.S.A. through the XV15 and V22 projects.

The EUROFAR (EUROpean Future Advanced Rotorcraft) program was launched in 1988 with the participation of AEROSPATIALE, MBB, AERITALIA, AGUSTA, CASA and WESTLAND around the examination of a new transportation system based on tilt-rotor aircraft.

The EUROFAR aircraft, called baseline aircraft, was corresponding to the following main requirements :

- 30 pax + 2 pilots + 1 flight attendant
- range 600 Nm
- cruise altitude 7500 m
- minimum cruise speed 300 kts
- cat A fulfilment

The corresponding aircraft has the following sizing :

- all-up weight 13650 kg
- length 22.4 m
- wing span 14.7 m
- rotor diameter 11.2 m

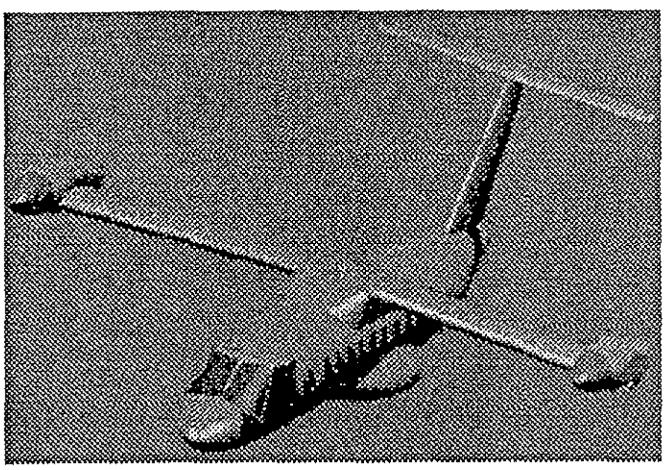

FIGURE 1 : EUROFAR BASELINE AIRCRAFT

The aircraft pre-design included computational calculations and wind tunnel tests relative to the aircraft architecture, the rotor/wing interactions and the isolated rotor.

During this phase, ECF was in charge of the rotor aerodynamics and asked ONERA for the aerodynamic definition of the blade to be optimized in hover and in cruise (M = 0.5).

The rotor wind tunnel tests were globaly under ECF responsability and had the following objectives :

- the assessment of the engineering computational methods
- *the examination of the rotor behaviour as far as aerodynamics, dynamics and acoustics are concerned.*

Therefore a reference rotor has been designed and manufactured by ECF and AGUSTA and tested at MARIGNANE and in MODANE S1 wind tunnel.

2 ROTOR DESCRIPTION

The design objectives of the aircraft rotor aimed at a good propulsive efficiency at low thrust level in cruise ($\eta > 0.83$ at $\tau = 0.032$ and M = 0.5) associated with a good figure of merit (FM > 0.78) with 30% thrust reserve in hover.

	HOVER	CRUISE
ALTITUDE	500 m ISA +20°C	7500 m ISA
MACH NUMBER	0.	0.5
THRUST τ	0.108	0.032
TIP MACH	0.63	0.57

TABLE 1 : AIRCRAFT ROTOR DESIGN POINTS

On this basis the wind tunnel model (called RC4 rotor) was designed according to the following characteristics :

ROTOR	AIRCRAFT	RC4 MODEL
Diameter	11.21 m	4.20 m
Number of blades	4	4
Offset		4.0 %
Pitch range		-2° to 58°
		±10° cyclic

TABLE 2 : AIRCRAFT AND WIND TUNNEL ROTORS CHARACTERISTICS

The maximum diameter allowable by S1 MODANE wind tunnel section is 4.20 m and as been chosen for easier test equipment's design.

2.1 Methodology for the rotor aerodynamic design

According to the required performance in hover and in cruise, the blade twist and chord distribution have been optimized for the RC4 rotor.
As described in reference (1) the twist was computed to be optimal in cruise flight and then adapted to meet hover requirements.
In the inner part of the blade, the airfoil lift coefficient distribution was constrained in order to avoid stall in hover mode ; this resulted in a reduced load of this part of the blade in cruise.
Similarly the twist was adpated in the outer part of the blade for hover conditions.
Under structural considerations a high absolute thickness was required at the root of the blade. In order to keep airfoils with a low relative thickness the chord was increased in this inner part.

The chord distribution also consists in a decrease around mid span with a small taper at the outer part (figure 2).
In order to perform quickly a low cost wind-tunnel campaign, on well known basis, it was decided to use helicopter airfoils on the blade.
The latest ONERA/ECF high performance OA3XX family has been used. However, it was been necessary to develop (and test) a new thick airfoil to be implemented on the blade root.

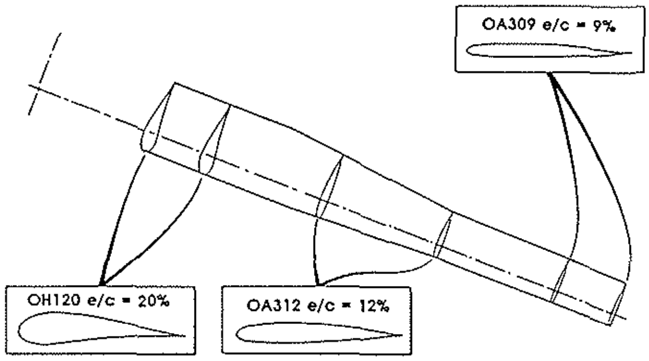

FIGURE 2 : RC4 BLADE

2.2 Rotor hub characteristics

The aircraft rotor definition is based on a gimballed homokinetic hub with a composite membrane.

As the test campaign objectives were mainly related to aerodynamics, a simpler hub technology has been chosen for the RC4 rotor to match these objectives with a reduced scale model.

Therefore the rotor hub is fully articulated (soft inplane) with a large pitch range in order to reach all the flight points (hover, cruise and conversion). The resulting head is shown on figure 3.

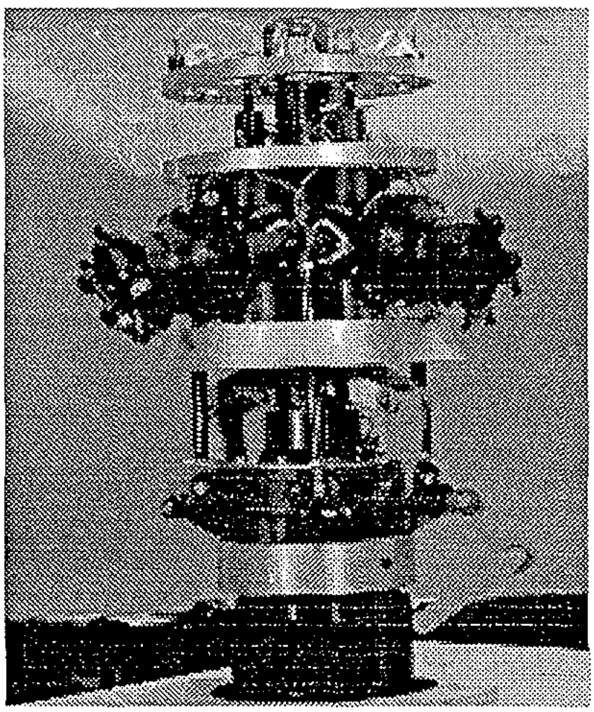

FIGURE 3 : RC4 ROTOR HEAD

This hub has been manufactured by ECF LA COURNEUVE and the blades by AGUSTA CASCINA COSTA.
Both of them are equiped with strain gages in order to record the static and dynamic loads on the rotor for monitoring and scientific purpose.
A detailed description of the manufacturing concepts is given in ref (6).

3 TEST FACILITIES

Hover tests were performed in MARIGNANE and tests in propeller mode and in conversion phase in the ONERA S1 wind tunnel.

3.1 Rotor bench

The rotor bench at MARIGNANE (figure 4) is used to test scale one tail rotors and main rotors wind tunnel models. Its main characteristics are as follows :

- maximum power 600 kW
- maximum torque 2000 N.m.
- *maximum thrust 100000 N downward.* (to avoid ground effect).
- rotation speed from 0 to 2300 rpm.

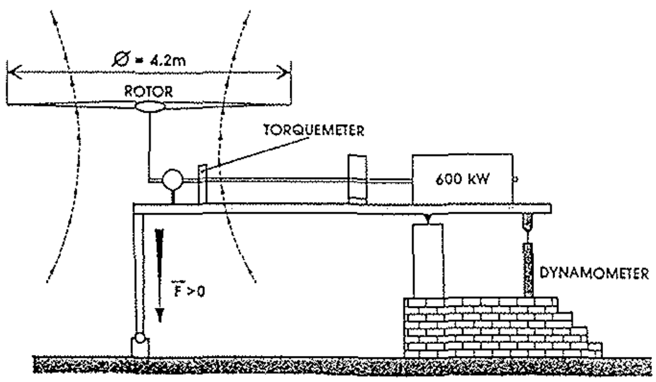

FIGURE 4 : SCHEME OF THE BENCH

FIGURE 5 : RC4 ROTOR ON THE BENCH

3.2 S1 MODANE test rig

The present rotor test rig was installed in 1987 in the large S1 wind tunnel of the ONERA MODANE AVRIEUX center. The test section of which is 8 meters in diameter and 14 meters in length (figure 6).
The maximum wind speed is about Mach 1.

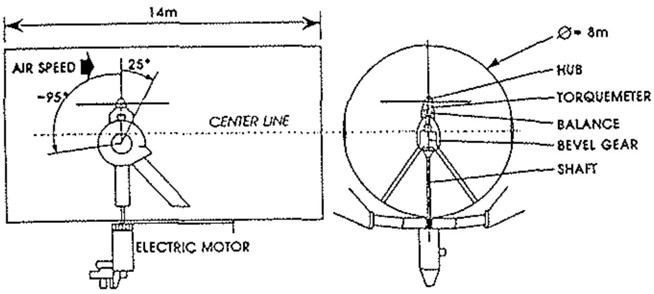

FIGURE 6 : SCHEME OF THE RIG

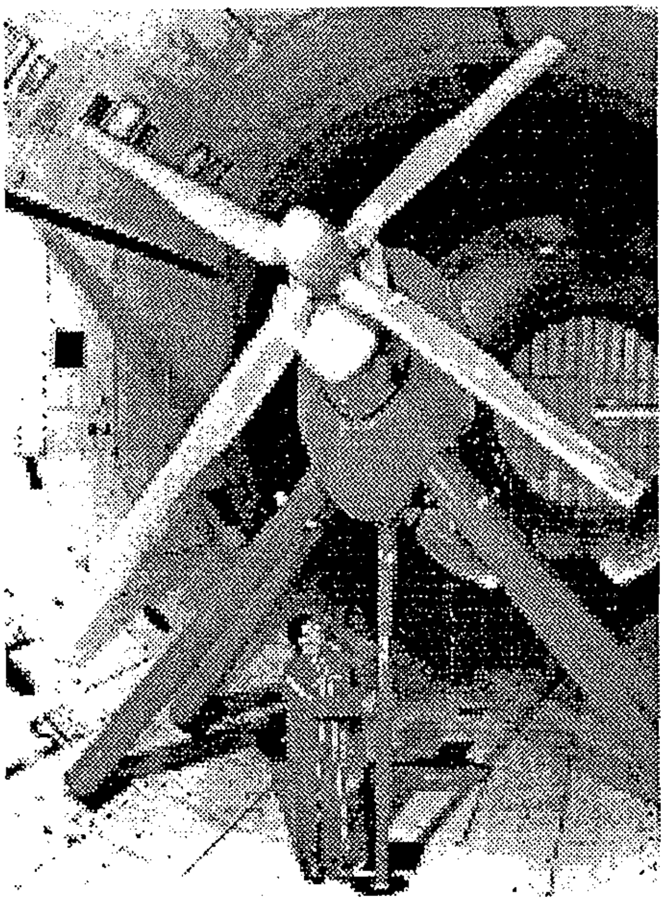

FIGURE 7 : RC4 ROTOR ON THE RIG

The rig main characteristics are as follows :
- maximum power 500 kW
- maximum torque 7000 N.m at 680 rpm
- tilt angle between + 25 degrees and - 95 degrees
- rotation speed from 0 to 1100 rpm
- high rigidity to avoid resonance problems.

A complete description of the rig can be found in ref. (2).
The wind tunnel test campaign was carried out in July and September 1991.

4 TESTS RESULTS

4.1 Hover test

The hover tests were performed in MARIGNANE for several tip Mach numbers by increasing the blade pitch up to stall.

For the hover conditions presented in table 1 ($Mp = 0.63$) the tests results are compared with calculations on figures 8 and 9. The evolution of thrust coefficients versus power coefficient is presented on figure 8.
The calculation results fairly match with the experimental data for the lower power level ($\chi < 0.035$) while they overpredict the experimental thrust by about 12 % at the higher power setting ($\chi = 0.05$).

On figure 9 the figure of merit is presented as a function of the thrust coefficient. One can notice on this detailed description of the rotor behaviour that the calculations slightly underpredict the experimental results in the lower thrust level zone ($\tau < 0.09$) and are in fair agreement with the test results in the zone $0.09<\tau<0.1$ where the figure of merit is maximum under test (FM= 0.8). For higher thrust level ($\tau > 0.1$) the decrease in figure of merit occurs earlier during test ($\tau = 0.1$) than in the calculations ($\tau = 0.13$).
Consequently at the nominal design point ($\tau = 0.108$) the measured figure of merit is 0.76 (0.80 in the calculations) ; additionally, the thrust reserve is about 15 % while a 30 % margin was predicted.

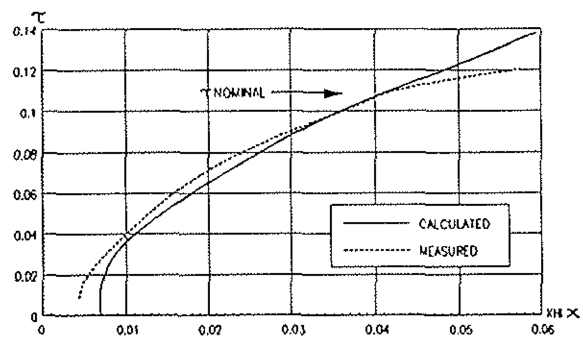

FIGURE 8 : RC4 ROTOR IN HOVER
POWER COEFFICIENT VERSUS THRUST COEFFICIENT

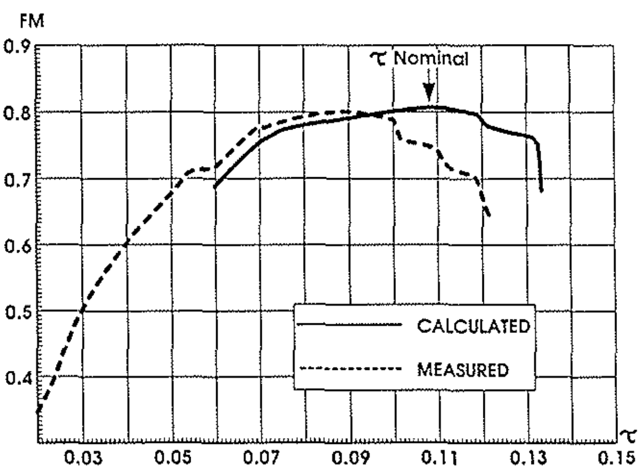

FIGURE 9 : RC4 ROTOR IN HOVER
FIGURE OF MERIT VERSUS THRUST COEFFICIENT

Such differences between the calculated and measured maximum thrust available in hover have already been observed. They can be due to three-dimensional effects, such as transverse pressure gradients leading to a modification of the boundary layer structure, or due to the modelization of the wake and more precisely the tip vortex (up to now, calculations were run with an actuator disk type method and a given contraction rate).
Further studies will be led to evaluate the influence of these parameters on the stall of highly twisted rotors.

4.2 Cruise test

The main goal of this part of the test campaign was to plot the aerodynamic polar curves in the propeller mode. The dynamic behaviour of the rotor has also been checked in the conversion corridor and in cruise with small angles of attack (simulation of a gust).
The range of tests which have been performed are as follows:

Airplane mode :

Wind tunnel Mach number	$0.20 < M < 0.53$
Tip Mach number	$0.498 < Mp < 0.620$
Nacelle tilt angle	$-90° < \alpha < -87°$
Thrust coefficient	$0.004 < \tau < 0.046$

Conversion phase :

Wind tunnel mach number	$0.10 < M < 0.21$
Tip Mach number	$Mp = 0.520$
Nacelle tilt angle	$-80° < \alpha < -10°$

Thrust and lift coefficients corresponding to the conversion corridor.

In the following paragraphs only the airplane mode will be dealt with.

4.2.1 Hub and rig correction

In order to accurately determine the rotor performance and to isolate precisely the contribution of the blades, a special experimental procedure was followed including a careful sealing of blade roots, special tare tests of the spinner with dummy blade roots and test rig interaction correction (figure 10).

$$T = Tb + Ts + \quad (pb - ps)dS$$

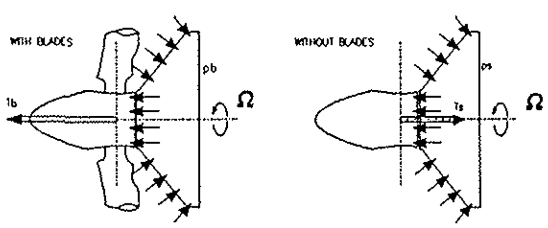

FIGURE 10 : HUB AND RIG CORRECTIONS

The power, the thrust and the pressures on the spinner and on the bench itself were measured with and without the blades for all the range of pitch and wind Mach numbers. Subtracting the second from the first leads to measure the thrust and power of the isolated blades.

All these elements have been recognized as key points for a precise efficiency measurement of tilt rotors in cruise mode (ref (5), (7)).

To illustrate this point, the efficiency of the rotor is shown on figure 11 with and without the corrections.

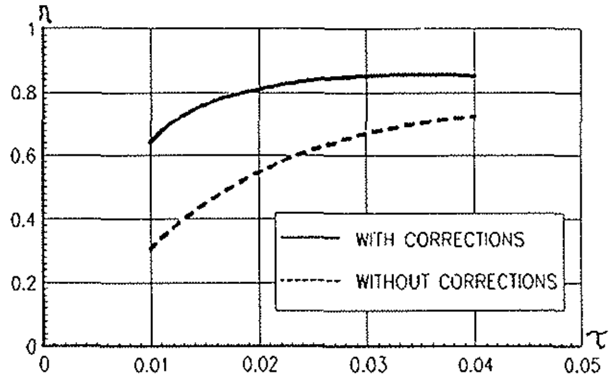

FIGURE 11 : ROTOR EFFICIENCY EFFECT OF THE CORRECTIONS

4.2.2 Rotor efficiency

The measured efficiency is presented on figure 12 (at the design 0.5 Mach number) as a function of thrust coefficient and compared with the results of a curve lifting line method (ONERA's L.P.C. code) which has been used to perform the design (ref (1)).
The measured efficiency is greater than the prediction for all thrust coefficients. In particular at the nominal design point (τ=0.032) the measured efficiency (η = 0.873) is 2.6 points greater than the calculated efficiency (η = 0.847).

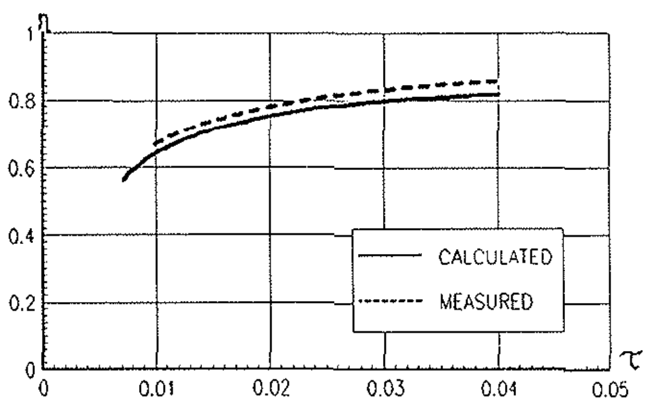

FIGURE 12 : EFFICIENCY AT M = 0.5 VERSUS THRUST COEFFICIENT

In order to analyse this excellent behaviour of the rotor under test, several checks have been made on the experimental data reduction as based on the calculation methods.

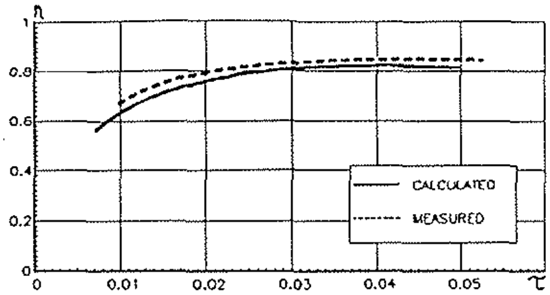

FIGURE 13 : EFFICIENCY AT M = 0.3 VERSUS THRUST COEFFICIENT

At first, the compressibility effect has been studied.

For the same tip Mach number (Mp = 0.568) figure 13 shows at M = 0.3 a slightly better agreement of the calculations with the test results than at M = 0.5 (Figure 12), meaning a possible overestimation of the compressibility effect in the prediction method.

This effect is further studied on Figures 14 and 15 for approximately the same advance ratio (0.77 < Λ <0.80) and different Mach numbers (M = 0.4/0.45/0.50). In this case the helical Mach number will be considered as the governing parameter. Despite the fact that few test points are available for this analysis, one can notice that the loss of efficiency is small from Mh = 0.653 to Mh=0.725, both in calculation (figure 14) and in tests (figure 15).

A larger loss due to compressibility effects occurs between Mh=0.725 and Mh=0.796. For a thrust coefficient close to the design point, one can notice a decrease of efficiency $\Delta\eta$=0.026 in the calculation (figure 14) larger than the decrease $\Delta\eta$=0.020 in tests (figure 15).

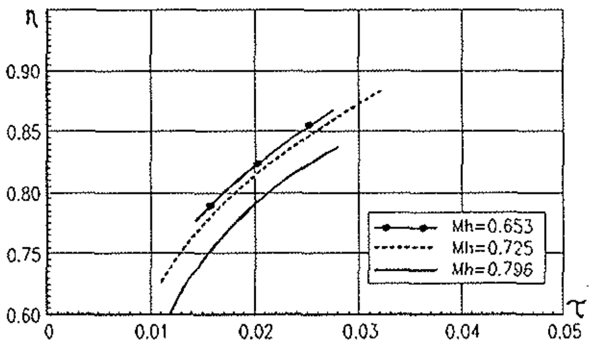

FIGURE 14 : MEASURED EFFICIENCIES VERSUS THRUST COEFFICIENT

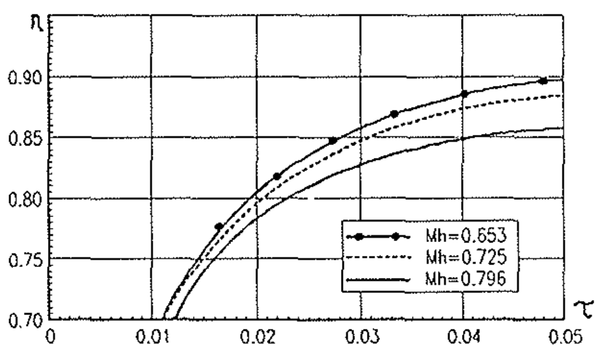

FIGURE 15 : CALCULATED EFFICIENCIES VERSUS THRUST COEFFICIENT

As a first conclusion the compressibility effect is probably slightly overestimated in the calculations.

In a second step, the interaction of the test rig and the spinner has been analysed by introducing the velocity field upstream of the test rig in the calculations.
This provides an increased rotor thrust and an increased efficiency (approximately 1 point larger than the efficiency of the isolated rotor : figure 16).
In fact the wind is slowed down in the inner part of the blade (near the rig) and accelerated in the outer part. The local angles of attack are changed as if the twist was higher, which improves the rotor efficiency.

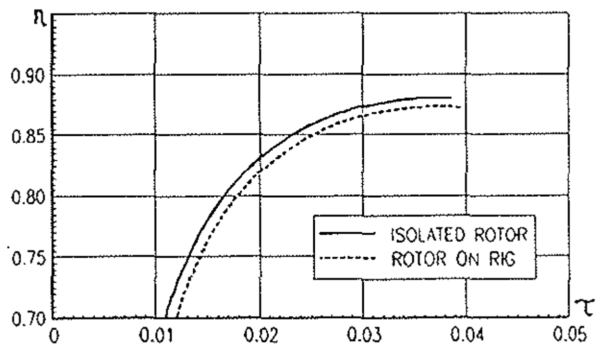

FIGURE 16 : EFFECT OF THE TEST RIG INTERACTIONS (CALCULATED)

In a third step the drag of the spinner and the thrust of the dummy blade roots have been checked.
The evolution of drag with the Mach number and the blade setting is consistent with pre-test evaluation.
These remarks together with the good repeatability of the spinner tare tests confirm that the tare drag is well measured under tests.

Finally, the rotor geometry was checked out.
The real twist of the blade appeared to be slightly less than required.
This difference is almost entirely balanced by the blade deformation in torsion which increases the blade twist.
A complete computation involving the blade measured geometry and the blade deformations was run out. The final result confirms the former calculations (rigid blade with the theoritical twist).

Such differences between calculations and test points have been reported on other tilt rotor studies (ref (4) and (5)).

4.3 Comparison with other tilt rotors

The X910 and V22 tilt rotor test campaign results can be compared with the EUROFAR results (figures 18 and 19).
The X910 test campaign was performed by ECF in S1 MODANE in 1975 and 1976 on a 3 bladed rotor.

This proportor (ref (3)) was mainly optimized for cruise flight and equiped with NACA64 airfoils (with relative thicknesses from 8 % at the tip to 30 % at the root).

ERRATUM

Figures below supersede corresponding figures 12, 13 and 16 of Paper n° 127 - B16. Vol. 1
«EUROFAR ROTOR AERODYNAMIC TESTS»

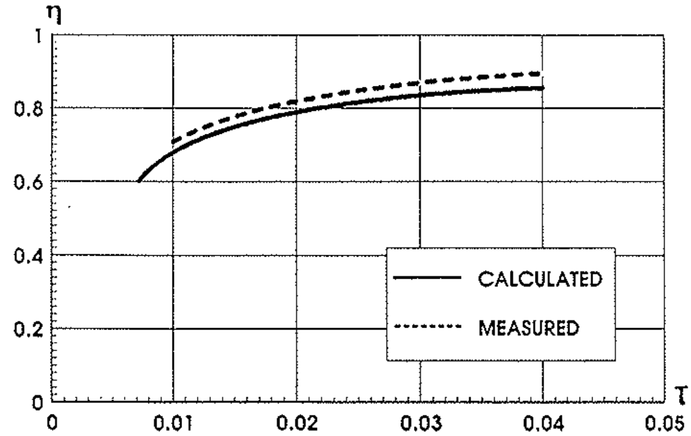

FIGURE 12 : EFFICIENCY AT M = 0.5 VERSUS THRUST COEFFICIENT

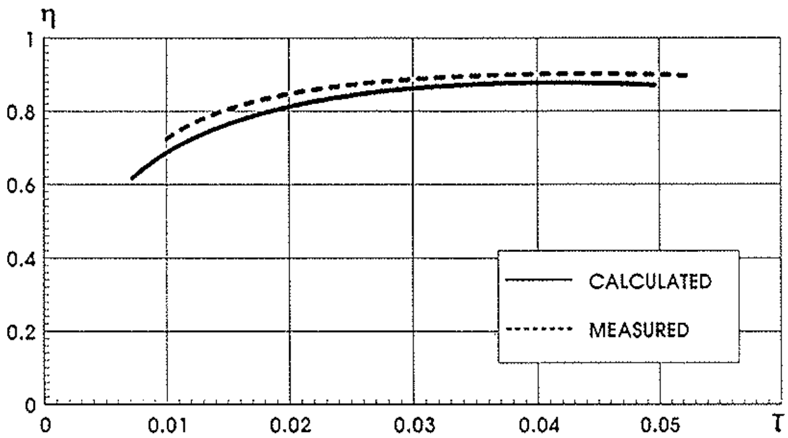

FIGURE 13 : EFFICIENCY AT M = 0.3 VERSUS THRUST COEFFICIENT

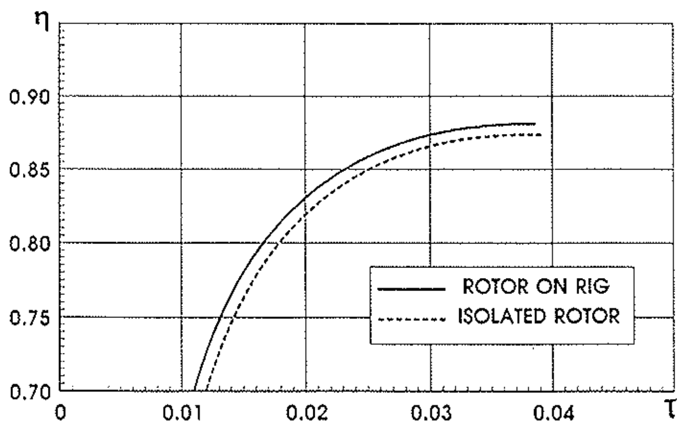

FIGURE 16 : EFFECT OF THE TEST RIG INTERACTIONS (CALCULATED)

This proportor offers good efficiencies in cruise but poor performance in hover.

The V22 test campaign is more interesting because of its advanced airfoils (as described in ref (4) and (5)) and consequently offers a good comparison point.

On figure 17 the figures of merit of the three tilt-rotors are compared.
The maximum figure of merit of X910 (FM < 0.7) is appreciably lower than the figure of merit of the new generation rotors (FM about 0.80).
At high thrust levels ($\tau > 0.1$), the V22 rotor presents a high value of figure of merit (FM > 0.8) with a maximum thrust ($\tau > 0.14$) larger than the RC4 rotor maximum thrust ($\tau = 0.124$).

On figure 18 the propulsive efficiencies (at M = 0.3) are shown.

The X910 rotor has a high efficiency ($\eta = 0.88$ at $\tau = 0.04$) in spite of its old airfoils. The RC4 tests points correspond to a tip mach number of 0.516 and not 0.568 as previous results in order to be compared with the V22 tests points (Mh = 0.67 and = 0.57).
The V22 and RC4 rotors have very close efficiencies for thrust coefficient in the range $0.025 < \tau < 0.04$.
At lower thrust levels the V22 rotor is slightly less efficient than the RC4 rotor ($\eta = 0.82$ for V22 and $\eta = 0.84$ for RC4 at $\tau = 0.02$).

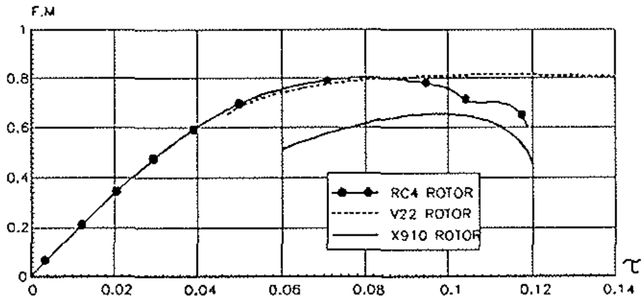

FIGURE 17 : COMPARISON BETWEEN TILT ROTORS FIGURE OF MERIT

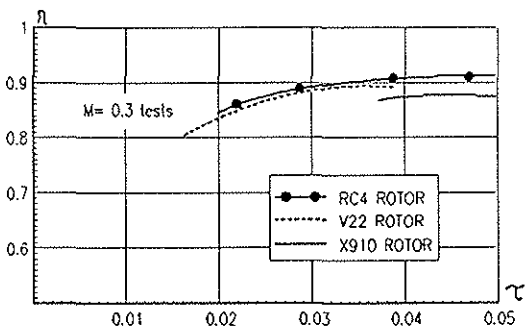

FIGURE 18 : COMPARISON BETWEEN TILT ROTORS EFFICIENCY AT M = 0.30

At the 0.5 typical flight Mach number for tilt rotor civil applications, the efficiencies are presented on figure 19. As the V22 test performance are not available at this Mach number, only computational results (from ref 1) are displayed.

According to our calculations the propulsive efficiency of the V22 rotor is about 3 to 4 points lower than the efficiency of the RC4 rotor.
At the design point $\tau = 0.032$, the RC4 performance is $\eta = 0.87$ under test and 0.85 in calculations, the V22 efficiency calculated is about 0.80.

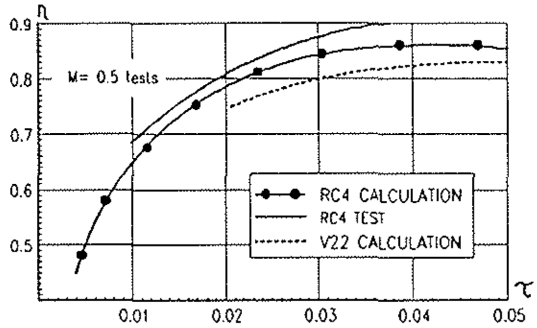

FIGURE 19 : COMPARISON BETWEEN TILT ROTORS EFFICIENCY AT M = 0.50

As a conclusion the RC4 rotor has better performance in cruise than the V22 rotor but presents a lower thrust available in hover.

4.4 Application on the EUROFAR aircraft

The main results of the tests can be summarised as follows :
- high maximum figure of merit
- low thrust margin at the design point in hover
- hight efficiency in cruise.

They can be directly applied to a full scale tilt rotor which would have :

- a twist decrease at the outer part of the blade (to improve the performance in hover even if the cruise efficiency is slightly reduced).
- an increased solidity about 10 % (in order to work at lower reduced thrust levels).

However an overall optimization procedure, including improved airfoils studies, could be made if major gains are required.

5 CONCLUSIONS

The tests of a model of the EUROFAR baseline aircraft rotor were successfully conducted on a Marignane rig in hover and within the ONERA MODANE S1 large wind-tunnel in conversion and cruise.

The full capability of the participating companies to design, manufacture and test a sophisticated rotor model has been confirmed, within a cost/efficiency procedure.

The experimental data base acquired during the campaign has been used to assess the engineering computational tools and to establish the baseline aircraft performance, as far as aerodynamics, dynamics and acoustics are concerned.

Despite the fact that this rotor was a baseline, fine performance were achieved in hover and more particularly in cruise.
The campaign analysis will indicate the way of action for the aircraft rotor improvements.

Acknowledgements

The authors would like to friendly express their gratitude to the EUROFAR team and ONERA felllows who gave their best for the campaign success.

They also would like to acknowledge the French Ministry of *Defence (the DRET agency)* and the D.G.A.C. authorities who have sponsored these studies.

6 REFERENCES

(1) B. BENOIT - J.M. BOUSQUET
«Aerodynamic design of a tilt rotor blade»
XVII *ICAS Congress*
STOCKOLM, September 1990

(2) M. ALLONGUE - J.P. DREVET
« New rotor test rig in the large Modane wind-tunnel»
XV European Rotorcraft Forum
AMSTERDAM, September 1989

(3) G. BEZIAC
«Composite Blade for a 5 m Diameter Tilt Rotor»
VERTICA Vol. 3 p 155-176 1979

(4) M.K. FARRELL
«Aerodynamic design of the V22 Osprey Proprotor»
45th Annual Forum of the A.H.S.
BOSTON, MA, May 1989

(5) Fort F. FELKER
«Results from a test of a 2/3-scale V22 rotor and wing in the 40- by 80-foot wind tunnel»
47th Annual Forum of the A.H.S.
PHOENIX, Az, May 1991

(6) V. CARAMASCHI - G. MAFFIOLI
«Design and manufacturing concepts of EUROFAR model 2 blades»
48th Annual Forum of the A.H.S.
WASHINGTON D.C., June 1992

(7) P. POISSON-QUINTON - W.L. COOK
«*A summary of wind tunnel research on tilt-rotors from* hover to cruise flight»
AGARD
MARSEILLE, September 1972