Y. Delrieux
(Onera)

E-mail : yves.delrieux@onera.fr

DOI : 10.12762/2014.AL07-02

From design to flight testing : overview of rotorcraft acoustic research at Onera for industrial applications

The reduction of noise emission has become a key commercial argument for helicopter manufacturers, such as Airbus Helicopters. For years, Airbus helicopters has placed emphasis on the good acoustic behavior of its helicopters, as proven by its communication on the fenestron concept, the acceptance of its aircraft for the Grand Canyon tours and the presentation of its recent Bluecopter™ Technology. Thus, Airbus helicopters has become one of leaders in the manufacture of low noise helicopters. Some of its advances in this field have been made thanks to its cooperation with Onera. The paper is aimed at presenting the way in which Onera has become a reliable partner for industry to face the challenge. Partly thanks to wind tunnel tests, Onera has developed a set of numerical tools and acquired a physical understanding of the noise emitted by the rotors of helicopters. These tools have been used to design new main rotor blades, optimized to reduce the vibration, to improve the aerodynamic performances and to reduce the noise emission for specific flight conditions. Both active devices and passive design have been developed and tested at model scale, before being provided to the industry for scale one developments and for implementation on actual helicopters and to be tested in flight. For the tail rotor, fenestron noise has also been studied numerically and during flight tests, in order to determine noisy flight conditions and to improve the tools and methodology for future definition and optimization.

Introduction

In the early 70s, acoustics became a key parameter for the design of new helicopters. One of the main arguments, among others such as safety, for the fenestron concept [16], developed by Sud-Aviation (integrated into Aérospatiale and then merged with Daimler-Benz AG to give birth to Eurocopter, which was renamed Airbus helicopters in 2014) was the reduction of the noise emission. At the same time, the first measurements of the noise emitted by helicopters were performed by Aérospatiale and Onera. The first studies have shown that noise is emitted by the engines predominantly under take-off conditions. Turboméca and Onera have thus worked on the determination of the noisy parts of the engines, by means of static bench tests. Nevertheless, for most flight conditions, the rotors (main and tail rotors) have been shown to be the main sources of noise.

In the 80s, Onera and the US Army started to collaborate within the framework of a MoU (Memorandum of Understanding) to study noise emission, by means of high and moderate speed flight tests and by means of wind tunnel tests in CEPRA19, in descent flight [1]. Onera then tested various different blades of a main rotor provided by Aérospatiale in descent flight in CEPRA19 [2] and at high speed in S2Ch [3].

In parallel to these experimental studies, the HSI noise was numerically analyzed using CFD/CAA or CFD/Kirchhoff methods. Thanks to the wind tunnel tests and to the numerical tools, some blade tip geometries have been proposed to reduce the HSI noise in forward flight.

To answer to the industrial demand, the main emphasis was thus placed on the understanding and acquisition of numerical tools for the prediction of the most penalizing noise source during the landing of helicopter (penalizing for implementation of helipads in urban areas): the so called BVI noise. The computational chain (composed initially of comprehensive codes and secondly by CFD/CAA) developed at Onera was validated by comparison with two different databases [4]. The first one is the HART database [5], obtained in 1994 by testing a four bladed BO105 rotor trimmed with HHC, within the framework of a multinational research cooperation (between NASA, the US Army, the DLR, the DNW and Onera), including aerodynamic measurements (blade pressure, vortex positions, field velocities, etc.), dynamics (elastic deformations) and acoustics. The second one is the ERATO [6] database, obtained in 1998 within the framework of the bilateral French-German cooperation between Onera, DLR and Airbus helicopters.

The tools have been used to design and optimize new blades, which were first tested at model scale in a wind tunnel, before being provided to industrialists for the scale one design and for flight tests on real helicopters.

Another noise source, the BWI noise, which may be dominant under some climb configurations, was studied at Onera mainly within the framework of two PhD theses [7;8]; however, at the present time, no activities are being carried out in this topic at Onera. As for HSI noise, it could be possible to launch new activities, in the event of renewed interest by industry or the international community, especially for flight conditions where BWI is more important than BVI in terms of intensity, in a frequency domain between BVI noise and turboshaft engine noise (around 1 to 3 kHz). BWI was studied during the HART wind tunnel test campaigns and some climb configurations were also analyzed. Onera showed that BWI was not related to isotropic turbulence, but rather to the blade interactions with coherent large-scale structures present in the flow, and linked these structures to short-wave vortex instabilities. These instabilities occur when an external strain field deforms the vortex core elliptically. The deformation induces the resonant coupling of two vortex modes (Kelvin modes). Thus, similarly to BVI noise, the reduction of BWI noise could be obtained by an appropriate control of the vortex generation.

For the reduction of BVI noise, both passive rotor blade design (ERATO) and active control concepts have been studied and optimized numerically and experimentally, such as active trailing edge flaps, which have been tested at high speeds in the S1 Modane wind tunnel and active twist (within the framework of French contracts and European programs), which will be tested in the DNW-LLF wind-tunnel. These solutions have been proven, both numerically and experimentally, to be efficient for high BVI noise reduction, the challenge being to implement them on actual helicopters by solving the unavoidable difficulties: adapting the model technologies to full scales blades and solving the problems linked to vibrations, weight or electrical consumption. In this second phase, the role of Onera is to provide support to industry for the transfer from this model scale to full scale (like the Blade 2005 program for the passage from ERATO to Blue Edge™ [15]).

At Airbus helicopters, new rotor technologies resulting from these helicopter main rotor BVI noise reduction studies have been developed within the framework of Bluecopter®: Blue Pulse™ active rotor, which is based on piezo-driven flap modules on the trailing edge, for both external noise and vibration reduction, and Blue Edge™, a passive concept, derived from the double-swept shape of the ERATO project. The full-scale developments of such technology have been supported by the DGAC and tested in flight.

The Fenestron™, a technology used for helicopter tail rotors, has been evaluated during a joint Airbus helicopters/Onera program including CFD/CAA computations and flight tests, where onboard and ground noise measurements were performed.

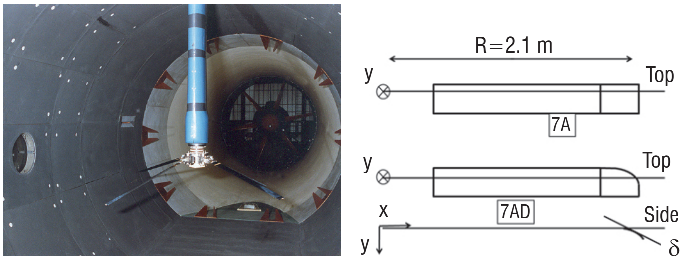
In parallel to these different programs aimed at reducing the noise at the emission, the computer codes have also been adapted to take into account maneuver flight conditions (such as decelerating or turning flights) in order to study low noise flight procedures (mainly within the framework of EU contracts). The purpose is to provide flight procedures to the pilots, in order to avoid noisy configurations during specific missions.

Experimental work in helicopter noise assessment

Two main kinds of helicopter tests are conducted. The first kind of tests is generally performed on model rotors mainly for the purpose of validating the numerical tools and showing the efficiency of the proposed technical solutions. These solutions are mounted on a mock-up, using dedicated technologies that may not be directly transposable to actual full scale helicopters. The second kind of the tests is performed by the industrialist on ground equipment, such as whirl towers or static benches, and then validated in flight.

Several testing facilities have been used for the characterization of helicopter rotor noise. For the analysis of the HSI noise, tests have been conducted in both the Onera S2Ch and S1MA wind tunnels.

The tests in the S2Ch (In Chalais-Meudon, near Paris) were conducted in the wind tunnel fitted with removable acoustic lining [9]. The test section had a diameter of 3 meters and the maximum wind speed was 110 m/s. Two different rotors were tested, a straight-tip one and a second one equipped with a sweptback tip, in order to compare the transonic effects between the two kinds of blades (figure 1). The measured dramatic increase of noise level when the tip Mach number goes over a value of around 0.9 was linked to the phenomenon of delocalization shown by aerodynamic computations. The sweptback tip was shown to induce much lower noise levels, thanks to the delay of the delocalization towards higher tip Mach numbers.



a) b)

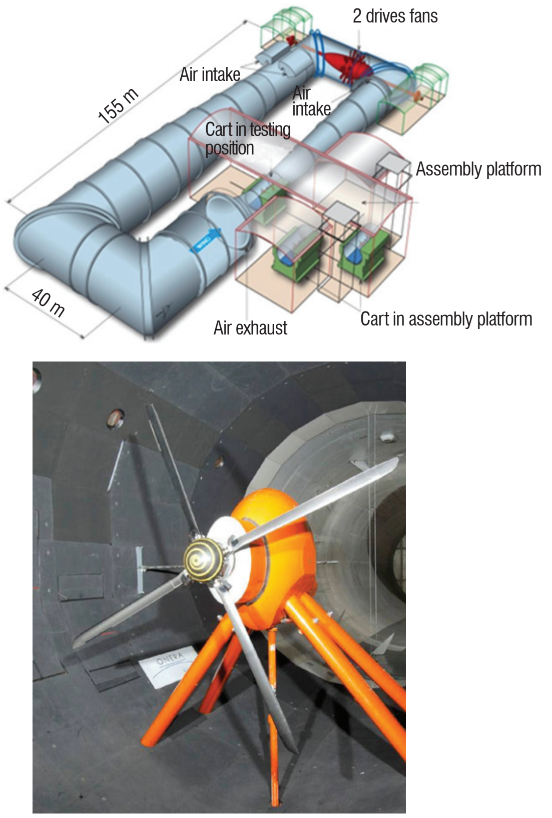
Figure 1 - a) S2Ch two bladed rotor tests [9]. b) 7A and 7AD blade shapes

The conclusions were confirmed during a second test campaign [10] conducted in the 8 m diameter S1 Modane wind tunnel, where two rotors provided by Airbus helicopters were tested, the 7A and 7AD rotors, which differ in their blade tip, the second one having a parabolic tip. The tests showed that at very high tip Mach numbers, the delocalization phenomenon can be dramatically reduced with suitable tip geometries, leading to noise reductions of up to 8 dBA, and also showed the influence of the rotation speed.

Several test campaigns have been conducted for the BVI noise analyses. During the first years of the studies on BVI noise, since no computation was available, the tests performed in CEPRA19 [2] led to a first quantitative characterization of the noise in descent flight.

Afterwards, the HART campaign in the DNW, ERATO in S1MA and DNW and RPA in S1MA enabled both the development of numerical methods and the validation of new rotor noise reduction concepts.

Due to the wind tunnel capabilities, noise measurements are generally devoted to high speed noise in the S1 Modane wind tunnel (figure 2) closed section facility, while BVI noise is studied in the open room of DNW-LLF (figure 3).



a)

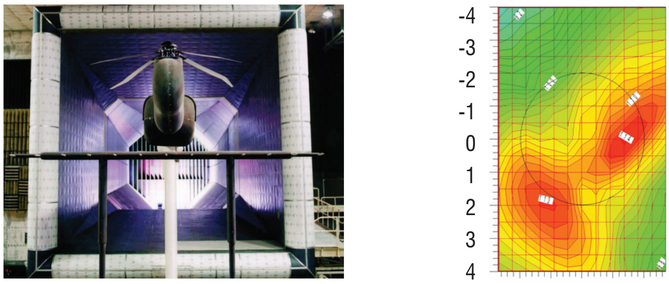
b)

Figure 2 - a) Onera S1 Modane wind tunnel, b) Helicopter main rotor tests in the S1 Modane wind tunnel (active rotor)

Both passive design (ERATO) [11] and the active rotor RPA have been tested in the S1 Modane wind tunnel [12, 13,14].

For the active flap rotor (figure 2b), a wind-tunnel test was first performed in September 2004 in the S1 Modane facility, to check the behavior of the active flaps under realistic aerodynamic loads. High speed noise and thickness noise can be evaluated in the S1 Modane wind tunnel, by means of in-plane microphones and the loading noise and BVI noise in level flight can be evaluated using microphones located below the rotor. Despite the unfitted geometry of the measurement in the S1 Modane wind tunnel, thanks to an acoustic liner and to the fact that the noise component of interest is tonal noise, the BVI noise was shown to be extractable by using synchronous time averaging of the signal, so that any background noise not synchronic with the harmonics of the rotor rotation could be removed. The tests were first conducted with a reference rotor and then using the studied rotor equipped with active flap, under the same flight conditions, to quantify the potential advantages of the concepts. Unfortunately, the expected tests in DNW-LLF to confirm these first results have not yet been conducted.

The DNW-LLF wind tunnel is particularly well suited to BVI noise measurement, since it has a very wide open section, in which a translating array of microphones can be implemented below the rotor, to obtain noise contours in a horizontal plane, including the maximum BVI noise zones on both sides of the rotor, as shown in figure 3b. It also allows the acoustics to be linked to the wake and the vortices, by means of PIV measurements performed simultaneously.



a) b)

Figure 3 - a) Helicopter main rotor tests in the DNW-LLF (passive design). b) Typical BVI noise measurements at DNW obtained with 13 mic. (vertical lines) at 17 streamwise locations (horizontal lines).

Complementarily to the wind tunnel tests, flight tests can be conducted. These are generally performed by industry once the new concepts or design have proven to be efficient for the objectives set. For example, the BlueEdge™ rotor [15] was successively tested in the laboratory for fatigue tests, then to check the main structural characteristics of the blade and to identify the blade modes and to cross-check the blade elastic model, then on a whirl tower to analyzethe dynamic behavior of the blades and finally in flight on an EC155 helicopter [15]. The rotor was tested during more than 75 hours. The performance of the rotor in terms of figure of merit, power consumption, vibration levels and dynamic loads was analyzed under different flight conditions and the noise reductions expected during the ERATO program were confirmed.

Onera and Airbus helicopters estimated that flight tests were appropriate for the study of the noise emission of a Fenestron because of the difficulty of having access to a wind tunnel that is able to simulate actual flight conditions, including a complete helicopter (with the fuselage and both rotors). A specific study was launched by Onera and Airbus helicopters, with support from the French Ministry of Civil Aviation (DGAC), to acquire an experimental comprehensive database to validate aerodynamic and aeroacoustic simulation tools that are accurate for Fenestron noise predictions.

The tests were conducted on a Dauphin 6075 [16, 17, 18] equipped with a first generation 13-blade Fenestron. It was equipped with steady wall pressure sensors on the rear part of the fuselage and tail, and with unsteady wall pressure sensors in the duct (figure 4). The blade pressures were measured by pairs of upper/lower thin layer unsteady transducers, mounted on four blades. Two series of flight tests were performed in 2009 and 2010, one for inboard noise measurements and the other one for ground noise measurements. For the first campaign, onboard acoustic measurements were performed using four microphones located on the horizontal empennage. For the ground measurements, eleven microphones were uniformly spaced on a 500 m linear antenna perpendicular to the direction of flight. Ground noise footprints were plotted for various flight conditions: level flights, approach and take-off. The recorded signals were processed in order to enable their comparison with CFD/CAA computations, by taking into account flight measurement specifications, such as the Doppler effect, propagation delays and aircraft location variation. By means of frequency analyzes, the Fenestron noise components were emphasized as function of the flight conditions and compared to computed ones.

a) b) c)

Figure 4 - a) Fenestron set-up. b) Microphone settings - c) Instrumented blade

Modeling tools for rotor design and optimization

Over the years, Onera has developed a set of prediction tools aimed at the computation of the noise radiated by the rotors as a function of the flight conditions and the corresponding kind of noise source. Indeed, there is a dominant type of noise source for each flight condition, which must be treated in a different way (typically quadrupolar noise at high speed, BWI noise in climb, BVI noise in descent etc..).

Moreover, even for a given flight condition, different phenomena are involved when considering the noise radiation at different microphone locations relative to the helicopter. This is due to the different noise radiation directivities, partly because of the nature of the noise (monopole, dipole or quadrupole, etc.) and because of the noise source displacement relative to the observation point. For example, during the flyover in descent flight at moderate speed, several noise sources may successively be dominant for a microphone on the ground close to the flight pass: first the main rotor thickness noise, then low frequency main rotor loading noise, then main rotor BVI noise, possibly engine noise and finally tail rotor thickness and loading noise. The common point of the various tools is the requirement of suitable prediction of the aeromechanics, of the aerodynamic field (strongly coupled) and then of the acoustic radiation.

For high speed noise predictions, the acoustic codes are based both on Lightill Acoustic Analogy (LAA) and Kirchhoff formulation. At the beginning of the studies at Onera, the aerodynamics were determined using a full potential code (FP3D) or an Euler solver (WAVES) and the acoustics were obtained with a LAA code and a Kirchhoff code (KARMA) [19], [20], [21]. In the LAA formulation, the determination of the quadrupole terms requires a volume integration of the Lighthill stress tensor. Using Kirchhoff integration, the difficulty of the volume integration is avoided thanks to the use of a prescribed surface, over which the pressure field must be provided. HSI noise can now be solved by the elsA solver [22, 23] followed by the Kirchhoff formulation of KIM [24], both presented further on.

As mentioned in the introduction, Onera and Airbus helicopters have mainly directed their efforts towards the prediction of BVI noise. The computational method used at Onera for the prediction of BVI noise [25] was implemented progressively between 1990 and 1995. The wind tunnel tests have shown that the radiated BVI noise is a consequence of several interactions between the vortices (generally tip vortices, but not always) emitted by the blades and the following blades; these interactions generate pressure fluctuations on the blades, which are the source of the BVI noise. The goal of the computational method is to accurately compute the unsteady pressure fluctuations encountered by the blades during their rotation. A key point is the good prediction of the wake convection between the emission of the vortices and the interactions; a change in miss-distance by a quarter-chord can lead to a variation of more than 5 dB (mid-frequency range, i.e., 6th to 40th bpf). At the beginning of these developments, the CFD methods (Euler or Navier-Stokes methods) were not accurate enough to convect vortices over large distances (more than one rotor revolution), so it was decided to develop a chain of comprehensive codes that could compute the wake characteristics and the resulting blade pressure fluctuations separately.

Actually, the computational method consists of five main steps: the rotor trim, the wake prediction, the roll-up model, the calculation of blade pressure and finally the noise radiation. The first step of the computational chain is to determine the rigid and aero-elastic dynamic response of the blades, depending of the flight conditions that must be simulated (advancing speed, rotor thrust, flapping piloting law, etc.). Up to 1996, this was done by the R85 code developed by Airbus helicopters for isolated rotor simulations. A more general tool (the HOST code), applicable not only to isolated rotors but also to a complete helicopter, has been developed since then by Airbus helicopters.

The wake model is computed by the METAR code and is defined by a prescribed helicoidal geometry described by vortex lattices. A coupling between R85/HOST and METAR [26,27] is made until convergence is reached on induced velocities at the rotor disk level. The flexibility of the blades is also taken into account by solving the Lagrange equations. The rigid and aero-elastic blade motion being known, a second step is necessary to iteratively distort the initial wake geometry under its own aerodynamic influence. This is performed by the MESIR code, which computes (using the Biot&Savart law) the velocities induced by all vortex lattices at each discretization point of the wake and modifies the wake geometry accordingly. First, comparisons between computation and experimental data have shown the necessity of an intermediate step between wake and pressure calculations. Indeed, the vorticity carried by the last lattice is generally not representative of the actual rolled-up vorticity. Due to the blade motion, the tip vortex may slide inboard and multiple vortices may appear. The vorticity roll-up code [28], called MENTHE, identifies the portions of the MESIR predicted vortex sheets whose intensity is sufficient to result in a roll-up. The intensities and radial locations of the rolled-up vortices, which constitute the interacting vortices, are determined at the emission azimuths. One important point is that this code (possibly adapted) is mandatory to determine the actual vortex roll-up for any kind of design resulting in unconventional vortex roll-up, such as trailing edge flaps, vane tip, active twist, etc...

Blade pressure distribution is then calculated by the unsteady singularity method ARHIS. This code assumes that the flow around the rotor is inviscid and incompressible. It performs 2D-by-slices calculations. Subsonic compressibility effects are included by means of Prandtl-Glauert corrections, combined with local thickening of the airfoil. In addition, finite span effects are introduced through an elliptic-type correction of the pressure coefficients. The interacting vortices are modeled as freely convecting and deforming clouds of vortex elements. The main advantage of this method is its ability to take into account the vortex deformation during strong blade-vortex interactions. A variable azimuthal step is used, depending on the impulsiveness of the interaction. Finally, the noise radiation is computed by the Paris code, starting from the blade pressure distribution provided by ARHIS[28]; PARIS is based on the Ffowcs Williams-Hawkings equations and predicts the loading and thickness noise. It uses a time domain formulation. One of the aspects of interest of Paris [29], is the ability to link the acoustic pressure peaks for a given microphone to the blade pressure fluctuations and to the blade-vortex interactions, which means that the vortices responsible for the noisiest interactions can be identified, as well as the blade portion that radiates most noise. This is a very efficient tool for rotor optimization, since it greatly helps to alleviate the noisiest phenomena. It was used, for example, to define the backwards and forward sweeps of the ERATO blade, which provide the main part of the noise reductions.

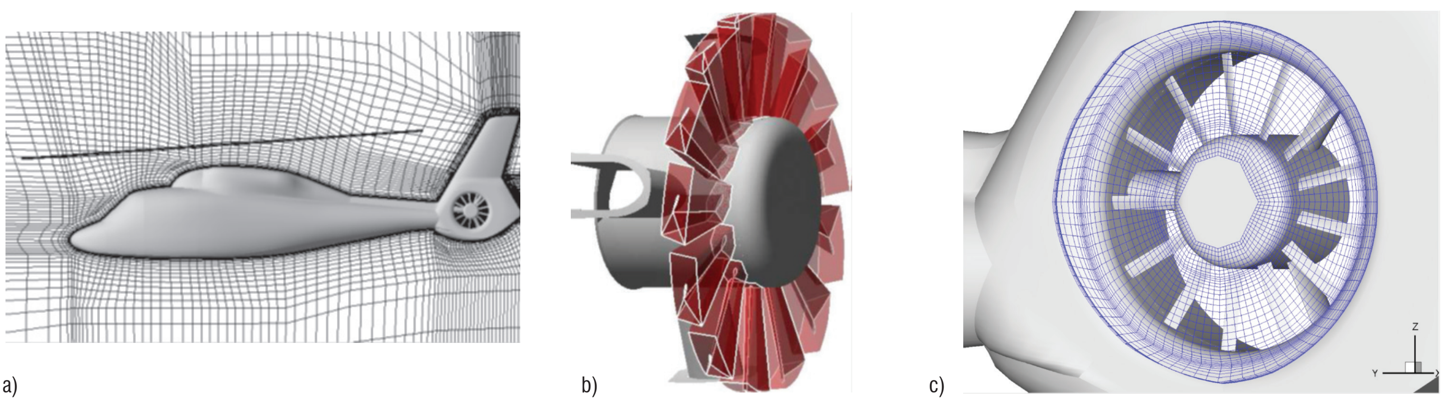
This numerical chain has been validated with the experimental data from HART (1 and 2) in terms of wake convection, vortex characteristics (number of roll-up vortices, spanwise location close to the emission, vortex strength versus azimuth, vortex core radius, etc.), blade deformations, blade loads and finally acoustics. Onera has participated in a large number of workshops for code validation and comparisons, within the framework of the HART programs, as well as within the framework of the NASA Ames 80- by 120-Foot Wind Tunnel, called the Caradonna tests [30]. Thanks to this, each step of the chain has been evaluated, validated or improved.

Thanks to its low CPU consumption, the comprehensive chain has been widely used for rotor design and the optimization explained in the following chapters; as from the year 2000, CFD methods began to be able to preserve the vorticity of the vortices, from their emission up to the interactions. Within the framework of the French-German cooperation CHANCE (2001-2006) [31], the Chimera techniques were developed and used for automatic mesh generation and adaptation in the *elsA* solver. In 2004, these methods were applied to the HART Baseline test-case, but no BVI was simulated due to excessively coarse blades and background grids. During the French-German program SHANEL, thanks to the use of higher order schemes, matrix dissipation and efficient vorticity confinement techniques, it became possible for CFD to capture the BVI and, when coupled with a Ffowcs-Williams and Hawkings (FW-H) code (KIM code at Onera), to provide a correct far field acoustic radiation compared to wind tunnel measurements. Nevertheless, these CFD/FW-H methods are still too costly to be intensively used for rotor design or optimization.

The *elsA* code gives a solution of the 3D compressible Euler equations in a reference frame attached to the rotating blade. A space-centered Jameson scheme is used for the spatial discretization and the time integration uses a four-stage Runge-Kutta explicit scheme. Onera developed a module called Cassiopée, which generates and refines the Cartesian background grids around the blades automatically and allows sophisticated methods to be used, such as high-order schemes, matrix dissipation and Vorticity Confinement. The Vorticity Confinement [32] method is a numerical technique that is aimed at reducing the artificial diffusion of vortices by numerical resolution schemes for the Euler/RANS equations. It was first introduced and developed for the incompressible formulation of the Navier-Stokes equations. During the SHANEL program, it was introduced in *elsA* and applied to helicopter BVI configurations.

The CFD field is treated by the integral method code KIM [24], which uses either the FW-H solid or porous surface formulations or the Kirchhoff formulation.

CFD/CAA methods are also used for the Fenestron noise predictions. The aerodynamic flow over the entire helicopter is obtained by solving the URANS equations over the complete aircraft, using the *elsA* solver. The main rotor is modeled using a non-uniform actuator disk method accounting for the load of the rotor over one revolution, in order to reduce the cost of the unsteady computation to densify the grid in the Fenestron area (figure 5a). The Fenestron blade motion is taken into account using the Chimera method developed at Onera [33] (figure 5 b). The far field acoustic radiation is computed using KIM code, by placing porous acoustic surfaces in such a way that they contain all of the acoustic sources of the Fenestron and that they account for any reflection or diffraction occurring in the shroud (figure 5c). This prediction method has been validated by comparison with acoustic measurements obtained during the Fenestron flight test.



a) b) c)

Figure 5 - Fenestron noise computation. a) Helicopter geometry. b) Chimera grids around the blades. c) Acoustic integration surfaces

Complementarily to these numerical tools, Onera has been developing simplified models, mainly for the conception and pre-design of new concepts [33].

Rotor optimization and design

HSI noise

Some experimental (S2Ch and S1 Modane wind tunnels tests) and numerical analyzes of the HSI were performed and different blade tips were proposed to reduce the Shock-like sound wave phenomenon called delocalization, which is responsible for a dramatic increase in the noise level, when the tip speed reaches Mach numbers close to 0.9. No specific studies on HSI have been performed at Onera for a long time, since this topic has not been identified as a priority recently.

BVI Noise

Passive design

The BlueEdge™ rotor was first designed at Onera and DLR during the ERATO program, which was a cooperative project between Onera and the DLR with the involvement of Airbus helicopters (France and Germany). The ERATO rotor was designed using the tools described further on and the physical understanding of the BVI phenomenon. It was than tested in two wind tunnels (DNW-LLF and S1MA). In view of scale-one application to a 4-to-6 ton helicopter, the ERATO program was 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 current technology reference rotor under ICAO descent flight certification conditions, that is, 6 degree descent at 125 km/h. Moreover, since the descent angle and the flight speed may vary in a real landing approach , some stability of the noise level improvement was sought with respect to the descent angle and to the flight speed. 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.

The main phase consisted in the continuation of the parametric studies, comprising refined rotor geometry parameters such as the airfoil, twist and chord length spanwise distributions and the quarter-chord line geometry. The goals of this new design were to reduce the blade vortex interactions, by modifying some of their characteristics. Indeed, the HART tests and the Caradonna experiment, as well as the numerical analyses, made it possible to rank the different parameters responsible for the BVI noise radiation. The design was thus performed by means of the parametric analysis of the effect of the selected parameters on the BVI noise.

One of the key features of ERATO is the double-swept planform (figure 6).

An inboard forward sweep is followed by an outboard backward sweep. The goal of this shape is to phase shift the impulsive pressure fluctuations occurring in the span direction and leading to constructive pressure accumulations for a given microphone. Moreover, the spanwise chord, twist and thickness distributions were optimized to reduce the intensity of the emitted vortices. An increased chord length was defined to accelerate the vortex convection, from its emission up to the interaction, in order to increase the blade vortex miss distance, which was shown to be one of the most influent parameters. The combination of the entire design parameter optimization was checked, in order not to alter the expected benefits of each of them taken separately.

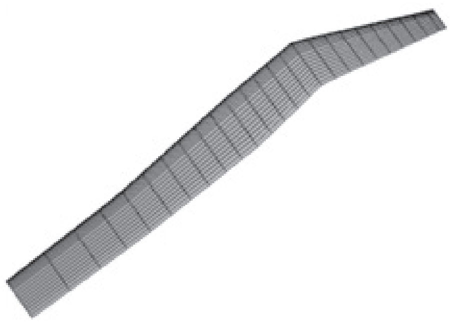
The last phase comprised the structural design and manufacture of the instrumented optimized rotor blades, the S1 Modane and DNW-LLF wind tunnel tests and a thorough analysis of the test results for validation of the design methodology.

At the end of 2000, Airbus helicopters signed a research agreement with Onera that was supported by the DGAC, in order to develop a full-scale blade for flight testing. Afterwards, Airbus helicopters, with the support of Onera, starting from the ERATO design, took into account the full scale constraints in terms of stability, deformation, structures, etc... to design a new blade, keeping the main features and advantages of ERATO, but able to fly on a real EC 155 helicopter. The design was finally validated in terms of vibration, performance and acoustics during flight tests.

Active design

Complementarily to passive design, active control solutions are expected to be more efficient, since it is possible to adapt the control laws depending on the flight conditions and closed loop controls can be expected to be efficient. The main constrains of this kind of solution

a)



b)

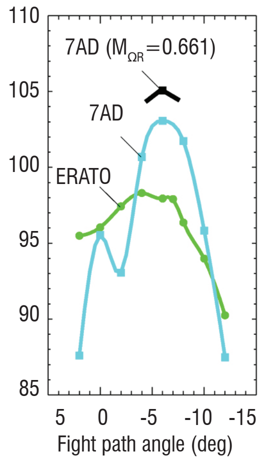


Figure 6 - a) ERATO blade shape. b) Noise reduction with ERATO blade measured at DNW (dBA) versus the descent angle at $M_{\Omega R}$=0.617.

are the cost, the weight increase, the additional power consumption and the maintenance. Nevertheless, it was judged important for industry and research centers to develop their competences in the field of active rotors. Thus, a project funded by the French Civil Aviation Authority, called the DTP RPA, also known as ABC, was launched in France at the end of 1998, involving Airbus helicopters and Onera. Similar activities were being addressed in Germany by the DLR and Airbus helicopters Deutschland, within the framework of ADASYS. Three main objectives were targeted: to decrease the BVI noise radiated during descent flight, to decrease the vibration level generated by the rotor and, finally, to increase the aerodynamic performance of the rotor, by either alleviating the dynamic stall effect, or decreasing the consumed power in fast cruise flight. Since one of the key parameters of the BVI noise emission are the blade vortex miss distances, the aim was to dramatically increase the vortex convection, from their emission up to the interaction, by means of the blade trailing edge flaps, so that the close interactions could be avoided. For a given rotor, the maximum noise is generally obtained at around 6° or 7° of descent angle. The level decreases very fast, by more than 6 dB (mid-range frequency, 6^{th} to 40^{th} bpf) for a change of ±2° in the descent angle. A ±2° modification in the slope corresponds to only around a half chord in the vertical position relative to the blade. It means that a gain of more than 6 dB can be expected by increasing (or decreasing) the wake convection between the emission and the interaction by 7cm for a model rotor. This can be performed by activating the flap for a range of blade azimuths corresponding to the travel of the vortices on the advancing side. Computations have shown that this effect can theoretically be easily achieved if the flap is sufficiently large and deep and can be activated with a sufficient deflection angle.

The flap is also expected to be able to reduce the vortex intensity at their emission, by means of adapted flap control laws. Numerical simulations have shown the efficiency of both effects. The main challenge remains to be able to implement efficient flaps (which means large ones, with strong deflections) on actual model rotor and full scale rotors.

As for ERATO, two wind-tunnel test campaigns were planned, one in the S1 Modane wind tunnel, mainly focused on dynamic aspects and one in DNW-LLF mainly dedicated to acoustic issues. During the first phase, the comprehensive code chain was adapted to take into account the trailing edge flap. Both the dimensions and locations of active flaps were determined, by means of numerical studies carried out on a full-scale ATR blade geometry provided by Airbus helicopters Deutschland. Since the efficiency of the flaps, in terms of noise reduction or vibration reductions, were obtained for different flap locations and dimensions, it was decided to keep the capability to choose three spanwise locations of 15% chord flaps, depending of the expected benefits: more inboard (70-80% R) for vibration, more outboard (80-90% R) for noise, for example (figure 7).

For each flight condition and flap geometry, optimal flap deflection laws were numerically determined at both full and wind-tunnel scales. In parallel, an active flap device was defined that could be implemented on the model scale blades to be tested in both wind tunnels. The second phase of the project, which started in 2001, was devoted to the manufacturing of a prototype blade by Onera and of a set of 5 "series" blades by the DLR for the tests in S1 Modane and DNW-LLF wind tunnels. The test campaign began in December 2005 in the S1 Modane wind-tunnel. Fourteen microphones were available for the acoustic measurements. Six of these were located on a vertical strut in front of the rotor shaft, for the determination of the thickness noise and eight were located below the rotor on the advancing blade side to determine loading noise (including BVI).

Measurements were carried out for different parametric sweeps of the phase actuation, for a given maximum flap deflection. For all of the flight conditions and for both flap positions, noise reductions were obtained with every flap deflection frequency for certain values of the phase. An example is provided in figure 8 for two different flap amplitudes in various phases, the flap being actuated at a frequency of 4-per-rev. By increasing the flap amplitude from 0.7° (figure 8a), to 1°, the noise reduction is increased from -1.2 dBA to -2.7 dBA.

For the active flap, noise reductions of up to 3 dBA have been obtained on the BVI component, although the flight conditions were not a descent flight with high BVI levels, showing the capability of the active flap concept for BVI reduction.

Blue Pulse™ technology, based on active flaps, has been flying since 2005, showing a noise reduction of up to 5 EPNDB [15]. Airbus helicopter evaluations with Blue Pulse™ are continuing on an EC145, while the development of a miniaturized system for production applications is advanced.

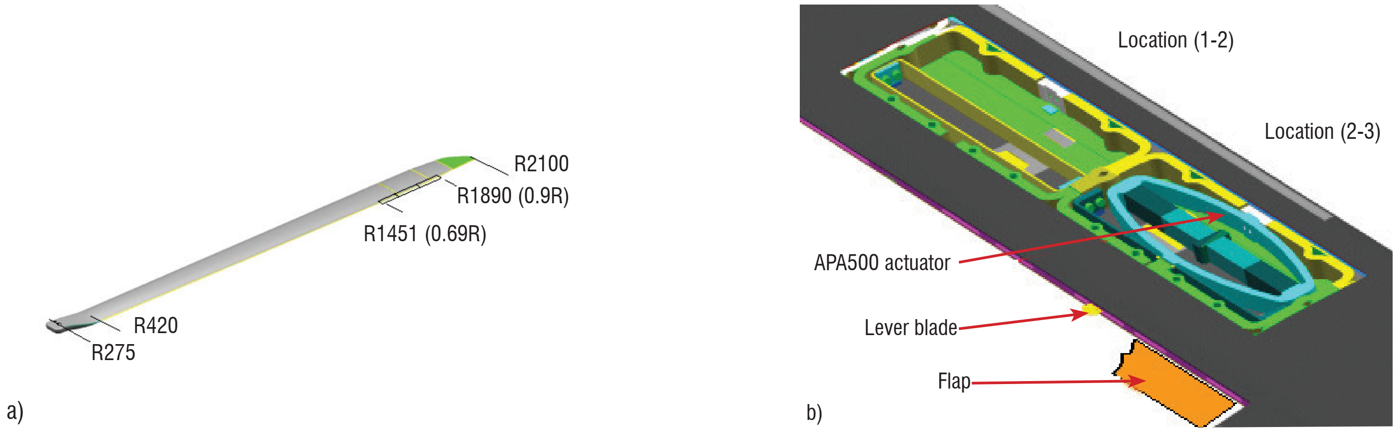


Figure 7 - a) ABC blade dimensions and b) flap positions [13]

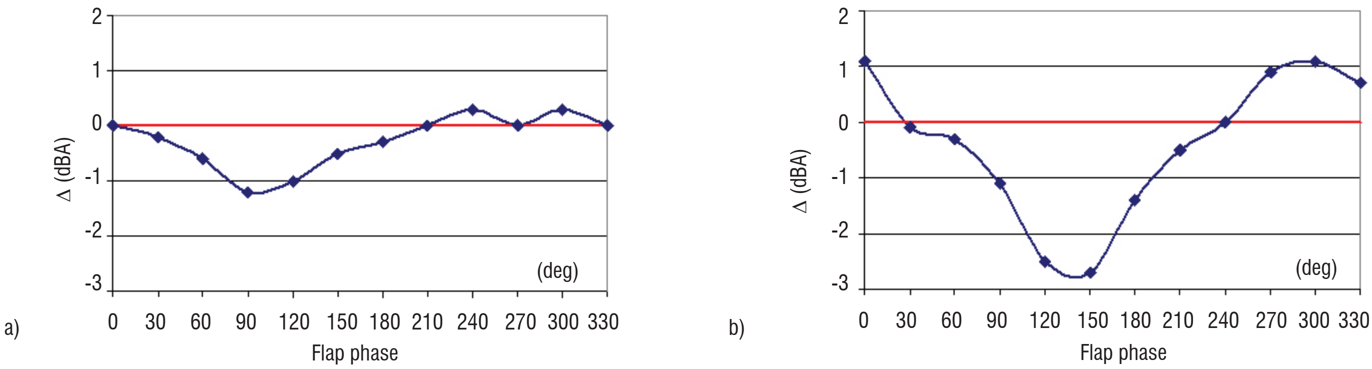


Figure 8 - Noise reduction versus the phase of actuation. 4w - a) 0.7° of amplitude. b) 1° of amplitude

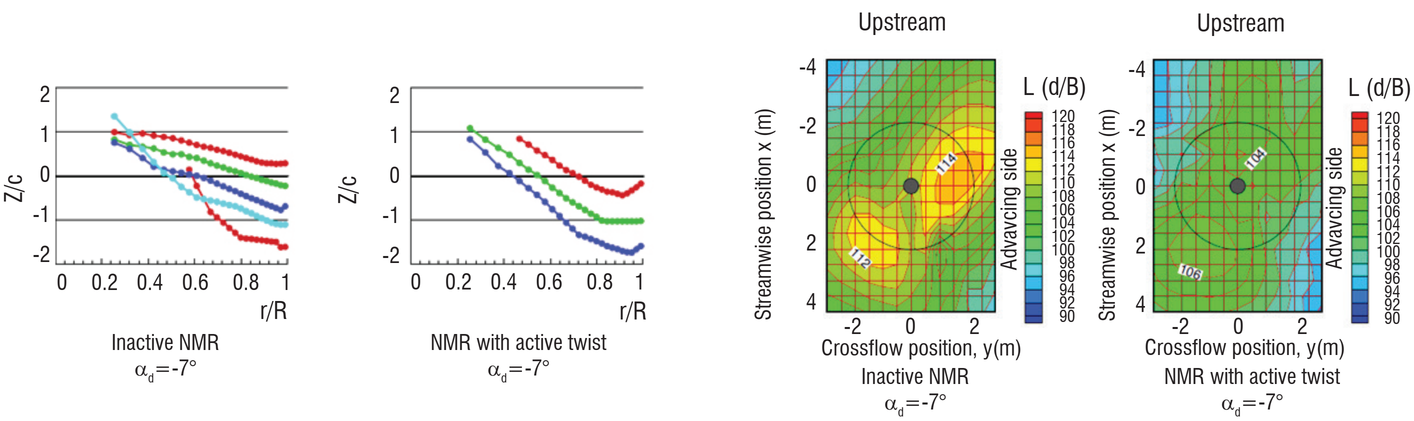
With the same objective as for the active flaps, a theoretically very promising way of reducing the BVI noise consists in modifying the spanwise twist distribution over the blade, in order to modify either the vortex generation or its convection. As for trailing edge flaps, numerical studies have been performed to show the theoretical efficiency of such a solution. The challenge is once again the capability to make blades equipped with active twist devices. Thanks to suitable twist laws, it is theoretically possible to dramatically decrease the BVI by increasing the induced velocities in a selected blade azimuth range. Onera performed an optimization of the twist laws within the framework of the European project Friendcopter and during an Onera/Airbus helicopter program [35]. The GADO optimizer was used to couple the R85 aero-elastic code with objective function of the induced velocity maximization near the blade tip on the leading edge. Thanks to the optimized law, the vortices are convected faster and a gain of more than 7 dBA is obtained on the maximum noise, which is even more important if only the leading edge is considered (right hand part of the contour plot in figure 9).

Low noise flight procedures

Complementary to the previous studies, numerous activities have been carried out using the codes developed (including simplified models [34] or using the Onera chain adapted to unsteady flight conditions [36]), in order to provide low noise flight procedures to the pilots for given missions, in terms of speed, rate of descent, etc.

Concluding remarks

Among the studies performed at Onera (with close cooperation from the DLR) within the framework of helicopter acoustics, several have led to industrial applications. To gain the confidence of industrialists in the proposed solutions and the numerical tools, research centers must prove the accuracy of their tools, using wind tunnel tests and thanks to international cooperation, within the framework of workshops. Onera has proven its capability to face this ambitious challenge, thanks to its efficient numerical tools and wind tunnel facilities ■



a) Blade-vortex miss-distances (Z/c) as a function of the blade span (r/R) at the azimuth of interaction

b) Noise contours (mid-range frequencies, 6th to 40th bpf)

Figure 9 - Noise reduction using active twist (New Model Rotor, NMR). Numerical simulations.

Acknowledgements

The author would like to thank all of the Onera teams that have been involved in the described activities and, in particular, the colleagues from the Applied Aerodynamics Department.

References

[1] C. DAHAN, C. LARNAUDIE, C. MALARMEY - *Synthèse des essais de rotors maquettes à la soufflerie CEPRA 19 dans le cadre du MoU*. Rapport de synthèse Onera 41/5094 PY, 1981.
[2] M. CAPLOT, A. DUPONT, C. LARNAUDIE - *Synthèse des essais de rotors maquettes de l'aérospatiale dans la soufflerie CEPRA 19.* Rapport de synthèse Onera 71/5094 PY, 1987.
[3] M. CAPLOT, P. LEBIGOT, P. LOOPUYT, J. PERRET-LIAUDET - *Essais acoustiques de maquettes de rotors d'hélicoptères de l'Aérospatiale dans la soufflerie S2Ch*. Rapport final Onera 81/5094 PY, 1988.
[4] P. SPIEGEL, G. RAHIER, B. MICHÉA - *Blade-Vortex Interaction Noise: Prediction and Comparison with Flight and Wind Tunnel Tests*. 18th European Rotorcraft Forum, Avignon, September 1992.
[5] R. KUBE, W. SPLETTSTOESSER, W. WAGNER, U. SEELHORST, Y. YU, A. BOUTIER, F. MICHELI, E. MERCKER - *Initial Results from the Higher Harmonic Control Aeroacoustic Rotor Test (HART) in the German–Dutch Wind-Tunnel.* 75th AGARD Fluid Dynamic Panel Meeting on Aerodynamics and Aeroacoustics of Rotorcraft, Berlin, October 1994.
[6] Y. DELRIEUX, J. PRIEUR, M. COSTES, P. GARDAREIN, P. BEAUMIER, H. MERCIER DES ROCHETTES, P. LECONTE, P. CROZIER, W.R. SPLETTSTOESSER, B. VAN DER WALL, B. JUNKER, K.-J. SCHULTZ, E. MERCKER, K. PENGEL, J-J. PHILIPPE, B. GMELIN - *The Onera-DLR Aeroacoustic Rotor Optimization Program ERATO: Methodology and Achievements*. AHS-Aerodynamics, Acoustics, and Test and Evaluation Technical Specialists Meeting, San Francisco, 2002.
[7] E. BOUCHET - *Étude du bruit d'interaction pale-sillage d'un rotor principal d'hélicoptère*. Thesis. Université du Havre, 2002.
[8] Y. MAUFFREY - *Contribution numérique à l'étude des mécanismes aéroacoustiques intervenant dans l'interaction pale-sillage d'un rotor d'hélicoptère*. Thesis. Université Pierre et Marie Curie, 2008.
[9] J. PRIEUR - *Experimental study of High Speed Impulsive Rotor Noise in a Wind Tunnel*. 16th European Rotorcraft Forum, Glasgow 1990.
[10] C. POLACSEK, P. LAFON - *High Speed Impulsive Noise and Aerodynamic Results for Rectangular and Swept Rotor Blade Tip Tests in S1-Modane Wind Tunnel*. 17th European Rotorcraft Forum, Berlin 1991.
[11] J. PRIEUR, W.R. SPLETTSTOESSER - *ERATO: an Onera-DLR Cooperative Programme on Aeroacoustic Rotor Optimisation*. 25th European Rotorcraft Forum Roma, 1999.
[12] P. CROZIER, P. LECONTE, Y. DELRIEUX, B. GIMONET, A. LE PAPE, H. MERCIER DES ROCHETTES - *Wind-Tunnel Tests of a Helicopter Rotor With Active Flaps*. 32nd European Rotorcraft Forum. Maastrricht 2006.
[13] Y. DELRIEUX, A. LE PAPE, P. LECONTE, P. CROZIER, B. GIMONET, H. MERCIER DES ROCHETTES - *Wind Tunnel Assessment of the Concept of Active Flaps on a Helicopter Rotor Model*. 63rd AHS Annual Forum. Virginia Beach, USA, 2007.
[14] A. LE PAPE, C. LIENARD, J. BAILLY - *Active Flow Control for Helicopters*. Aerospace Lab Issue 6, June 2013.
[15] P. RAUCH, M. GERVAIS, P. CRANGA, A. BAUD, J-F. HIRSCH, A. WALTER, P. BEAUMIER - *Blue Edge™: The Design, Development and Testing of a New Blade Concept*. 63rd AHS Annual Forum. Virginia Beach, USA, 2007.
[16] P. GARDAREIN, S. CANARD, J. PRIEUR - *Unsteady Aerodynamic and Aeroacoustic Simulations of a Fenestron Tail Rotor.* 62nd AHS Annual Forum, Phoenix, 2006.
[17] P. GARDAREIN, F. FALISSARD, L. BINET, J.-C. CAMUS - *Validation of Aerodynamic and Aeroacoustic Computations of a Fenestron in Real Flight Conditions*. 36th European Rotorcraft Forum. Paris, 2010.
[18] F. FALISSARD, F. DESMERGER, P. GARDAREIN, L. BINET, J.C. CAMUS - *Aeroacoustic Flight Test and Data Analysis for the Validation of Fenestron Noise Computations*. 67th AHS Forum, Virginia Beach 2011.
[19] J. PRIEUR - *Calculation of Transonic Rotor Noise Using a Frequency Domain Formulation.* AIIA Journal vol 26, 1988.
[20] C. POLACSEK, M. COSTES - *Rotor Aeroacoustics at High Speed Forward Flight Using a Coupled Full Potential/Kirchhoff Method.* 21st ERF, St Petersburg, 1995.
[21] C. POLACSEK, J. PRIEUR - Hi*gh-Speed Impulsive Noise Computation in Hover and Forward Flight Using a Kirchhoff Formulation*. 1st Joint CEAS/AIAA Aeroacoustics Conference, Munich, 1995.
[22] L. CAMBIER - *The els*A *Solver*. 1st Onera-DLR aerospace symposium. Paris 1999.
[23] L. CAMBIER L, M. GAZAIX - *els*A *: an Efficient Object-Oriented Solution to CFD Complexity*. AIAA Paper 2002-0108, 2002.
[24] G. RAHIER, J. PRIEUR - *An Efficient Kirchhoff Integration Method for Rotor Noise Prediction Starting Indifferently from Subsonically or Supersonically Rotating Meshes.* 53rd Annual Forum of the American Helicopter Society, Virginia Beach, USA 1997.
[25] P. BEAUMIER, Y. DELRIEUX - *Description and Validation of the Onera Computational Method for the Prediction of Blade-Vortex Interaction Noise*. Aerospace Science and Technology Journal. 2004.
[26] M. ALLONGUE, T. KRYSINSKI - *Aéroélasticité appliquée aux rotors d'hélicoptères - validation du code R85*. 27ème Colloque d'Aérodynamique Appliquée, AAAF, Marseille 1990.
[27] B. BENOIT, A.-M. DEQUIN, K. KAMPA, W. GRUNHAGEN, P-M. BASSET, B. GIMONET - *HOST, A general helicopter simulation tool for Germany and France*. 56th AHS Annual Forum. Virginia Beach, May 2000.
[28] G. RAHIER, Y. DELRIEUX - *Blade-vortex interaction noise prediction using a rotor wake roll-up model*. Journal of Aircraft, Vol.34, N° 4, 1997.
[29] P. SPIEGEL, G. RAHIER - *Theoretical Study and Prediction of BVI Noise Including Close Interactions*. AHS Technical Specialists Meeting on Rotorcraft Acoustics and Fluids Mechanics, Philadelphia, PA, October 1991.
[30] F. CARADONNA, C. KITAPLIOGLU, M. MCCLUER, J. BAEDER, G. LEISHMAN, C. BEREZIN, J. VISINTAINER, J. BRIDGEMAN, C. BURLEY, R. EPSTEIN, A. LYRINTZIS, E. KOUTSAVDIS, G. RAHIER, Y. DELRIEUX, J. RULE, D. BLISS - *A Review of Methods for the Prediction of BVI Noise.* Journal of the American Helicopter Society, Vol. 45, n° 4, pp 303-317, October 2000.
[31] M. COSTES, K. PAHLKE, A. D'ALSACIO, C. CASTELLIN, A. ALTMIKUS - *Overview of Results Obtained During the 6-year French-German CHANCE Project*. 61st AHS Annual Forum, Grapevine, USA 2005.
[32] M. COSTES - *Development of a 3rd-Order Vorticity Confinement Scheme for Rotor Wake Simulations.* 38th ERF, Amsterdam, 2005.

[33] C. BENOIT, G. JEANFAIVRE, E. CANONNE - *Synthesis of Onera Chimera Method Developed in the Frame of CHANCE Program.* 31st ERF, Florence, Italy, 2005.
[34] G. REBOUL and A. TAGHIZAD - *Semi-Analytical Modeling of Helicopter Main Rotor Noise*. 38th European Rotorcraft Forum, Amsterdam, 2012.
[35] J. BAILLY, Y. DELRIEUX - *Improvement of Noise Reduction and Performance for a Helicopter Model Rotor Blade by Active Twist Actuation.* 35th European Rotorcraft Forum, Hamburg, 2009.
[36] G. PEREZ, M. COSTES - *A New Aerodynamic and Acoustic Computation Chain for BVI Prediction in Unsteady Flight Conditions.* 60th Annual Forum Baltimore, 2004.

Acronyms

ABC (Active Blade Concept)
BVI noise (Blade Vortex Interaction noise)
BWI noise (Blade Wake Interaction noise)
CFD (Computational Fluid Dynamics)
CAA (Computational Aeroacoustics)
DNW-LLF (Deutsch-Niederländische Windkanäle-Large Low-speed Facility)
DTP RPA (Développement Technique Probatoire Rotor à Pale Active)
ERATO (Etude d'un Rotor Aéroacoustiquement et Technologiquement Optimisé)
FW-H (Ffowcs Williams-Hawkings)
HART (Higher harmonic control Aeroacoustics Rotor Test)
HHC (Higher Harmonic (pitch) Control)
HOST (Helicopter Overall Simulation Tool)
HSI noise (High Speed Impulsive noise)
LAA (Lightill Acoustic Analogy)
NMR (New Model Rotor)
STAR (Smart Twisting Active Rotor)
S1MA (Soufflerie 1 Modane Avrieux)

AUTHOR

Yves Delrieux has been a researcher at Onera since 1988. He leads the acoustics studies on rotors and propellers in the Computational Fluid Dynamics and Aeroacoustics Department. He obtained a PhD degree from Ecole Centrale de Lyon in 1991. He is mainly involved in noise prediction and optimization of rotary wings.