WIND-TUNNEL TESTS OF A HELICOPTER ROTOR WITH ACTIVE FLAPS

Pascal Crozier[1], Philippe Leconte[2], Yves Delrieux[3], Bernard Gimonet[4], Arnaud Le Pape[5], Hugues Mercier des Rochettes[6]

[1]ONERA / DGMT / DTEX
Centre de Modane-Avrieux, BP25,
73500 Modane, France
pascal.crozier@onera.fr

[2]ONERA/DDSS/AE
29 avenue de la Division Leclerc,
92322 Châtillon, France
philippe.leconte@onera.fr

[3]ONERA/DSNA/ACMT
29 avenue de la Division Leclerc,
92322 Châtillon, France
yves.delrieux@onera.fr

[4]ONERA/DCSD/IDCO
Centre de Toulouse, BP 4025, 2 avenue
Edouard Belin, 31055 Toulouse, France
bernard.gimonet@onera.fr

[5]ONERA/DAAP/H2T
29 avenue de la Division Leclerc,
92322 Châtillon, France
arnaud.lepape@onera.fr

[6]ONERA/DMSE/RCS
Centre de Lille, 5 boulevard Paul Painlevé,
59045 Lille, France
hmdr@onera.fr

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Abstract : Within the frame of a project called DTP RPA (Développement Technique Probatoire Rotor à Pale Active), also known as Active Blade Concept, carried out in cooperation between ONERA, Eurocopter, DLR and Eurocopter Deutschland, a four-bladed Mach-scaled rotor was tested in December 2005 in ONERA S1 Modane wind-tunnel. The main objective of this test was to validate the concept of using active flaps located on the trailing edge of the blades of the main rotor of a helicopter to decrease the vibration level generated by this rotor. The present paper gives a general description of the experimental set-up which allowed testing the active flap-equipped rotor including the control strategy, as well as first significant results related to aerodynamics, aero-acoustics and dynamics of such a rotor, showing the efficiency of active flaps with respect to the objectives of the study.

1 INTRODUCTION

The reduction of the vibration level transmitted by the main rotor of a helicopter to its fuselage has been for decades the objective of many optimization studies [1,3]. This phenomenon, essentially due to the intrinsic aerodynamic imbalance between advancing and retreating blades coupled to the structural response of the blades, needs to be alleviated in order to increase the comfort of pilots and passengers, by passive or active means. In the latter category, active flaps have already drawn interest from many researchers, on both numerical and experimental levels [4,9]. In a very similar approach, the decrease of the BVI noise generated by a rotor in descent flight could make use of the same kind of active device in order to increase the acceptance of rotary wing aircraft in inhabited areas. Following some preliminary numerical studies, a project called DTP RPA (Développement Technique Probatoire Rotor à Pale Active), also known as Active Blade Concept (ABC), was launched in France at the end of 1998. This project, involving Eurocopter and ONERA, has been funded by French Civil Aviation Authorities. As similar activities were being addressed in Germany by DLR and Eurocopter Deutschland within the ADASYS framework, the ABC project became naturally part of ONERA-DLR partnership on helicopter research program. The three main objectives of this project were, by decreasing priority order, to : reduce the BVI noise radiated in descent flight, decrease in the broadest possible flight domain the rotor vibration level and finally increase the rotor aerodynamic performance, by either alleviating the dynamic stall effect or decreasing the consumed power in fast cruise flight. From the start of the project, two wind-tunnel test campaigns were planned, one in S1 Modane mainly focused on dynamic aspects and one in DNW-LLF mainly dedicated to acoustic issues. A first phase of the project addressed, thanks to numerical studies carried out on a full-scale ATR blade geometry provided by Eurocopter Deutschland, the optimization of both the dimensions and locations of active flaps on a main helicopter rotor [10]. Once the flap geometries frozen, associated optimal flap deflection laws, with respect to the three aforementioned objectives, were calculated at both full and wind-tunnel scales. In parallel, was carried out a specific study to design an active flap device that would be implemented in the rotor model to be tested in both S1 Modane and DNW-LLF. The second phase of the project, which started in 2001, was devoted to the detailed design of the wind-tunnel scale blades featuring the active flap device, the establishing of the manufacturing process, several steps of experimental validations of the active flap system, the manufacturing by ONERA of a prototype blade and by DLR of a set of 5 "series" blades (including one spare blade) for the wind-tunnel tests [11]. The latest main step of the ABC project was the test campaign in December 2005 in S1 Modane wind-tunnel of this active flap-equipped rotor model which is described in details in the present paper, along with first results coming from the analysis of the comprehensive database recorded there.

2 TECHNICAL ASPECTS OF ABC ROTOR MODEL

Design, manufacturing process and mechanical characteristics of the rotor model blades are described in details in [12] and briefly recalled hereafter.
The overall diameter of the Mach-scaled rotor is 4.2 m while the maximum blade chord is 140 mm. The mean flap dimensions are 210 mm in span and 21 mm in chord. Significant vibration and noise reductions had been calculated with ONERA simulation codes for three spanwise locations of the flap as illustrated in Figure 1. The most outboard location was deemed as most rewarding for acoustic issues, whereas the most inboard one gave the best results for vibration alleviation.
The blade is made up of four main parts (R being the total radius of one blade) :

- blade root area, from 0.131R (fastening section to the articulated hub) to 0.2R (first aerodynamic section) ;
- current section, from 0.2R to 0.69R ;
- sections in flap area, from 0.69R to 0.9R ;
- tip section, from 0.9R to R.

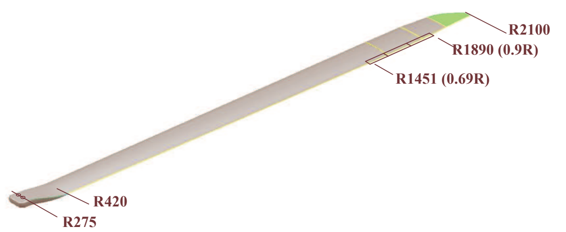

Figure 1 – ABC blade dimensions and flap positions

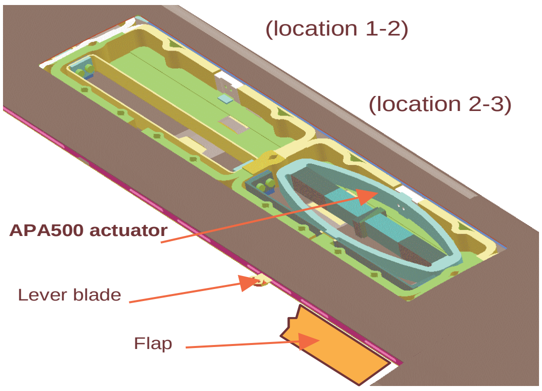

Figure 2 – ABC blade : flap area

The basic concept of the flap deflecting device (see Figure 2) is to actuate the 15% chord flap with an elliptic piezoelectric actuator (APA 500 from CEDRAT Recherche company) alternatively centered at R1602 mm or R1764 mm from the rotor axis, according to the selected flap location :

- actuator position 1-2 at R1602 : flap inboard position (70-80% R) or at middle position (75-85% R) ;
- actuator position 2-3 at R1764 : flap outboard position (80-90% R).

Each actuator is clamped on the rear face of the main spar by means of a metallic insert embedded in the roving during its layering.

The actuator deflects the flap by means of a lever blade, which is clipped and screwed to the flap. Thin wedges can be slit between the actuator and the lever blade to trim the pre-set of the flap when the actuator is not powered. The flap is linked to the trailing edge of the blade thanks to composite hinge blades, which are complemented by fork joints, the latter prescribing a pseudo-rotation axis. Each moving component of the flap device is assembled so that the bending stresses in hinge blades should be zero at mid stroke. The hinge blades come assembled to the flap from the manufacturing process and are screwed in a reinforcing frame inside the rotor blade using specific metallic inserts. Dummy flaps are used to ensure the continuity of the trailing edge of the blade and are screwed to the frame using the same kind of inserts. The experimental validation of the operation of the active flap system can be found in [13].

3 ACTIVE FLAPS CONTROL SYSTEM

The active flaps on the ABC rotor model are controlled thanks to a specific system, based on a dSPACE device and developed at ONERA, which has two main roles :

- calculate and deliver various types of deflection law to be performed by the flap, whatever the type of law (sweeps, pre-calculated, optimization [14,15]) ;
- handle the eventual perturbations brought by the flap deflection to the rotor trim by delivering small correcting signals, which are added to the manual pitch controls (collective and cyclic).

The flap control system basically features two PCs, among which one is devoted to code generation, compilation and Man Machine Interface tasks while the other is dedicated to the real-time generation of the flap driving signals.

The synchronization between the flap control system and the rotation of the rotor is guaranteed by two signals built in the rotating system (inductive sensor in front of a cogwheel) : the first one delivers one pulse per rotor revolution when blade 1 passes through its rear azimuth position, the second one delivers 256 pulses per revolution. Consequently, the flaps are driven by a signal featuring 256 values for one revolution.

Some specific quantities related to the operation of the rotor, such as reduced lift, drag, vibratory components, are fed into the dSPACE-based flap control system via a RS232 link.

The flap driving signals are not delivered directly to the actuators but to a specific control rack, made of four PI (Proportional Integral) channels, the outputs of which are the input signals of four CEDRAT power amplifiers, the latter driving the actuators through a slip-ring. The actual deflections of the flaps are measured by Hall effect sensors located on the flaps themselves. For safety reasons, an additional specific rack is able to deliver a constant voltage to the four flaps simultaneously in case one stage of the control system would fail.

When the control system is used in the closed-loop configuration, either to decrease the vibratory level of the rotor or to keep the flight case constant, a set of Kalman filters estimates the sensitivity matrices of forces and moments versus 0/rev to 5/rev harmonic components of the flap deflections and pitch control corrections. One interesting feature of the control system is the possibility to take into account the actual transfer function of each flap system (discrepancies coming from the manufacturing for instance), hence ensuring that all four flaps behave the same way in the end. In order not to address the complexity of an autonomous vibration optimizing control system, two human validation steps were, from the start of the project, kept in the system : the first one deals with the set of data provided by the recording system of the wind tunnel, the second one addressing the progressive delivery of a new flap deflection law to the power amplifiers or of corrections to the pitch rack. The overall flowchart of the flap control system is presented in Figure 3.

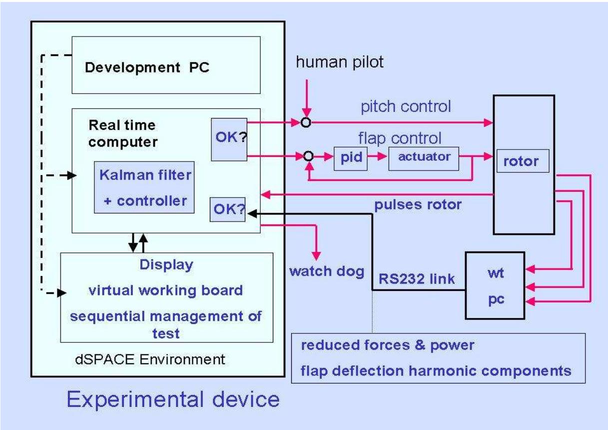

Figure 3 – Flowchart of the active flap control system

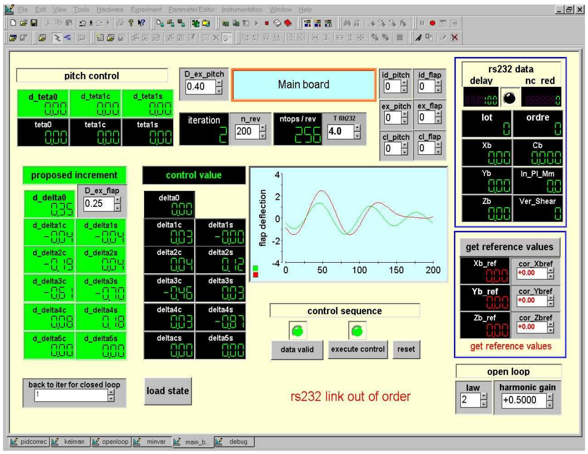

Figure 4 – Main control board

As briefly mentioned above, one PC of the control system is used to generate a set of instrument panels which allow the pilot of the flap to monitor all the aspects of the control tasks.

Figure 4 presents a screen capture of the main control board where the following features can be noticed :

- the right hand side of the panel is dedicated to the measurements coming from the wind-tunnel ;
- a scope provides the pilot with the flap deflection law being delivered to the system (green curve) and the new law proposed by the computer (red curve) ;
- the components proposed by the algorithm (green digits on black background) and the corresponding proposed increments (black digits on green background), for both the flap system and the pitch rack ;
- the two push-buttons for human validations…

Other instrument screens allow to take care of the following aspects : fine tuning of the Kalman filters for identification of the flap sensitivity, weighting factors for the optimization tasks, manual setting of harmonic components of deflection laws… All these possibilities resulted in a very versatile control system perfectly suited to the needs of wind-tunnel test activities.

4 WIND-TUNNEL TEST SET-UP

ABC tests, presented in this paper, were achieved in the S1 Modane wind-tunnel in December 2005. This closed-circuit, continuous flow wind-tunnel is one of the largest transonic wind-tunnels in the world. It is located in the French Alps in the ONERA Modane test center (see Figure 5), where supersonic and hypersonic facilities are also available. Thanks to its two fourteen meters diameter contra-rotating fans, Mach numbers between 0.05 and 1 can be reached. Fans are directly driven by Pelton turbines, the maximum power of which is 80 MW. Three interchangeable test sections (carts) of eight meters in diameter and fourteen meters in length are available. While one test is performed, two others can be prepared in parallel (see Figure 6). All the major European aircraft have been tested in this wind-tunnel (complete and half models) but also missiles at scale 1 with engine on, weapon stores separation thanks to a captive trajectory system, air intake and of course propellers (A400M for example), helicopter and tiltrotors.

Figure 5 - ONERA Modane test center

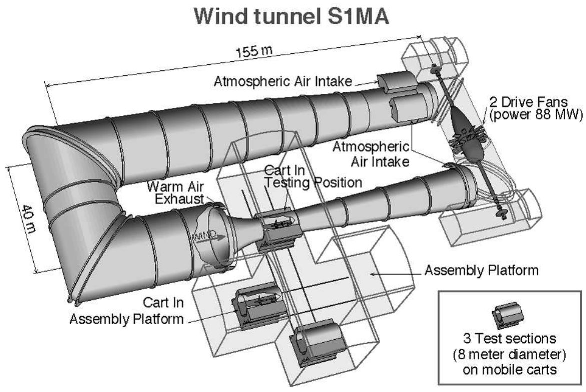

Figure 6 - ONERA S1 Modane wind tunnel

The helicopter test rig enables helicopter and tiltrotor tests to be carried out on isolated rotors with a maximum diameter of 4.2 meters. For these ABC tests, a new slip-ring was implemented inside the test rig. While the former slip-ring was limited to 150 rings, the new one features 252 silver rings : 212 rings are dedicated to measurements, 4 rings bring various shields from the hub to the wind-tunnel acquisition control room and the final 36 rings, each of which can withstand 2 A, are used for supplying power to the actuators of the flaps.
The main characteristics of the rig are :

- clockwise or anti-clockwise rotation ;
- rotation speed between 0 and 1100 rpm ;
- maximum power of 500 kW ;
- rotor shaft tilt angle between +20° (backward) and -95° (forward) ;
- maximum tilting speed : 2° per second.

More detailed information about this bench is available in [16].
Figure 7 shows the ABC blades on the helicopter test rig during the tests.

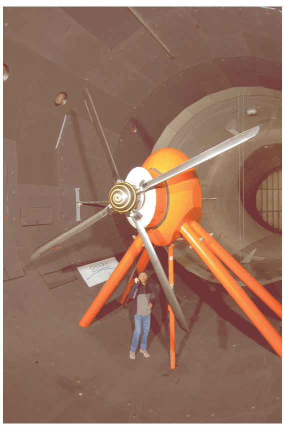

Figure 7 - ABC blades on S1 Modane test rig

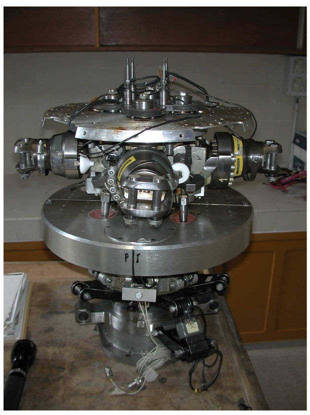

Figure 8 - ORPHEE hub used for ABC tests

The Eurocopter ORPHEE hub was used for these ABC tests (see Figure 8). This fully articulated hub was already used eight times for helicopter tests in S1 Modane between 1991 and 2004, including the well-known ERATO tests in 1998. Thanks to a special agreement between Eurocopter and ONERA, S1 Modane team has been appointed responsible for this hub maintenance since 1993. As such, in close collaboration between Eurocopter and ONERA, each maintenance phase is taken as an opportunity to improve the hub characteristics. As an example, maintenance before ABC tests enabled a complete refurbishment of the pitch arm lubrication system. New types of grease and V-rings were selected to optimize the lubrication of the ball-bearings which sustain the centrifugal loads and thus are one of the most sensitive parts of the hub. Characterization of elastomeric lead-lag dampers, another sensitive activity to guarantee hub integrity, is also realized by Modane team.

5 MEASUREMENTS

A very large number of sensors was implemented not only on the blades but also on the rotating and fixed parts of the hub and fourteen microphones were located in the test section.
The 168 pressure sensors, distributed on the four blades, were essentially located in six heavily-instrumented sections spread between 50 and 97.5% of rotor radius. Considering the unavoidable stress introduced on the sensors during the blade manufacturing process, original Kulite thermal compensation could be less efficient. Hence, a specific calibration procedure in pressure/temperature was done at ONERA Modane to reach an accuracy of ±200 Pa. Pressure and temperature ranges covered during this calibration were 0.275 to 1.4 bar and –5° up to +55°C respectively. During the test itself, pressure distribution of the six highly-instrumented sections was integrated to obtain in real-time the local lift and pitching moment coefficients at a rate of 256 points per revolution.
All the blades were equipped with nine strain gauges bridges distributed in three sections. These gauges were used for on-line monitoring of the blades, thanks to pre-calculated Goodman diagrams. Figure 9 shows Goodman diagram, as plotted in real-time during the tests. As long as stresses remained inside the green curve, blades did not suffer any damage (red curve indicates a 5-hours lifetime). Additional fifteen gauges bridges could be found on blade 2. These gauges, distributed all along the span, allowed the calculation of the unsteady blade deformations (flap and torsion) as well as the calculation of some unsteady vibratory terms using the SPA (Strain Pattern Analysis) method [17].
Hub instrumentation was divided into two types depending on their finality. For monitoring aspects, temperature sensors were implemented on the pitch housing, on the mast and on the swash-plate, while strain gauges were located on the scissors. The majority of the hub sensors was used to determine the dynamic forces at rotor centre. Indeed, not only the SPA method mentioned above but also a balance method, corrected for inertia, and an analytical method based on blade motions and inertia [18], were used to measure these forces. Consequently, no less than 28 accelerometers and 12 inductive angular sensors were implemented on the hub.
To conclude on instrumentation, even if BVI noise is generally observed for descent flight configurations, it had been observed in S1 Modane during previous tests for cruise flight configurations. As a consequence, acoustic measurements were estimated interesting, thus the acoustic linings (black foam) were installed to ensure good noise measurements as one can see in Figure 7. Furthermore, a preliminary study, in collaboration between ONERA acoustics and wind-tunnel Departments, enabled to define the wind-tunnel area of main interest to capture BVI noise and to optimize the profiles of the struts and tube which hold the microphones. A total of fourteen microphones were thus located under the rotor disk in the area of the advancing blade as shown in Figure 10. Although satisfactory measurements could

be recorded as illustrated in the acoustics paragraph, further improvements are already planned, such as a traversing array of microphones below the rotor disk in order to be able to plot noise contours.

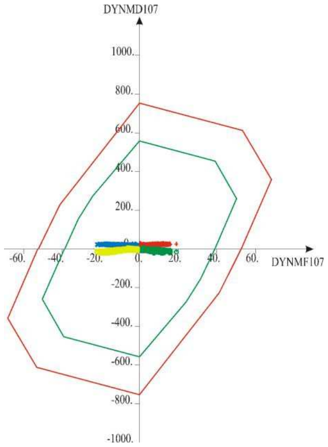

Figure 9 - Goodman diagram

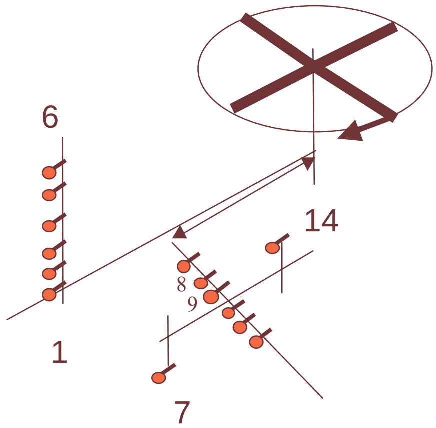

Figure 10 – Microphone implantation

6 PRELIMINARY TESTS AND EXPERIMENTS

In order to minimize technological risks and time losses during S1 Modane wind-tunnel tests, a global strategy was agreed between all the ONERA Departments involved in these ABC tests. Two main milestones of this process are listed below along with a description of the obtained results.

Firstly, after the delivery of the prototype blade manufactured at ONERA, a wind-tunnel test was performed in September 2004 in the S3 Modane facility. For this test, the blade was clamped on the wind-tunnel walls as shown in Figure 11 and the blade angle of attack was manually varied between two blow-downs. The test objectives were to :

- check the behavior of the active flaps under realistic aerodynamic loads ;
- obtain an identification of the flap system transfer function to achieve a fine tuning of the control system including dSPACE, PI and safety racks (stability, bandwidth) ;
- validate the exchange of data between the dSPACE and the wind-tunnel system thanks to a RS232 link ;
- improve the **M**an **M**achine **I**nterface based on the different screens available on the dSPACE ;
- make the final selection of the power amplifiers driving the actuators.

The S3 Modane test was a success since all the objectives were fulfilled and flap deflections up to ± 3° under Mach numbers ranging from 0.3 up to 0.8 were obtained.

Figure 11 – ABC prototype blade in S3 Modane

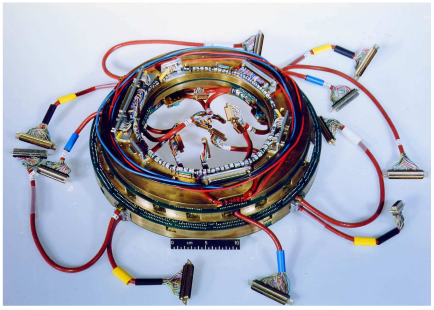

Figure 12 – S1 Modane multiplexer system

The second milestone was the realization of a preliminary test involving all the test set-up components : helicopter rig, ORPHEE hub, complete flap control system, complete electronic devices to ensure power supply and sensor conditioning, wind-tunnel acquisition system. The only difference between this experiment and the final test, was the absence of wind since this experiment was performed outside the aerodynamic circuit of S1 Modane. Although the number of measuring rings of the new slip-ring was increased, it was still not large enough to simultaneously transmit all the measurements coming from more than 300 rotating sensors. Hence, a multiplexing system, studied and manufactured at ONERA, was implemented in the rotating frame (see Figure 12). At first, a detailed check of the wiring between the hub and the wind-tunnel acquisition system was performed. Then, hub balancing, track adjustment and finally dynamic controls of the four flaps in rotation were realized over a large frequency/amplitude domain. These experiments led to some improvements of the dSPACE control system such as an individual adjustment of the flap control as mentioned above.
Finally, the opportunity to use the flaps as excitation means was grasped to carry out a rotating dynamic identification of the blades. The blades were excited one at a time, for rotation speeds ranging from 400 to 800 rpm by increments of 100 rpm, sine swept excitation between 2 and 220 Hz with linear progression being applied. The signals of all the gauges equipping the blades were recorded and later on processed. A comparison of the theoretical and experimental Campbell diagrams is presented in Figure 13.

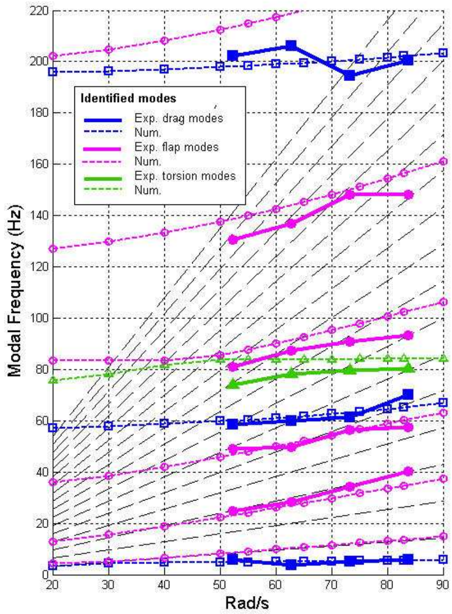

Figure 13 - Comparison theoretical / experimental Campbell diagram

7 ORIGINAL TEST MATRICES FOR S1 MODANE TESTS

Initially, tests for the three spanwise positions of the flap, inboard, middle and outboard, were planned. However, time constraints and limited interest in the middle position, underlined by numerical predictions, led to this position to be dropped. The initial test matrices are presented on the tables below. Inboard configuration, most promising for vibration reductions, had a priority 1 while a priority 2 was applied to the outboard position, more dedicated for acoustic purposes. For all the test points, requested test conditions were : Mach number at blade tip 0.637, drag coefficient $CXS/S\sigma = 0.1$ and zero-flapping rotor trim law.

Inboard position

Z / μ	0.3	0.35	0.4	0.45
12.5	R V $\underline{V}$ $\underline{P}$	R $\underline{V}$	$\underline{R}$ V $\underline{V}$ P $\underline{P}$	R V $\underline{V}$ $\underline{P}$
15			R $\underline{V}$	
17.5			R V $\underline{V}$ P $\underline{P}$	

Outboard position

Z / μ	0.3	0.35	0.4	0.45
12.5	R V $\underline{V}$ P		$\underline{R}$ V $\underline{V}$ P $\underline{P}$	
15				
17.5			R V $\underline{V}$ P $\underline{P}$	

In order to obtain the broadest possible range of information about the operation of a flap-equipped rotor, the following types of measurements were planned :

- R : reference point with flaps set at 0° deflection ;
- $\underline{R}$: reference point + sweeps of the flap deflection in amplitude, phase and harmonic (0 to 5-per-rev) ;
- V or P : pre-calculated flap deflection laws respectively applied for vibration decrease and performance improvement ;
- $\underline{V}$ or $\underline{P}$: closed-loop control of the flap deflection laws with the dSPACE system optimization feature, respectively for vibrations and performance.

8 TEST PERFORMANCE

ABC wind-on tests in S1 Modane were carried out in December 2005 for three weeks. It was the first time the active flap-equipped blades were operated under both centrifugal and aerodynamic loads. First of all, it has to be pointed out that the flaps and all their associated control systems (mechanics and electronics) were successfully operated since no problem was ever encountered during three weeks of intensive tests. Still, a flapping-torsion mode was found to be closer than expected to the 4-per-rev harmonic of the rotation speed, inducing fatigue limitations on the blades. Furthermore, because of some slight reversibility in the flap driving system, the intrinsic motion of the flap, although slaved at 0°, was too large for the highest advance ratios. Consequently, the test conditions were reviewed as follows :

- rotation speed was lowered from 980 to 800 rpm ;
- maximum advance ratio was decreased from 0.45 to 0.35 ;
- reduced lift was kept unchanged.

Finally, the actual test conditions for the two flap positions were the following, keeping excursions in both reduced lift and advance ratio :

Inboard position

Z / μ	0.18	0.22	0.26	0.3	0.35
10		R V $\underline{V}$			
12.5	R	R V $\underline{V}$ $\underline{P}$	R V $\underline{V}$	R V $\underline{V}$ $\underline{P}$	R
15		R			
17.5		$\underline{R}$ V $\underline{V}$			

Outboard position

Z / μ	0.18	0.22	0.26	0.3	0.35
10		R			
12.5	$\underline{R}$	$\underline{R}$ V $\underline{V}$	R	$\underline{R}$ V $\underline{V}$	R
15		R			R V $\underline{V}$
17.5		$\underline{R}$ V $\underline{V}$			

Despite changes to the original test matrices, the obtained database is still very well documented since more than 2243 millions signals were recorded (380 test points).

From the start of the tests, flexibility of the test matrices was constantly in the minds of the specialists attending the campaign in order to maximize the gathering of valuable information. This was perfectly complemented by the possibility for them, offered by the wind-tunnel test team, to perform almost on-line analysis of the measurements for aerodynamics, acoustics and dynamics. This resulted for example in more priority given to both open and closed-loop activities for vibration alleviation instead of similar activities for performance, since experimental measurements for decreasing consumed power yielded no significant results,

corroborating numerical simulation predictions. Beside this, satisfactory results could also be gathered for the closed-loop control of the trimming of the flight case.
To enable this on-line analysis, a sophisticated computation program had been developed and a large number of video screens were implemented inside the control room to plot elaborated data as soon as acquisitions were done. Figure 14 and Figure 15 provide samples of these plots. Figure 14 was plotted to check that flap deflections on the four blades (G1 to G4) were identical and consistent with the theoretical control law requested for each test point (blue curve). Local lift coefficients on the blades, obtained by integration of pressure distributions, were plotted for the most outboard sections as shown in Figure 15 (repeatability for three blade sections). Thanks to these plots, pressure measurements on the blades were on-line validated and detailed analysis of lift coefficient versus flap motion was done with confidence by ONERA Applied Aerodynamics Department. The same philosophy was applied for dynamics and acoustics with control screens plotting in real time elaborated results to validate the quality of the measurements.

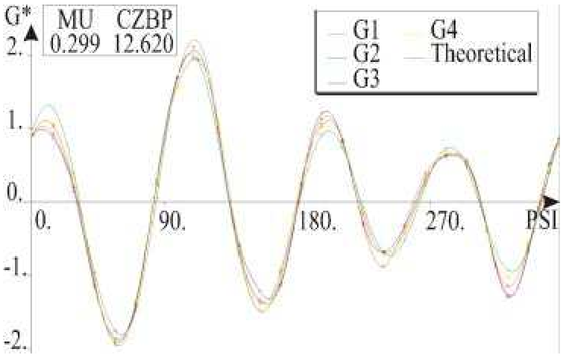

Figure 14 - Comparison theoretical / applied flap deflections

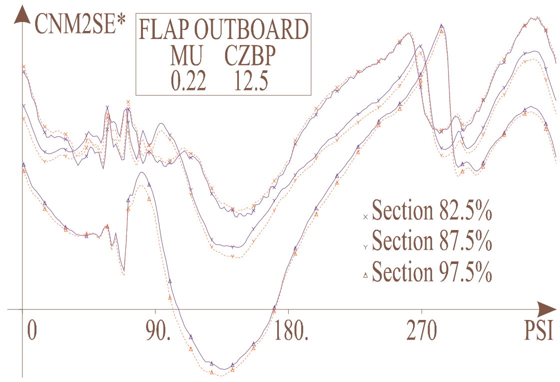

Figure 15 - Repeatability on blade local lift coefficients

9 AERODYNAMIC ASPECTS

The flap influence on aerodynamics was first to be experimentally validated. The wind-tunnel tests showed that the aerodynamic effects of the flaps are restricted to the sections where the flaps are located. Figure 16 shows the lift coefficient in three sections, the flaps being in the outboard position (80-90%), and for two test points, namely with and without flap actuation. The flap influence on the lift coefficient can only be seen in the section r/R=87.5%, i.e. where the flap is located, and no difference on the lift coefficient can be seen elsewhere.

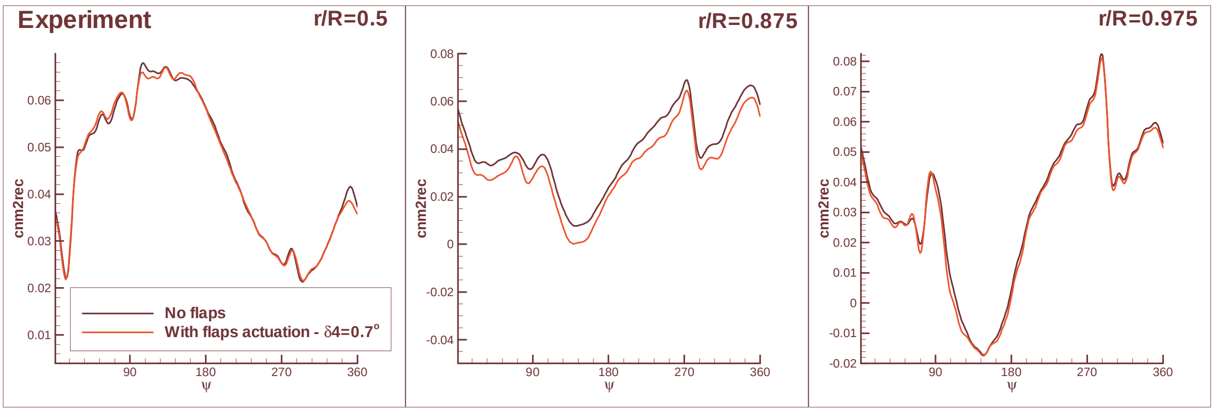

Figure 16 – Local flap effect on rotor aerodynamics

A harmonic analysis has been performed in order to determine the aerodynamic response to the flap actuation, depending on the harmonic content of the flap deflection laws. Figure 17 presents, for the outboard flap position, an example of the harmonic analysis of the CnM2 coefficients in each instrumented section for a parametric phase sweep, the flaps being deflected at 2-per-rev. The static value of the lift coefficient is not affected by the flap deflections in comparison to the non-actuated case, whatever the phase of the deflection law might be. This is the same for every harmonic component of the lift coefficient except for the 2-per-rev harmonic, where large deviations appear. The harmonic content of the aerodynamic response to the flap actuation is thus very well correlated to the harmonic content of the flap deflection laws. In addition, one can also notice here that the flap effects on the lift coefficient are restricted to the flap area.

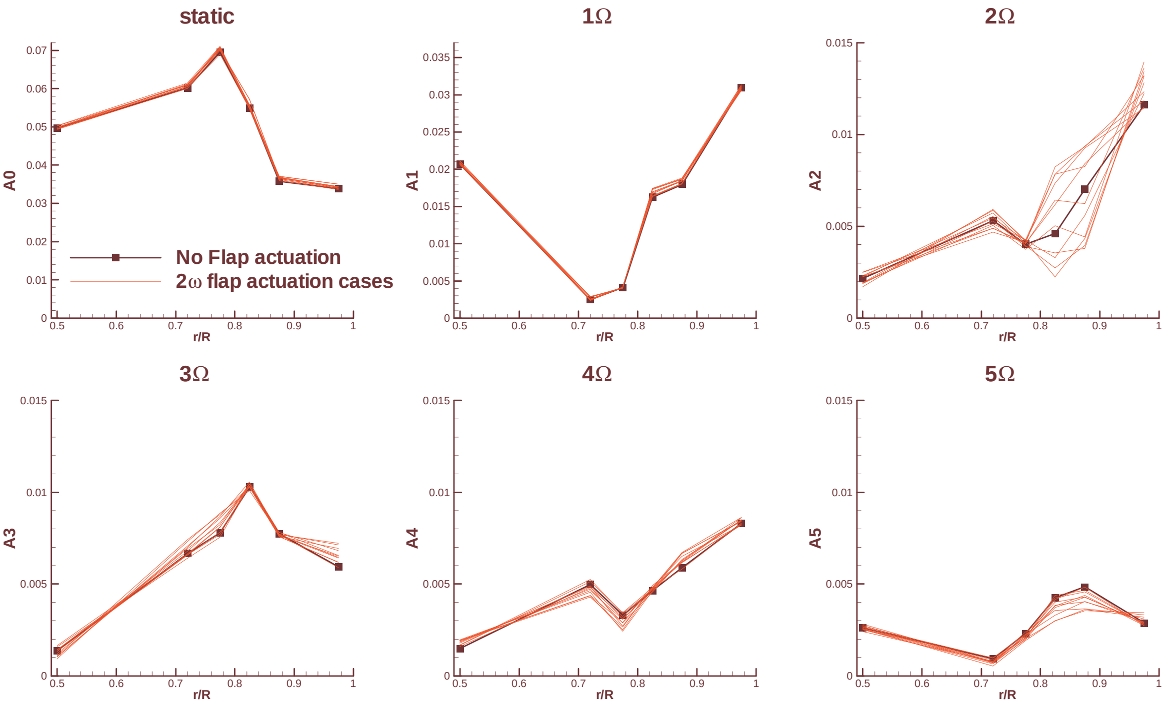

Figure 17 - Harmonic content of the lift coefficient response to several 2-per-rev flaps deflection laws (various phases)

As BVI noise was expected for some low speed configurations, a filtering of the aerodynamic coefficients was performed for each test point during the tests in order to suppress the mean value and low frequencies and to detect the higher frequencies fluctuations. This is illustrated in Figure 18, where the filtered CnM2 are plotted for a non-actuated case and a case with flap deflection. Such processing allowed to detect cases with BVI noise occurring on the advancing blade side near 80° of azimuth. Additionally, it enabled to detect configurations with flaps being actuated for which the lift coefficient fluctuations and thus pressure fluctuations were lowered, leading to noise reduction which was confirmed by microphones measurements.

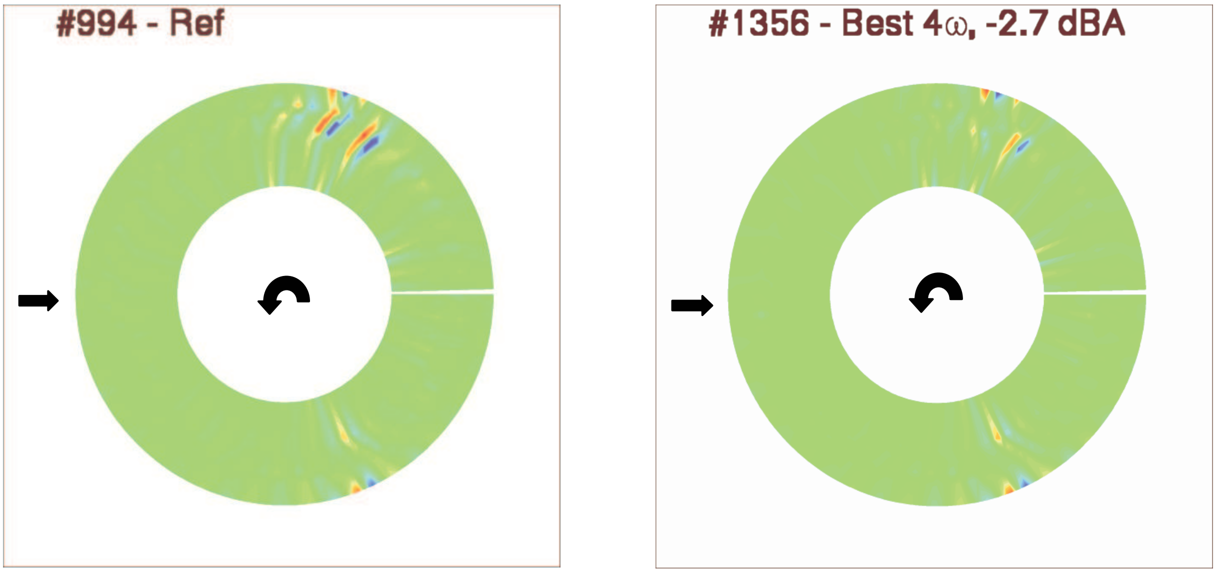

Figure 18 - Comparison of lift coefficient fluctuations measured for a non-actuated case (left) and a case with flap actuation (right)

The database that could be collected during the S1 Modane tests features a lot of information with respect to the aerodynamics of a flap-equipped rotor and its analysis is still on-going. The modeling of the flap effects in comprehensive simulation codes will certainly benefit from such data, improving the quality of the numerical predictions of such rotors.

10 ACOUSTIC ASPECTS

As already mentioned, fourteen microphones were available, six of them being located on a vertical strut in front of the rotor shaft (see Figure 10).
The upper microphones, close to the rotor plane, are supposed to better capture the thickness noise component while the loading noise component should be dominant on the lowest microphones. Eight microphones were added under the advancing blade area to better quantify loading and BVI noise (compared to previous tests such as ERATO campaign). Thanks to these microphones, noise directivity could be taken into account more accurately.
Microphone acquisition was synchronous with rotor rotation in order to eliminate the part of the signal not correlated to the rotor rotation (wake of the struts, turbulence, etc.). Its duration was approximately one minute which allowed to obtain an averaged signal over more than 800 revolutions.
Because of the reduced advance ratio, the maximum noise directivity was generally more downwind than expected, so that it was best detected by microphone 14. An example of averaged time signatures is shown in Figure 19 (flight case : μ=0.22, Z=12.5, outboard flap not actuated). The BVI component clearly appears on microphone 2, 7 and 14 (lower microphones) but not on microphone 6 (upper microphone). The filtering in the 6 to 40 blade passage frequency range enabled to isolate the BVI peaks, the amplitudes of which are maximum for microphone 14.
Measurements were carried out for all the parametric sweeps (harmonic, phase, amplitude). For all the flight conditions and both flap positions, noise reductions were obtained for every flap deflection frequency, although the optimal phase could somewhat change from one point to another. An example is provided in Figure 20 in the same flight conditions as for Figure 19, the flap being actuated here at a frequency of 4-per-rev. By increasing the flap peak-to-peak amplitude from 1.8° to 2.2°, the noise reduction was increased from -1.2 dBA to -2.7 dBA.

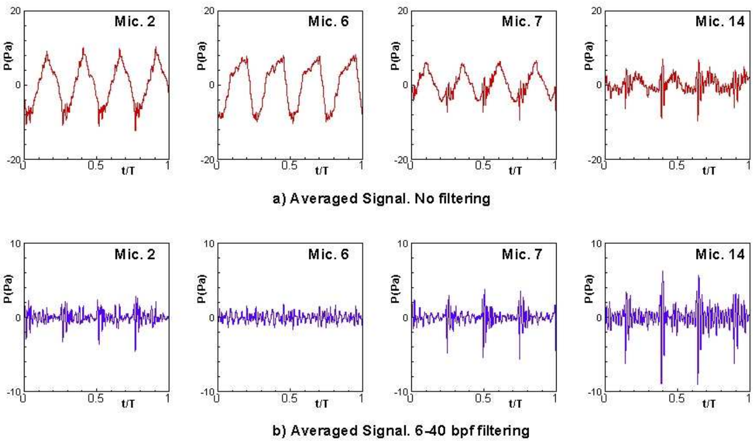

Figure 19 – Typical averaged time signature

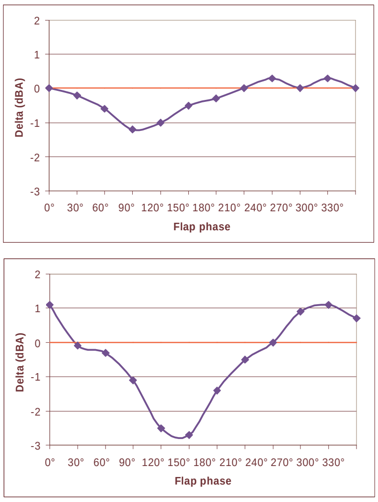

Figure 20 – Noise reduction

The acoustic database recorded during the tests in S1 Modane, although not being the main objective of these tests, is seen as very interesting and also encouraging with respect to the future tests planned in DNW-LLF, which will focus on acoustic aspects.

11 DYNAMIC ASPECTS

The possibility to use active flaps on the rotor to decrease the vibratory level was the main objective of the tests. As already stated, various types of flap deflection laws were used to document the dynamic behavior of such a rotor. The parametric sweeps, during which the amplitude, phase and harmonic content were varied, allowed to learn about the actual sensitivity of some unsteady terms with respect to flap deflections. Figure 21 shows, for the inboard flap position at an advance ratio of 0.22 and a reduced lift of 12.5, the sensitivity (per degree of flap deflection) of the 4-per-rev vertical force for 1 to 5-per-rev flap excursions. It can be noticed that a reduction of almost 15% per degree of deflection could hence be obtained. Due to the slight reversibility of the flap driving system, a maximum flap deflection of ±2.3° could be reached during the tests. Similar analysis could be made for other terms (such as the 3-per-rev in-plane moment in the rotating frame) and the other flap position.

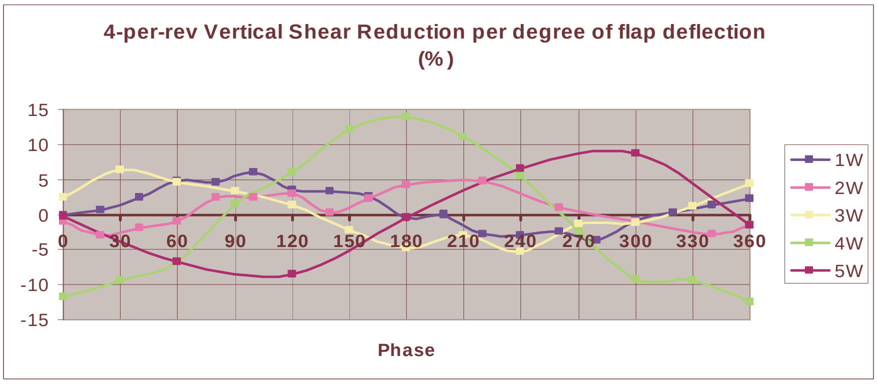

Figure 21 – Sensitivity of 4-per-rev vertical force to harmonic flap deflections

Beside this, some pre-calculated laws, featuring multi-harmonic components and delivered by the dSPACE-based control system, were applied to the flaps. Due to the modification of the test matrices presented above, these laws could not be delivered at the exact flight conditions for which they had been simulated (there was no time during the tests to re-calculate these laws). Still, some valuable results were obtained, with either decrease or increase of some unsteady terms and will be of great help in progressing in the modeling of active flaps.

Finally, the dSPACE-based control system was used in a closed-loop configuration, for which the input (treated as the objective function) was the value of the 4-per-rev balance vertical force transmitted via the RS232 link. Figure 22 shows a typical example of what could be obtained during the optimization process (advance ratio of 0.22, reduced lift of 12.5), showing a progressive decrease of the non-dimensional 4-per-rev vertical force for the various steps of the optimization, the flap being here in the inboard position. The process was only stopped by the maximum total amplitude that could be actually applied to the flaps. Figure 23 shows the flap deflection laws corresponding to the steps of the optimization process. These optimizations were carried out using different possible harmonic contents, and the conclusion could be drawn that the 4-per-rev component was essential to achieve significant vibratory level alleviation, which could be easily anticipated for a four-bladed rotor.

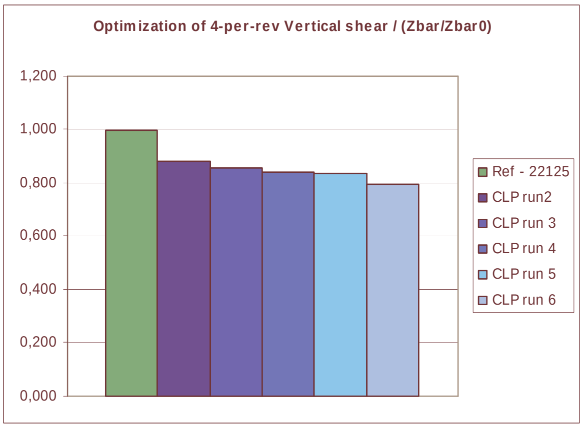

Figure 22 – Vibration reduction thanks to closed-loop optimization

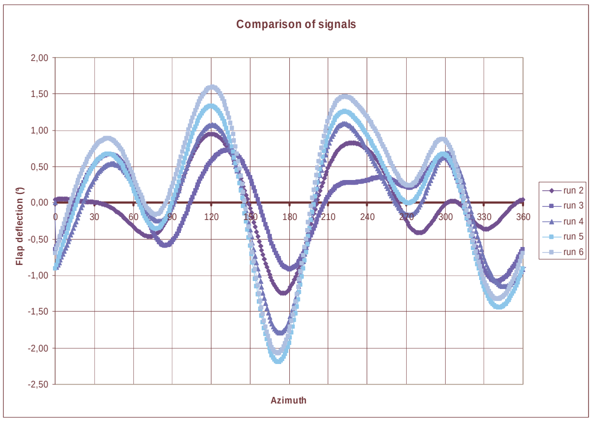

Figure 23 – Flap deflection laws during optimization process

12 CONCLUSIONS

The DTP RPA, also known as ABC project, launched in 1998, aimed at validating the use of active flaps on the trailing edge of the blades of a helicopter main rotor for decreasing BVI in descent flight, decreasing vibratory level generated by the rotor and increasing fast cruise performance. The dimensions and locations of the flaps, as well as associated deflection laws, were determined in a first phase, thanks to numerical simulations. Subsequent activities dealt with the design and manufacturing of blades, featuring an innovative active flap system to be tested in both S1 Modane and DNW-LLF wind-tunnels. A remarkable achievement was obtained in December 2005 by the successful tests in S1 Modane of such a flap-equipped rotor. Wind-tunnel ability to provide elaborated on-line results in all the fields of interest, allowed ONERA specialists to adapt continuously the test matrices to the most promising test conditions. Furthermore, the high level of instrumentation, with more than 300 sensors in the rotating frame, enabled the generation of a comprehensive database related to aerodynamics, acoustics and dynamics. The soundness and ruggedness of the design of the active flap system could be demonstrated as well as the efficiency of active flaps to alleviate the vibratory level generated by the rotor, notably using a closed-loop control strategy developed at ONERA on the basis of a dSPACE system. Off-side aspects, such as the influence of the active flaps on the radiated BVI noise in cruise flight could also be brought into light.

The next step of the project will consist in testing the same flap-equipped rotor in DNW-LLF wind-tunnel to document BVI noise reduction in descent flight using active flaps.

13 ACKNOWLEDGEMENTS

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14 REFERENCES

[1] R. H. Blackwell, *«Blade Design for Reduced Helicopter Vibration »*, AHS National Specialists Meeting on Helicopter Vibration, Hartford, Connecticut, USA, 1981

[2] P. P. Friedman, P. Shanthakumaran, *«Optimum Design of Rotor Blades for Vibration Reduction in Rotorcraft in Forward Flight »*, 39th AHS Annual Forum, St. Louis, Missouri, USA, 1983

[3] P. Leconte, P. Geoffroy, *«Dynamic Optimization of a Rotor Blade »*, AHS Aeromechanics Specialists Conference, San Francisco, California, USA, 1994

[4] J. Milgram, I. Chopra, *«A Parametric Study for Actively Controlled Trailing Edge Flaps »*, AHS Journal, Vol. 43, April 1998

[5] M. V. Fulton, R. A. Ormiston, *«Small-Scale Rotor Experiments with On-blade Elevons to Reduce Blade Vibratory Loads in Forward Flight »*, 54th AHS Annual Forum, Washington, D.C., USA, May 1998

[6] B. van der Wall, W. Geissler, *«Experimental and Numerical Investigations on Steady and Unsteady Behaviour of a Rotor Airfoil with Piezoelectric Trailing Edge Flap»*, 55th AHS Annual Forum, Montreal, Canada, May 1999

[7] F. Toulmay, V. Kloeppel, F. Lorin, B. Enenkl, J. Gaffiero, *«Active Blade Flaps – The Needs and Current Capabilities »*, 57th AHS Annual Forum, Washington, D.C., USA, May 2001

[8] B. Enenkl, V. Kloeppel, D. Preissler, P. Jänker, *«Full-scale Rotor with Piezoelectric Actuated Blade Flaps »*, 28th European Rotorcraft Forum, Bristol, UK, 2002

[9] O. Dieterich, B. Enenkl, D. Roth, *«Trailing Edge Flaps for Active Rotor Control – Aeroelastic Characteristics of the ADASYS Rotor System»,* 62nd AHS Annual Forum, Phoenix, Arizona, USA, May 2006

[10] P. Leconte, M. Rapin, B. van der Wall, *« Main Rotor Active Flaps : Numerical Assessment of Vibration Reduction »*, 57th AHS Annual Forum, Washington, D.C., May 2001

[11] M. Höfinger, P. Leconte, *«Development of an Active Flap Rotor Model»*, 6th ONERA-DLR Aerospace Symposium, Berlin, Germany, June 2004

[12] H. Mainz, B. van der Wall, P. Leconte, F. Ternoy, H. M. des Rochettes, *«ABC Rotor Blades : Design, Manufacturing and Testing»*, Paper 118, 31st European Rotorcraft Forum, Florence, Italy, Sept 2005

[13] P. Leconte, H. M. des Rochettes, *« Experimental assessment of an active flap device »*, 58th AHS Annual Forum, June 11-13, 2002, Montreal, Canada

[14] S. Germanetti, B. Gimonet, *«Méthodologie de développement d'algorithmes de commande pour l'optimisation des performances rotor par commande multicyclique sur hélicoptère (OCAPI) »*, AGARD Conference Proceedings, Vol. 473

[15] M. Gauvrit, *«Adaptive Control applied to the Reduction of Vibrations in Helicopters »*, Digital Control System, C. Fargeon editor

[16] P. Crozier, *«Recent Improvements in Rotor Testing Capabilities in the ONERA S1MA Wind-tunnel»*, 20th European Rotorcraft Forum, Amsterdam, Netherlands, October 1994

[17] N. Tourjansky, E. Szechenyi, *«The Measurement of Blade Deflections – A New Implementation of the Strain Pattern Analysis»*, 13th European Rotorcraft Forum, Avignon, France, Sept 1992

[18] P. Crozier, *«Analytical Method to Determine Dynamic Loads on Reduced Scale Helicopter Blades at ONERA»*, 29th European Rotorcraft Forum, Friedrichshafen, Germany, September 2003