ERATO – an ONERA-DLR Cooperative Programme on Aeroacoustic Rotor Optimisation

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Abstract

The research programme named ERATO (an acronym for Etude d'un Rotor Aéroacoustique Technologiquement Optimisé) was a cooperative project of ONERA and DLR with involvement of Eurocopter (France and Germany). The ERATO project was directed towards a novel aeroacoustically optimised helicopter rotor blade design. It had the ambitious goal to design, build, and test a quiet model rotor that would be 50 percent less noisy in specific descent and level flight conditions than a reference rotor of current technology for a helicopter of the 4 – 6 ton class, with the constraints of minimum penalties with respect to power and vibration. The paper describes the aerodynamic and acoustic prediction tools used in the optimisation process. It presents the different phases of the project: that is the parametric study, the optimisation and the validation phase which comprises the structural design, the fabrication of highly instrumented blades, and the wind tunnel validation tests conducted in S1 Modane-Avrieux (S1MA) and DNW. Emphasis is laid on the optimisation methodology and on its validation by comparison of the main achievements to the objectives. A noise reduction potential of the ERATO rotor design up to 7 dBA in descent flight and up to 13 dBA at high speed is demonstrated. Furthermore, significant rotor performance gains (4 to 12 %) were found for high speed level flight, but limited to moderate blade loadings. In summary, the comparison of the predicted and measured results shows that the quiet rotor design methodology was globally successfully verified. Some improvements of the accuracy of the prediction tools used would however be desirable.

1. Introduction

Blade-Vortex Interaction (BVI) is known to be responsible for the nuisance of helicopters in low speed landing approach and maneuvers. It can also be a major source of impulsive noise radiation toward the ground in level flight at medium and even relatively high speed [1]. For these reasons, reducing BVI noise is presently a key issue for the development of the civil market of helicopters.

Early attempts at reducing BVI noise in the seventies and eighties were essentially empirical based on physical considerations on the effect of the blade tip shape on vortex generation. They led to more or less sophisticated blade tip geometries aiming at modifying the tip vortex structure to decrease maximum induced velocities, causing the vortex to diffuse before it interacts with the following blades or dividing it into several vortices [2]. Limited success was achieved, sometimes because of performance penalties, and there were no significant practical output of these passive device studies. Then, Active Blade Control (ABC) concepts started being tested like Higher Harmonic Control (HHC) first implemented in flight in 1985 [3] and more recently Individual Blade Control (IBC) [6].

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Both HHC and IBC have successfully been implemented on model and full scale rotors and noise reductions up to 6 dBA have been reported [4-6]. Other promising ABC concepts such as active flaps and active twist are currently being investigated in parallel with the development of smart materials [7].

By the time the studies reported in [2] were launched and early HHC tests conducted, there were no prediction tools for numerical investigations and quantitative assessment of the various noise reduction concepts. The need for further understanding of physical mechanisms and reliable noise predictions together with the availability of new aeroacoustic facilities and international cooperation led to the sophisticated experimental wind tunnel study [5]. The resulting data base was used for developing or improving BVI noise prediction tools [8 –13].

In a complementary way to the study of ABC concepts which is part of their cooperative research programme on helicopters, DLR and ONERA started in 1992 a new attempt to reduce BVI noise by passive means in the framework of a bilateral cooperation named ERATO. By balanced sharing of workload, responsibilities and costs, the maximum return of the invested resources was envisaged from both partners. Eurocopter (France and Germany) was asked to define the objectives and to provide all along the programme advices in setting a technically feasible and acceptable design.

The ERATO project had the ambitious goal to design, build, and test a quiet model rotor that would be 50 percent less noisy in specific descent and level flight conditions than a reference rotor of current technology, for a helicopter of the 4 – 6 ton class, with the constraints of minimum power and if possible no vibration penalties compared to the reference rotor. At the difference with the above-mentioned passive mean noise reduction studies, it was intended to take full advantage of recent improvements of the physical understanding and aeroacoustic prediction capability.

The paper recalls the aerodynamic and acoustic prediction tools available at ONERA and DLR and addresses the three different phases of the programme. It describes the parametric studies, the optimisation procedure, on which emphasis is laid, and the validation phase which comprises the structural design and the fabrication of instrumented blades, and the wind tunnel validation tests. These tests were conducted in S1 Modane-Avrieux (S1MA) in the high-speed range (up to 350 km/h) and DNW in the low to moderate airspeed range (70 to 260 km/h) to check compliance with the noise reduction goals and to verify the design methodology employed. The experimental results, presented and analysed in detail in [1] are synthesised and illustrated by sample results. The main achievements are compared to the objectives.

2. Objectives and work organisation

In view of scale-one application to a 4-to-6 ton helicopter, the ERATO programme aimed at designing, building and testing a quiet model rotor which would be 6 dBA less noisy (in terms of averaged ground noise level) than a reference rotor of current technology, in ICAO descent flight certification condition, that is 6 degree descent, 125 km/h (67 kts). Moreover, since in real landing approach, the descent angle α and the flight speed may vary, a certain stability of the noise benefit with respect to α and to the flight speed was looked for. Significant noise reductions were also envisaged for medium and high-speed level flight. This ambitious goal was to be accomplished with the constraint of minimum penalties with respect to rotor vibrations and performance.

At the demand of Eurocopter, a priority ranking of flight conditions for low noise optimisation was decided as follows.

Priority 1: descent flight at 125 km/h (67 kts),

Priority 2: level flight in the range 215 to 260 km/h (115 to 140 kts),

Priority 3: high-speed flight at 350 km/h (190 kts).

The programme was organized in three different work phases that is the exploratory phase, the main phase and the validation phase. The exploratory phase comprised aerodynamic and acoustic prediction code improvements and initial validation followed by parametric studies on rectangular rigid blades varying the rotation speed, the number of blades and the chord length. A numerical assessment of potential benefits from HHC was also performed.

The main phase consisted first in the continuation of the parametric studies, still with rigid blades, comprising more refined rotor geometry parameters such as the airfoil, twist and chord length spanwise distributions and the quarter-chord line geometry. The parametric studies were followed by the final optimisation, taking into account at that time the blade deformation, given the pre-design blade mass and stiffness distributions.

The third phase or validation phase comprised the structural design and manufacture of the instrumented optimised rotor blades, the S1MA and DNW wind tunnel tests and a thorough analysis of the test results for validation of the design methodology.

Remark: The scale-1 application of ERATO is a rotor which would equip a Dauphin-type helicopter, that is a helicopter with prescribed mass and fuselage drag coefficient. To comply with this objective, nominal values for the non-dimensional helicopter weight coefficient: $Z_W^* = 200Mg/(\rho S\sigma(R\Omega^*)^2)$ and for the fuselage drag coefficient: $(C_X S^{'})_f / S\sigma = D/(0.5\rho V_\infty{}^2 S\sigma)$, corresponding to this helicopter, were defined. In these formula, ρ represents the air density, σ the rotor solidity, S the rotor disk area, $S^{'}$ the fuselage drag section, Ω^* a reference rotor angular velocity, D the fuselage drag and V_∞ the flight velocity. For each calculation, the trim was recalculated accordingly.

3. Numerical aerodynamic and acoustic prediction tools

3.1 Descent flight and low-to-moderate speed level flight

DLR prediction method: The S4 rotor simulation code was used to predict the spanwise blade loading provided as input to the acoustic code AKUROT. The S4 code [14] is based on three main modules, which altogether are controlled by the rotor trim algorithm. These modules comprise an aerodynamic model based on lifting line theory and analytical functions allowing calculation of unsteady aerodynamics, a prescribed distorted wake model following Beddoes approach, an aeroelastic model and a trim algorithm. In the wake model, in addition to the tip vortex, a second more inboard trailed vortex can be modelled.

The acoustic code AKUROT [11] is based on the Ffowcs Williams-Hawkings equation (Farassat Formulation 1A). It predicts the thickness and loading noise and, in an approximate way, the quadrupole noise (not considered here). The calculation is performed in the time domain.

A free wake code [15], not available when the optimisation was started, was developed in the meantime at DLR. The computation method is as follows: the S4 code is used, together with the free wake code, iteratively by passing over the blade motion and the blade circulation distributions, while the free wake code computes both the wake geometry and induced velocities on the blades, including a vortex roll-up for multiple vortices, if present. A simple core radius development model is used derived from HART test data. Both codes are iterated until convergence.

ONERA prediction method (MESIR-MENTHE-ARHIS-PARIS or MMAP): The prediction of BVI helicopter rotor noise uses the following computation chain described in detail in [12]. First, the trim is calculated using the code R85-METAR [16]. R85 computes the dynamic (quasi-steady) response of the blades and their elastic deformation. METAR performs a wake calculation using a lifting line/vortex lattice method. A coupling between R85 and METAR is made until convergence on induced velocities. The power consumed by the rotor is a result of R85 calculations.

Second, the wake prescribed geometry obtained from R85-METAR is distorted using a free-wake vortex lattice model name MESIR [17]. The free-wake calculation takes into account the blade deformations predicted by R85-METAR. The full vortex sheet is considered in the distorsion process.

Third, the vortex roll-up model MENTHE [13] identifies the portions of the discretized MESIR wake of sufficient intensities to cause a roll-up and builds the resulting vortices. Their intensities and locations are computed starting from the characteristics of the MESIR wake and provided as inputs to the aerodynamic code ARHIS [18].

Remark: Building the vortex roll-up model MENTHE was found necessary at the starting of the optimisation phase because the complex geometry studied were generating non-classical spanwise loading distributions capable of creating vortex patterns more complex than a simple tip vortex configuration.

In a fourth step, ARHIS predicts the unsteady blade pressures based on a singularity method.

In the case of strong interactions, the vortex is modelled as a cloud of elementary vortices in order to take into account the effect of its deformation. The vortex core radius is calculated, depending on its age, using a law derived from experimental results.

In a fifth step, the acoustic code PARIS [19] predicts the loading and thickness noise radiation. The method is based on the FW-H equation and a time domain formulation. BVI noise is calculated from ARHIS blade pressure distributions. An efficient spanwise interpolation method is implemented in the code in order to minimise the amount of aerodynamic data required for the BVI noise calculation. A PARIS subroutine locates on the rotor disk the sources responsible for the noisiest interactions.

3.2 High-speed flight

Euler and full potential computations using respectively the code FLOWER [20] from DLR the code FP3D [21] from ONERA were used for prediction of delocalisation. In both cases, isolated blade calculations were performed, the inflow being prescribed for modelling the influence of other blade wakes. The same inflow data were used.

4. Exploratory phase: parametric study on rectangular blades

The rotor radius was chosen equal to 2.1 m and was not allowed to vary. The parametric study of this first phase was performed by considering a blade with rectangular planform and using the ONERA 7A rotor as a reference. The following nominal values (corresponding to the 7A) were defined:

- rotation tip speed $\Omega R_{nom} = 210$ m/s,
- number of blades $n_{b\,nom} = 4$,
- chord length $c_{nom} = 0.14$ m.

Remark: ΩR_{nom} and every value of the rotor rotation speed are expressed in the paper in m/s for convenience. For the calculations and wind tunnel tests, of course, only Mach numbers were considered. Here 210 m/s corresponds to a Mach number of 0.617.

The rotating tip speed, blade number and chord length were allowed to vary as follows: $\Omega R =$ 185 , 210 and 225 m/s, $n_b = n_{b_{nom}}, n_{b\,nom} \pm 1$, $c = c_{nom}, c_{nom} \pm 25\%$.

Power calculations were performed first. On the 27 combinations, 16 were discarded either because of predicted excessive power consumption and/or insufficient maneuver capability. Acoustic calculations were performed for the 11 remaining rotors. At the end, two best rotor candidates remained: a reduced tip speed, 5-blade, nominal chord rotor and a reduced tip speed, 4-blade, enlarged chord rotor. Though tip speed reduction was found very effective on these rectangular rotors, a tip-speed reduction from 210 m/s to 185 m/s as assumed in the study would have led, according to Eurocopter, to unacceptable weight penalties. For this reason and since only marginal gains were predicted with the 5-blade rotor, a mutually agreed decision was made to pursue further more refined parametric studies on a 4-blade rotor rotating at 210 m/s.

5. Main phase

5.1 Parametric study on advanced blade geometries

<u>List of parameters and conditions of the study</u>:

A 4-blade rotor with a rotating tip speed of 210 m/s and ONERA OA2xx airfoils was chosen as a reference. It was agreed to use existing OA2xx airfoils for the parametric study and use more advanced OA3xx and OA4xx airfoils for the final design. The blades were considered rigid. The influence of the following parameters on noise and performance was investigated:

- blade thickness (by varying the OA2xx airfoil distribution along the blade span)
- twist distribution (linear and non linear),
- chord length distribution (with constant airfoil),
- quarter-chord line geometry (by sweeping the blade, keeping the chord length constant).

Furthermore possible additional gains with HHC were assessed.

For each parameter studied, dBA (corresponding to scale 1) noise levels, at about 200 observer locations, in a horizontal plane lying 10 diameters below the rotor, were calculated. Noise level contours in this plane were plotted and logarithmic spatial averaged noise levels were computed. Not only the final averaged sound power levels were considered but, more particularly, the influence of each separate parameter variation on:

- the blade spanwise loading distribution (which governs the intensity of emitted vortices) at those azimuthes, in the second and third quadrants, where interacting vortices are generated,
- the convection of these vortices (which governs the blade-vortex miss-distance at the time the vortices cross the rotor plane as well as the parallelism of the interactions).

Two sample results from the parametric study are provided below, concerning the influence of the chord length distribution and the quarter-chord line geometry respectively.

Influence of the chord length distribution

Varying the blade chord is expected to redistribute the loading along the span, and modify the trailed vorticity. Particularly a translation of the maximum loading inboard is expected to result in a decrease of the tip vortex intensity. During the parametric study, several geometries were generated by varying the spanwise chord distribution (equal to c_{nom} at the blade root) with the constraint of a constant value of the integral $\int_0^R c(r)r^2dr$ to ensure a constant mean thrust coefficient over the rotor disk for the considered rotors. A typical (but not necessarily realistic) blade geometry named C70 is shown in Fig.1. The corresponding BVI (spatially averaged) predicted noise level in low speed level and descent flight is compared to the one of the reference rotor in Fig.2. In this particular example, a 7 dBA noise reduction was predicted at 6 degree descent.

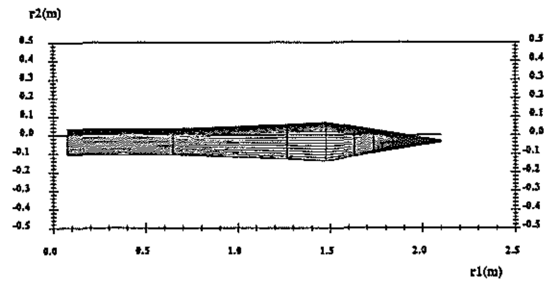


Fig.1: Example of blade planform considered in the parametric study (Blade C70)

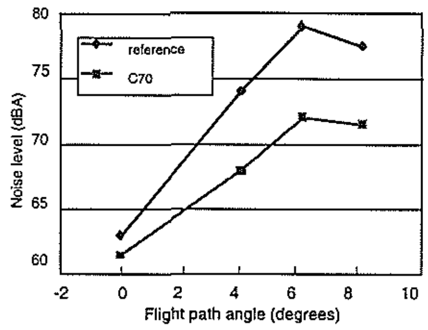


Fig.2: C70-reference acoustic comparison at 125 km/h (MMAP prediction)

As expected, thickness noise was predicted to be reduced for this kind of blade, particularly at high speed, leading to a noise reduction in the rotor plane but only marginal gains below the rotor.

The effect of chord tapering on the consumed rotor power was found dependent on the flight speed, being the net result of a decrease in profile drag on the advancing side and an increase in drag on the retreating side due to stall.

Influence of the quarter-chord line geometry

An important parameter in the construction of the BVI noise wave front is the phase delay between the acoustic pressure peaks emitted by the consecutive spanwise blade sections as they are affected by a vortex passage. To this respect, in the conditions were a straight blade would experience a parallel interaction, any sweep of a part of the quarter chord line is potentially beneficial in view of noise reduction. A blade with a backward swept tip will only experience parallel BVI on outer blade sections on the advancing side and not on the retreating side. It will be the contrary for a blade with a forward swept tip.

In order to quantify the influence of sweep on acoustics, several blade geometries were considered. The S85 design shown in Fig.3., for instance, is swept forward in the inner part of the blade, and swept backward in the outer part with the change in sweep at 0.85 R.

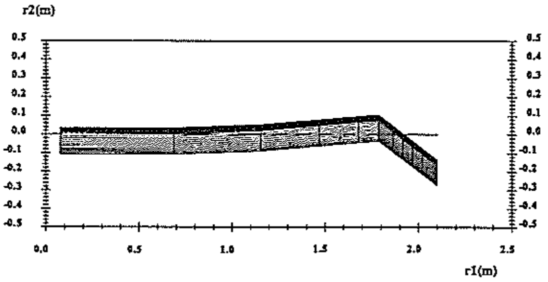


Fig.3: Example of blade planform considered in the parametric study (Blade S85)

Noise prediction results at 125 km/h as a function of α are presented in Fig. 4.

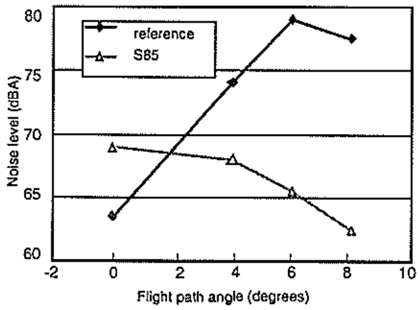


Fig.4: S85-reference acoustic comparison at 125 km/h (MMAP prediction)

Significant noise reductions of more than 10 dBA (possibly overestimated) are predicted at 6 degree descent. Furthermore, it can be seen on the figure that a backward sweep at the blade tip changes the descent angle at which maximum BVI's occur: 6 degrees for the reference and 0 degree for S85. This is coherent with the kinematics of BVI as a function of the descent angle which causes for instance, on the advancing side, the crossing of the rotor plane by the vortices to occur at higher azimuths when $|\alpha|$ decreases and thus enables parallel encounters with a sweptback tip.

In the same way as the previously considered C70 blade, S85 was predicted to provide a significant decrease of thickness noise in the vicinity of the rotor plane but no gains below the rotor.

<u>Effect of HHC (straight blade)</u>

A potential for about 5dBA maximum noise reduction was predicted at 6 degree descent (S4-AKUROT computations).

5.2 Optimisation

<u>Objective function</u>: An attempt was made for defining an objective function which would have made unnecessary the calculation of noise level contours. This objective function would have been calculated as a function of unsteady loads related to BVI's. Adjustment of this criterion took in fact more time than expected so that the idea was temporarily abandoned for the optimisation. Recent works by DLR on such a criterion have led to a satisfactory result validated during flight tests in the case of the straight BO105 main rotor blades [6].

<u>Conduct of the optimisation</u>: Since the reliability in predicted noise levels for such non-conventional blades was reasonably limited and since understanding of basic physical mechanisms related to geometry changes was required for guiding the optimisation, it was decided to proceed as follows. Instead of blind calculations with an optimiser, a fine-tuning of the parameters starting from an initial guess based on the parametric study, together with engineering judgement was preferred. By doing this way, examination of every kind of intermediate result in the computation chain could be performed. Starting from the identification of the noisiest interactions, the geometry and intensity of the involved vortices could be assessed and the relationship with the blade circulation distribution at the azimuth where these vortices were generated, and ultimately with the blade geometry modifications, could be established.

The nominal rotation speed for the optimisation was chosen equal to 210 m/s with control computations to be performed at 200 and 220 m/s. The nominal non-dimensional helicopter weight coefficient Z_W^* was chosen equal to 12.5 and the nominal fuselage drag coefficient $(C_X S')_f / S\sigma$ to 0.1. Furthermore, it was decided not to optimise the very blade tip geometry for high speed and use a straight tapered tip instead of an advanced parabolic tip, for instance.

According to the priorities defined by industry (Section 2), systematic calculations of dBA noise levels below the rotor in low speed flight at 125 km/h (67 kts), with a sweep in flight path angle from 0 degree to 8 degrees and check of the stability of the results at 67 kts

± 10%, were decided, corresponding to Priority 1. Computations were also to be performed in the final design phase, for level flight at 215 and 260 km/h (resp. 115 and 140 kts), corresponding to Priority 2.

With respect to high-speed flight at 350 km/h (190 kts, Priority 3), it was decided to check numerically at certain steps of the optimisation, that the rotor designed for low and medium speed would not cause any acoustic or performance penalty in this flight condition. Particularly, a checking of shock delocalisation, using the CFD codes FP3D and FLOWER, was planned.

Differently from the parametric study during which computations were simplified by assuming the blades to be rigid, the optimisation had to take into account the blade deformation. To do that, the mass and stiffness distributions used as inputs by dynamic and aeroelastic models were calculated from iterations between ONERA-IMFL (responsible for the pre-design of the blades to be manufactured) and dynamicists.

The ONERA/EC 7AD rotor [21] was chosen as a reference rotor. The 7AD has – 8.3^0/R linear twist, OA2xx airfoils and an advanced parabolic tip with 12.5^0 anhedral (Fig.5). The nominal rotation speed of the 7AD rotor is 223 m/s which is higher than that selected for the optimised rotor (210 m/s).

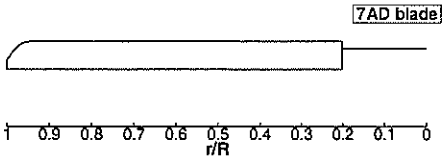


Fig.5: 7AD blade planform

Initial blade geometry for the optimisation: Based on the results of the parametric study, DLR and ONERA proposed a low noise rotor design to initiate the optimisation. This rotor design was based on the double sweep concept in order to prevent constructive interference of the acoustic signals. Since implementation of a forward swept tip was considered risky by industry from an aeroelastic stability standpoint, a backward swept tip concept was chosen. A starting rotor for the optimisation named OPT1 with – 10^0/R linear twist, maximum chord at 70% R and change in sweep at 80% R was defined. The OA2xx airfoils were replaced by the more recent and efficient OA3xx and OA4xx airfoils.

Summary of the iterations: In workshare between DLR and ONERA, the geometry parameters were varied separately in small ranges, starting from OPT1 values. Then an optimised geometry was defined with the quarter chord line geometry adjusted for best balancing of lifting surfaces with respect to the pitch axis and thus minimise pitch link loads. A final dynamic and stability optimisation was then performed.

Dynamic and stability optimisation: A dynamic and stability optimisation of the blades supposed mounted on the hub to be used in S1Modane was performed by ONERA using the coupled codes R85-METAR/CONMIN for dynamics and the code ROTOR [22] for stability. Cross checks calculations were performed by DLR using the S4 code. The objectives of the dynamic optimisation were, particularly at high speed, to minimise the 3/rev in-plane moment in the rotating frame and to ensure that the 4/rev vertical and in-plane shears in the fixed frame and the pitch link loads were lower than the corresponding values for the reference rotor. The optimisation procedure was performed with the constraint of avoiding couplings between the blade natural frequencies and harmonics of the rotation frequency. Stability checks were performed to ensure that no damping problems would be encountered during wind tunnel tests.

The optimisation variables were:
- the mass distribution,
- the flapping, lead-lag and torsion stiffness distributions.

At the end of this optimisation, control computations with the hub to be used in DNW were performed for secureness.

Optimised geometry and predicted acoustic, aerodynamic and dynamic performance: The final result of this optimisation is the ERATO rotor shown in Fig. 6. It has the same mean blade chord and solidity (0.085) as the 7AD but differs in twist (- 10^0/R linear instead of - 8.3^0/R), airfoils (OA3xx and OA4xx instead of OA2xx) and planform.

The predicted acoustic comparisons between both the 7AD and ERATO at 125 km/h, in a horizontal plane located 10 rotor radii below the rotor hub, are shown in Fig. 7.

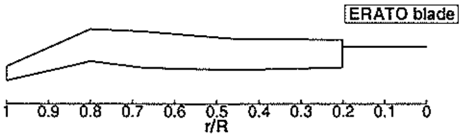


Fig.6: ERATO blade planform

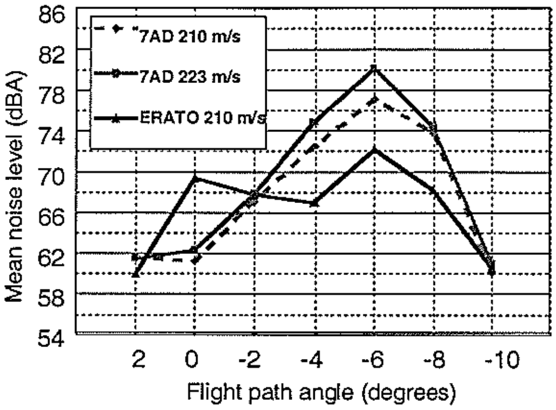


Fig.7: 7AD-ERATO acoustic comparison at 125 km/h (MMAP prediction).

As seen on the figure, up to 8dBA mean noise level reduction were predicted for 6 degree descent for the ERATO blades rotating at 210 m/s (ERATO nominal ΩR) compared to the 7AD rotating at 223 m/s (7AD nominal ΩR). A 5.3 dBA reduction is predicted when the rotors are compared at the same ΩR of 210 m/s. Significant radiated noise reductions below the rotor were also predicted at 215 and 260 km/h (115 and 140 kts): 7 to 9 dBA with both rotors operated at their respective ΩR. At these level flight speeds as well as in low speed descent flight, these computed noise reductions were the result of decreased BVI noise thanks to the ERATO blade geometry.

In level flight at 125 km/h, a BVI noise increase is predicted for the ERATO rotor. This is the previously above-mentioned consequence of sweeping the blade tip backwards. This was not considered as a penalty because the corresponding noise level is more than 10 dBA below the maximum of the 7AD, on the one hand, and because 125 km/h is much lower than the cruise speed for minimum noise of a Dauphin helicopter.

For high-speed flight at 350 km/h (190 kts), which was only Priority 3, no acoustic calculations were made. However CFD computations were performed which predicted no shock delocalisation penalty for the ERATO blades.

Power reductions of about 15% were predicted at 350 km/h for the ERATO rotor compared to the 7AD with both rotors operated at their respective nominal ΩR (a 6% reduction was predicted with both rotors operated at ΩR = 210 m/s). In hover, the predicted figures of merit of the ERATO and 7AD rotors were found very close, with a slight advantage for the ERATO rotor at $Z_W^* = 12.5$ and the opposite at $Z_W^* = 15$, for $\Omega R = 210$ m/s.

With respect to vibration and stability, gains in the in-plane moment and no significant penalty on other unsteady terms was predicted for the optimised rotor.

6. Validation phase

When the ERATO programme was launched, it was decided that an instrumented model of the optimised rotor would be built and that extensive wind tunnel tests of this rotor and of an existing instrumented model of the 7AD rotor would be performed to check fulfilment of the objectives and to verify the design methodology. Particularly the capability of numerical codes to accurately predict the aerodynamic, dynamic and acoustic behaviour of the blades would be checked, as far as possible, at each intermediate step of the calculations. These intermediate steps are: the trim conditions, the blade kinematics and deformations, the blade loading time history (which governs the generation of the vortices and their vertical convection), the location w/r to the blade, geometry (orientation and viscous core radius) and intensity of major interacting vortices and their vortex velocity field, the unsteady blade pressure time histories and ultimately the acoustic radiation (level and directivity).

To do this, the ERATO rotor would have to be equipped with large number of pressure transducers (with certain sections densely instrumented) and strain gauges (to provide blade deformations by means of appropriate analysis like the Strain Pattern Analysis, for instance). The blade deflections/deformations would also be provided by the Projected Grid Method (PGM) developed by DNW [5]. The vortex geometry and blade-vortex miss distance at the locations of noisiest BVI's would be provided by the Laser Light Sheet technique (LLS) [23] and the vortex velocity fields would be measured by Particle Image Velocimetry (PIV).

6.1 Structural design and blade manufacture

The reference 7AD rotor being already instrumented with 118 pressure sensors and 28 strain gauges, it was decided to equip the ERATO model rotor with 124 absolute Kulite pressure sensors and 32 strain gauges.

The structural design and blade manufacture, because of the complexity of the blade geometry and because of the density of the instrumentation (700 wires cabled at the root of the pressure-instrumented blade) were a challenge . This work was shared between ONERA and DLR, with a very close collaboration of specialists of both sides. The structural design of the model rotor was performed by ONERA-IMFL: the stiffness and mass distributions were determined through iterations with ONERA dynamicists, to avoid undesirable mode couplings. A technological blade including strain gauges and dummy transducers was built by ONERA-IMFL for verification of the process in a first step. Prototype blades were then built by ONERA and DLR and the series instrumented blades manufactured by DLR. The blades are made of a glass fibre spar with a carbon torsion box and a pre-cured carbon skin in which the strain gauges are included. Because of the complex geometry of the ERATO blades and because of sensor integration requirements, the raw spar was pre-cured in a first step then machined.

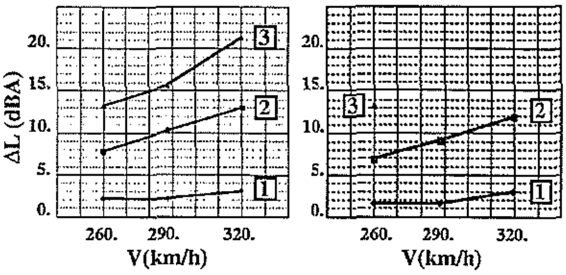
6.2 validation tests

The validation tests were performed in the S1 Modane-Avrieux (S1MA) wind tunnel in the high-speed range (up to 350 km/h) and in the DNW in the low to moderate airspeed range (70 to 260 km/h). The measurement techniques implemented together with the experimental results are described in detail in [1]. Only sample results are presented below, with the objective of a global assessment of the fulfilment of the objectives and of the validity of the design methodology.

It must be mentioned that the noise calculations were performed in a horizontal observation plane located 10 R below the rotor to correspond to ICAO certification conditions. This is much farther than the measurement distances in S1MA (of the order of 3R) and DNW (1.1R). The predicted absolute values for maximum noise levels thus cannot be directly compared to experiment. To do this, acoustic calculations will have to be repeated to correspond to wind tunnel microphone locations. As a first approximation, however, the predicted and measured maximum noise level differences between both rotors can be compared.

6.2.1 Acoustics

<u>S1 Modane test results</u>: The difference (7AD - ERATO) between the maximum measured noise levels below the rotors in S1 Modane, for two values of Z_W^* : 12.5 and 15, are presented in Fig.8. The 7AD rotor was run here at its nominal rotation speed of 223 m/s and the ERATO rotation speed was varied.



a) b)

Fig.8: 7AD-ERATO acoustic comparison in level flight, S1MA measurements
/1/ 7AD, $\Omega R = 223$ m/s, ERATO, $\Omega R = 223$m/s
/2/ 7AD, $\Omega R = 223$ m/s, ERATO, $\Omega R = 210$ m/s
/3/ 7AD, $\Omega R = 223$ m/s, ERATO, $\Omega R = 195$ m/s
a) $Z_W^* = 12.5$, b) $Z_W^* = 15$.

The ERATO rotor appears quieter than the reference rotor in every case. For the ERATO rotating at its nominal speed, the measured gains are about 7 dBA at 260 km/h and 10 dBA at 290 km/h which is very close to the predicted gains. The corresponding measured gains are respectively 2 and 3 dBA when the ERATO rotor is operated at 223 m/s. These noise reductions are the consequence of reduced BVI noise radiation by the ERATO blades compared to the 7AD, in these conditions, as confirmed by examination of microphone signals. As an example, Fig.9 compares typical rotor time signatures at maximum measured noise locations and clearly shows the reduction of BVI pressure peaks in the ERATO signature.

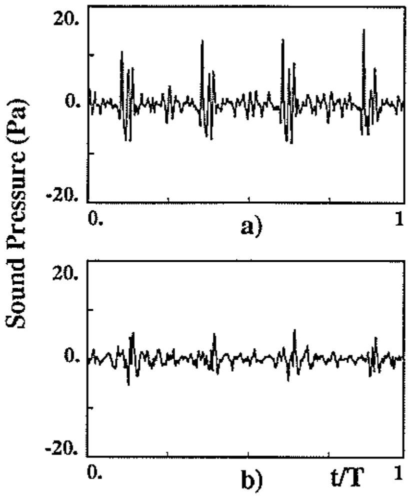


Fig.9: 7AD-ERATO acoustic comparison at 215 km/h, $Z_W^* = 15$, $\Omega R = 210$ m/s, S1MA measurements, a) 7AD rotor, b) ERATO rotor

<u>DNW test results:</u> In DNW, the BVI noise measurements were performed in a horizontal, plane located 1.1 R underneath the rotor hub. Fig.10 compares mean experimental noise levels for the 7AD rotor at its nominal rotation speed (223 m/s) and the ERATO rotor, at three values of ΩR and for $Z_W^* = 12.5$. At its nominal ΩR, the ERATO rotor appears 4 dBA quieter than the 7AD at the descent angle of maximum mean noise level, that is close to 5 degrees, which is lower than the predicted value of 8 dBA. This noise reduction is increased to about 6 dBA for $\Omega R = 195$ m/s. The optimised rotor remains even quieter when its rotation speed is raised to 223 m/s which is outside the range of variation of ΩR retained for the optimisation. When Z_W^* was increased to 15 and 17.5, larger noise reductions were recorded [1] As an example, Fig.11 compares both rotors at $\Omega R = 210$ m/s and $Z_W^* = 17.5$. A noise reduction by more than 5 dBA can be noticed on the figure.

<u>Remark</u>: For the same Z_W^*, about 7 dBA reduction would be found, if the comparison would be made with the reference rotor operated at $\Omega R = 223$ m/s (from HELISHAPE [24] 7AD test results extrapolation).

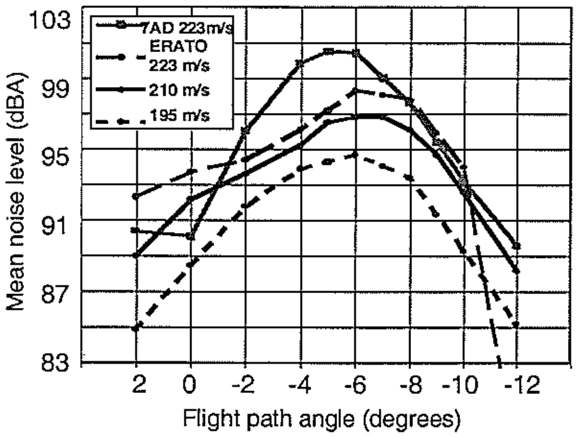


Fig.10: 7AD-ERATO acoustic comparison at 125 km/h, $Z_W^* = 12.5$, DNW measurements.

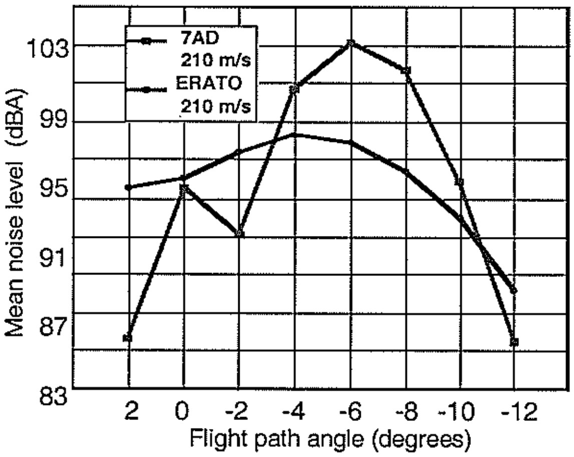
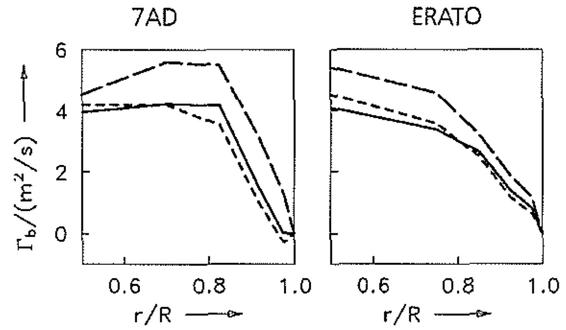


Fig.11: 7AD-ERATO acoustic comparison at 125 km/h, $Z_W^* = 17.5$, DNW measurements.

An important acoustic feature of the ERATO rotor, which was looked for during the optimisation, is the low sensitivity of the BVI noise radiation to variations of the flight path angle compared to the 7AD (the noise level evolution as a function of α is much flatter than the 7AD one). This character is increased with larger Z_W^*. As shown in [1] and noticeable through comparison of Figs. 10 and 11, the sensitivity of BVI noise radiation to variations of Z_W^* is also by far much lower than the one of the 7AD.

As shown in [1], preliminary examinations of the acoustic, aerodynamic, wake (through LLS) and PIV velocity field measurements, show that these noise reductions are the consequence of reduced BVI's in clear correlation with the aerodynamic behaviour of the ERATO rotor. This is illustrated by Fig. 12, taken from [1], which compares radial blade circulation distributions (calculated from chordwise integration of blade pressures) for both rotors at the azimuth 140°, where the noisiest interacting vortices are generated. Several wind tunnel conditions are considered. It is immediately noticeable from the figure that in every case, compared to the 7AD, the maximum circulation on the ERATO blade is translated towards more inboard sections and exhibits much lower radial gradients, both characteristics which were looked for during the blade geometry optimisation. From Fig. 12, it can be inferred that the intensity of the generated vortices should be lower, which first results from the processing of PIV data tend to confirm [1]. This was the objective of the ERATO blade geometry optimisation.



Parameters			7AD	ERATO
line	$\varphi/°$	Z_W^*	$M_{\Omega R}$	$M_{\Omega R}$
——	0	12.5	0.661	0.617
----	-6	12.5	0.661	0.617
--	-6	17.5	0.617	0.617

Fig.12: Compared 7AD-ERATO circulation distributions at Azimuth 140°, at 125 km/h, from DNW measurements.

6.2.2 Performance

A comparison of the power consumed by the 7AD and ERATO rotors at ΩR = 210 m/s, from S1 Modane measurements, is displayed in Fig.13 taken from [1]. As shown in the figure, whatever the advance ratio μ^*, the ERATO rotor consumes less power than the reference rotor. The power reduction reaches the maximum value of 12% at low Z_W^* and μ^*= 0.423 (320 km/h). It seems to decrease with increasing Z_W^*, an aerodynamic deficiency at high lift which was also measured by Eurocopter (in term of figure of merit) during hover tests performed in Marignane. At μ^*= 0.344 (260 km/h), the power reduction is larger than 4%, whatever the thrust. The objective of the ERATO programme which was that the new design would not cause any penalty in power at nominal conditions is thus, largely exceeded.

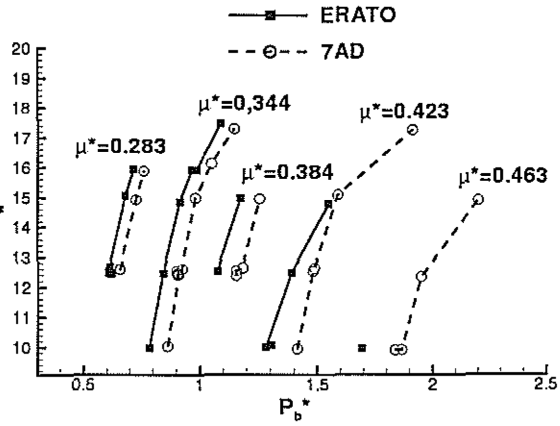


Fig.13: 7AD-ERATO performance comparison, S1MA measurements.

6.2.3 Dynamics and stability

We recall that the dynamic and stability constraints for the optimisation were, particularly at high speed, to have no penalty in terms of the 3/rev in-plane moment in the rotating frame, of the 4/rev vertical and in-plane shears in the fixed frame and of the pitch link loads. The experimental results, presented in [1], show that the constraint on the 3/rev in-plane moment is fulfilled. Differently, the constraint on the vertical shears is fulfilled at ΩR = 195 m/s and no longer at ΩR = 210 m/s, at medium to high speed level flight, because of an unpredicted coupling between deformation modes and closeness to a rotation harmonic.

7. Conclusion

The ONERA-DLR ERATO programme has been successful in designing a low noise rotor geometry, taking as a reference a rotor of current technology. Furthermore a highly instrumented model rotor of complex geometry has been designed and manufactured and extensive wind tunnel measurements with sophisticated measurement techniques have been performed, which have generated a large amount of experimental data for code validation.
With respect to the objectives relative to both

rotors operated at their respective nominal rotation speed,

- in descent flight at 125 km/h, a 4 to 5 dBA mean noise reduction is achieved in the conditions of highest noise radiation (between 5 and 6 degree descent angles), at the nominal $Z_w^*=12.5$ and 5 to 7 dBA, at $Z_w^*=15$ and 17.5. These numbers are increased by about 2 dBA when the rotation speed of the ERATO rotor is lowered to the minimum value considered in the optimisation (195 m/s);
- at level flight, the gains are of 4 to 7 dBA, in the range 220 to 260 km/h and more than 10 dBA at 290 km/h and 320 km/h, with a large gain increase at high speed when the rotation speed of the ERATO rotor is lowered to 195 m/s;
- the ERATO rotor has excellent aerodynamic performance at moderate to high-speed level flight with power reduction from 4 to 12%. This advantage is however limited to low-to-medium loads, at the maximum speed tested of 320 km/h. The performance in hover also show a penalty at high lift;
- the dynamic behaviour of the ERATO rotor needs to be improved. The 3/rev in-plane moment is satisfying but the 4/rev vertical shears, at medium to high speed level flight, are too high because of unpredicted couplings.

With respect to the accuracy of the prediction codes,

- the achieved noise reduction of 4 dBA at low Z_w^* is less than the predicted 8 dBA. The reason for this overestimation (presumably related to the wake prediction) needs to be investigated;
- the performance predictions are in very good agreement with experiment;
- the dynamic/stability prediction needs improvement.

The comprehensive high-quality data base generated in S1 Modane and DNW will serve for investigating the physics of BVI noise generation for the tested advanced blade geometries and to improve, where needed, the accuracy of numerical prediction tools in view of future designs.

8. Acknowledgement

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