A. Le Pape, C. Lienard, J. Bailly
(Onera)

E-mail: alepape@onera.fr

Active Flow Control for Helicopters

Several active flow control helicopter applications aimed at improving aerodynamic performance have been studied at Onera and are presented in this paper. The distinction between applications for non-rotating or non-lifting parts and for rotating parts is presented. A first part deals with the application of steady/unsteady blowing to simplified rotor hub and fuselage shapes. The objective is to achieve significant drag reduction by suppressing the flow separation occurring in these areas. Numerical and experimental investigations are jointly performed to identify the best control strategies. The numerical efforts take into account the experimental constraints in the simulations. Significant work is done on the simplified fuselage drag reduction using various blowing actuations: synthetic jets, pulsed jets and steady blowing. The second part of the paper is dedicated to active flow control on rotor blades. A first application of deployable vortex generators for dynamic stall control is discussed. Then, more general active technologies aimed not only at improving the aerodynamic performance but also at reducing the vibratory loads or the noise radiation, are presented. Among the several active blade technologies that have been studied at Onera, both experimentally and numerically, this paper focuses on the active flap blade and the active twist blade concepts. The paper highlights the diversity of flow problems occurring on a rotorcraft and the various flow control strategies that must be considered to handle them. The numerical challenges to account for flow control in an unsteady environment are discussed for each flow control application.

Introduction

Flow control has been a very active area of research in recent years for the aerodynamic improvement of aerial vehicles [3], [24]. Based on simple and academic configurations [2], the significant first success of flow control led to more complex and realistic geometries being considered. Flow control techniques have since been applied to rotorcraft and in particular to helicopters. Helicopter aerodynamics is intrinsically highly unsteady, due to the main and tail rotor rotations. The non-rotating parts of helicopters may also have large separations, the design of the machine being generally more driven by the specified mission of the aircraft than by a quest for aerodynamic efficiency. The variety of helicopter missions fits in well with active devices that can be activated on-demand, on non-rotating or non-lifting parts. Separation control effectiveness has also been shown using active actuators [8], [15], [16]. Rotorcraft configuration applications are generally focused on separation control for drag reduction. It has been, for example, applied to hub fairing or hub pylon separation control [4], [49], [37] and this application will be discussed in the first part of the paper. Separation control for drag reduction has also been studied by several authors, on blunt fuselage using vortex generators [7], steady blowing [27], [40], synthetic jets [32], [50], [27], [40], combustion actuators [50] or plasma actuators used as vortex generators [13]. The Onera activities on this topic are discussed in the first part of the paper: different types of actuation (steady blowing, pulsed jets and synthetic jets) are used to reduce the drag of a simplified blunt fuselage.

On rotating parts, active flow control is well suited to the unsteady environment that the helicopter rotor experiences. The retreating and advancing blades are subjected to very different aerodynamic conditions: active flow control enables a particular phenomenon to be acted upon only in the needed azimuth range. For example, dynamic stall is a phenomenon that occurs on the retreating blade and that induces large penalties for high speed forward flight. Its control has been a topic of many studies and several devices have been proposed. Dynamic stall is linked to the shedding of a strong leading-edge dynamic stall vortex and therefore most authors have proposed devices acting at the airfoil leading-edge. For example, suction at the leading-edge [25], blowing [20][21] and plasma actuation using Dielectric Barrier Discharge (DBD) actuators [38] were shown to bring some benefits. Large modifications of the airfoil shape were also investigated using a deforming leading-edge [11], a droop leading-edge airfoil [17] or leading-edge slats [9]. Vortex generators at the airfoil leading-edge were also successfully applied [31][30] to limit dynamic stall penalties and this idea has been extended at Onera by the addition of a deployable feature of the vortex generator device. Activities on dynamic stall control using Deployable Vortex Generators (DVGs) are presented in the second section of this paper.

A more global influence on the flow can be obtained using active blade technologies. The objectives of the actuation are generally not only to improve the aerodynamic performance of the rotor, but also to limit the noise radiations or the vibratory loads. The last part of the paper presents the Onera outcomes for two active blade technologies; the first is the active flap blade and the second is the active twist blade.

The objective, status and outcome of each application are discussed from both experimental and numerical aspects.

Active flow control for non-rotating components

Compared with fixed wing aircraft fuselage drag, the fuselage drag of a helicopter may be up to an order of magnitude larger. Due to the operational requirements for rotorcraft, the fuselages are typically not cleanly integrated with the engine, pylon, nacelle, hub, or landing gear. This may result in adverse flow interactions and excessive drag, due to the bluff body shape and separated flow. Suppressing the flow separation on non-rotating components of a helicopter can consequently lead to significant drag reduction and improve the overall performance of the machine. Massive separation occurs generally in two different regions of the fuselage: downstream from the rotor hub and downstream from the fuselage cabin (especially for rearward loading capability rotorcraft). The following sections present the application of active flow control on simplified geometries representing these two key-areas.

Pylon fairing separation control

Helicopter rotor hubs are characterized by a highly complex design ensuring the proper helicopter rotor control. If the rotor hub cannot be fully faired, the pylon that supports the rotor hub is generally faired using a streamlined shape. Usually, symmetric thick-airfoil shapes are used for pylon fairings [46]. Flow separation on those airfoils may appear at very low angles of attack, producing large drag penalties and unsteady vortex shedding that can impinge the rear lifting surfaces and lead to severe handling quality problems. Under the US/French Memorandum of Agreement on helicopter aeromechanics, a typical thick airfoil, a NACA0036 (figure 1), used for helicopter pylon fairing has numerically been investigated without and with flow control in a joint US Army/Onera effort [37]. Active flow control was ensured by zero-net mass-flux jets (or synthetic jets [19]) blowing and sucking air through slots located on the upper surface of the airfoil ([4], [37], [49]).

Wind-tunnel test measurements were available for both baseline and actuated configurations and the joint US/French work focused on computational work to assess the ability of computational fluid dynamics (CFD) tools to reproduce the experimental observations. The results of the computations are detailed and discussed, comparing with available experimental data in Ref. [37]. The baseline case is a very difficult one for CFD, with a large flow separation over the upper surface of the airfoil at a very low angle of attack. The flow is largely separated at the trailing-edge of the airfoil at a 0° angle of attack and separates totally over the upper surface at a 5° angle of attack, leading to a decrease in lift at low angles of attack. The numerical simulations performed with the Onera CFD solver *e*l*s*A on this configuration in 2D and 3D show limited quantitative agreement with experimental measurements, in particular for lift and drag values. Some of the discrepancies could be linked to the experimental set-up (corner flow in the tunnel, roughness that triggers laminar-turbulent transition at the airfoil leading-edge) and were investigated using CFD, but the overall agreement was poor. It was however possible to investigate the modeling of the synthetic jet actuators in the simulation for actuated cases. The first significant conclusion identifies the required temporal resolution of the blowing and suction cycles in the simulation.

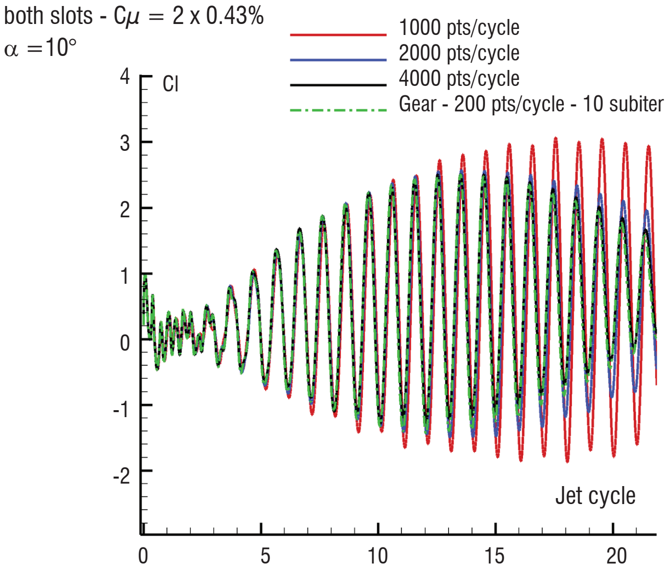

Figure 2 - Temporal convergence study of the synthetic jet cycle resolution in the simulation

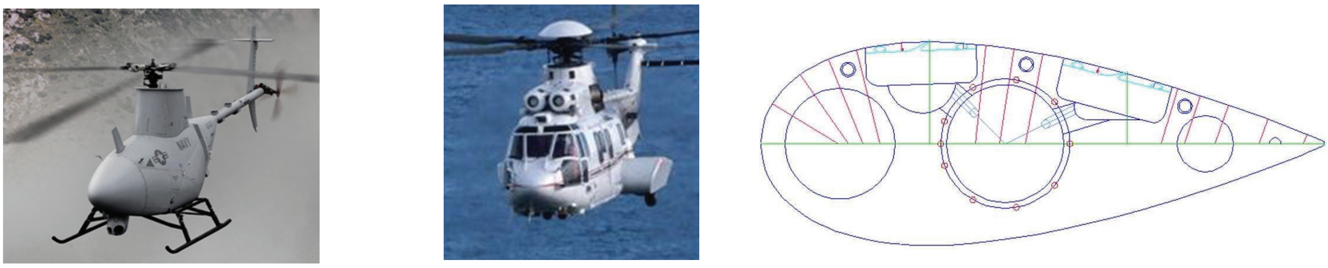

Figure 1 - Examples of rotorcraft with faired pylon (left), NACA0036 airfoil model (right) (from [37] and [4])

The results (figure 2) showed that a number of 2000 time steps per jet blowing/suction cycle (or 200 time steps with 10 sub-iterations per time step) were necessary to describe the synthetic jets effect correctly and consistently. This figure must be related to the typical separation timescales that can appear on a helicopter pylon; it should be also compared with the timescale of the rotor rotation, if active flow control is considered on the rotor. For example, for a rotor spinning at 200 rpm and a synthetic jet oscillating at f=120 Hz, a rotation corresponds to 400 synthetic jet cycles. Using a sub-iteration time scheme, 8.10^4 time steps per rotor revolution would be required, corresponding to a time step of 0.0045° of rotation, which is two orders of magnitude less than what is usually used in CFD, in the rotorcraft community.

Another important result is the identification of the influence of the active flow control phasing, in both the experimental and the numerical investigations. The different actuators implemented in the model can indeed be actuated to have the blowing/suction in phase or out-of-phase with each other. Here, the actuators located in the front part of the model are out of phase with the actuators on the aft part of the model. Wind-tunnel tests showed that phasing the jets improved the drag reduction and reduced the overall model vibration. CFD computations show similar trends and highlight the importance of the phase influence when using synthetic jets for flow separation control. The CFD investigations were performed for a limited number of phasing cases and no complete understanding of the phasing effect was drawn. A comprehensive understanding of the physics involved in jet phasing remains a topic for further research. This result has been important for the simplified blunt fuselage separation suppression [40] studied in the following section.

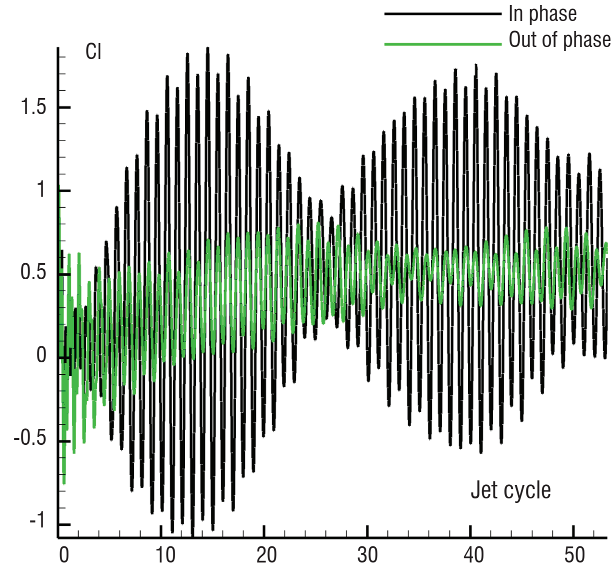

Figure 3 - Lift history for in-phase and out-of-phase synthetic jets

Helicopter blunt fuselage separation control

In high-speed forward flight, a major component of helicopter parasite drag is due to the fuselage and to the massive flow separation that occurs on its rear, especially for helicopters with a very pronounced aft loading ramp. A combined numerical and experimental investigation has been conducted within the Green Rotorcraft ITD of the CleanSky project, to obtain a better understanding of the flowfield around a helicopter generic fuselage and to investigate different flow control approaches to decrease this pressure drag. Many numerical and experimental baseline results are presented in ref. [27], as well as some active flow control computations, which helped in the designing of the actuators for the wind-tunnel tests. This research effort is applied on a generic fuselage, the ASF2, based on a fully open geometry. Already studied around 1985-1990 at Onera [18], this fuselage has a pronounced ramp, in order to produce a large area of separation (figure 4). Three promising flow control devices were chosen for study: steady blowing, pulsed jets and synthetic jets.

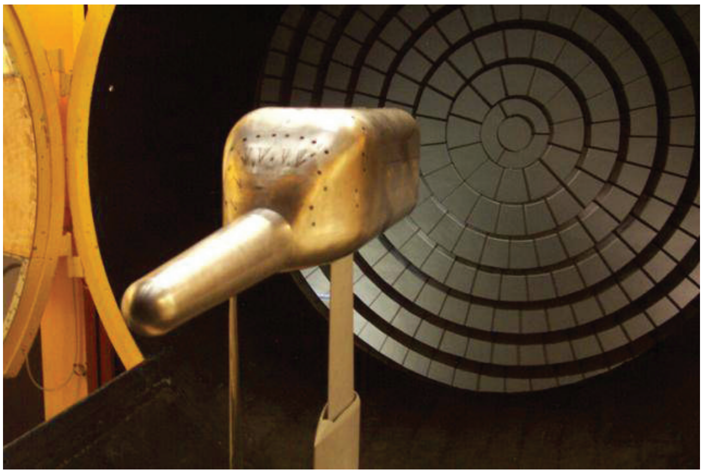

Figure 4 - ASF2 model mounted in Onera L1 wind-tunnel

Baseline case

The data presented in figure 5 shows a good correlation between numerical and experimental results for the baseline configuration, especially for angles of attack (AoA) higher than -2.5° (fuselage nose-down), considering the massive separation that occurs in the ramp region.

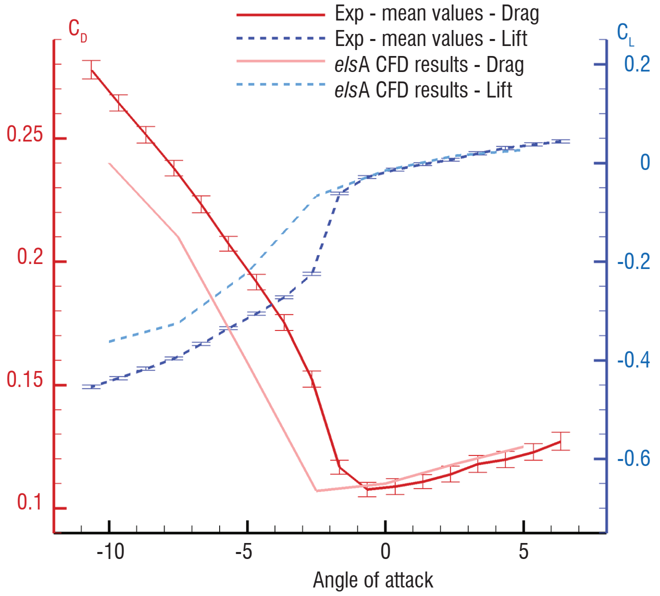

Figure 5 - Numerical/experimental comparison of the drag and lift coefficients for the baseline case

A detailed analysis of the flow allows two topologies to be identified, depending on the angle of attack, already established by Seddon [41]:

- an "eddy flow" for a nose-up angle of attack (AoA), which is the classic bluff-body flow consisting of cross-stream eddies and results in low drag but unsteady loads

- a “vortex flow” for a nose-down AoA, which is characterized by streamwise vortices and leads to high drag values.

However, the critical angle of attack is not well estimated by the numerical simulations. One possible explanation for this error could be the lack of the struts [39], and to a lesser extent of the wind-tunnel walls, in the simulations.

Flow control cases

Many simulations with flow control have been performed on this simplified blunt fuselage. In this investigation, simplified CFD simulations (half configuration with symmetry plane and coarse grids) with synthetic jets were used to get some idea of the effectiveness of active flow control on the ASF2 fuselage. Subsequently, numerical simulations have been performed to develop a flow control strategy and to identify actuator design parameters for the experiment, such as the slot location, width and angle.

Despite the approximations, those simulations resulted in a definition of the experimental flow control configuration to be tested in the wind-tunnel (0.67 mm-wide and 30 mm-long slots, slightly downstream from the separation line obtained for $\alpha=0°$, 45° jet angle). They also helped to quantify the drag reduction that could be expected, these predicted around 15 - 20% in good agreement with state of the art drag reduction by active flow control on helicopter blunt fuselages [32], [40], [1], [34]. These also provided an initial idea of the flow control strategies to be applied, such as velocity ratios higher than 1 and phasing out of synthetic jets.

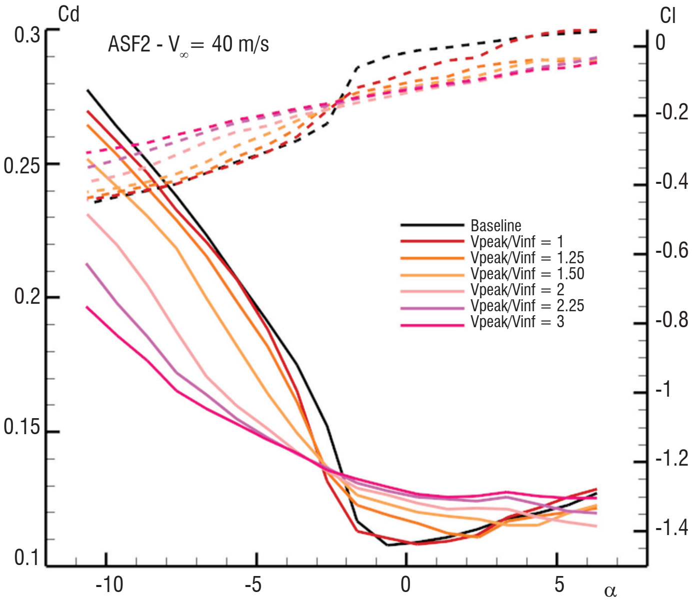

Figure 6 - Experimental drag (solid line) and lift (dashed line) for several steady blowing velocities

Confirmations of these potential benefits by wind-tunnel tests have been performed at Onera in the low-speed L1 facility. Specific attention was paid during the test preparation to actuator properties and performance. Laboratory tests were conducted on each individual actuator, to check the homogeneity of the actuators and to evaluate the output velocity peak and profile, frequency and voltage responses.

Then, an extensive parametric study including different velocity ratios, frequencies, duty cycles, phasing and slot schemes was successfully performed for the three chosen flow control devices. Experimental results are very promising, with significant drag reductions of 15 - 35% being observed. Higher drag reduction is achieved for negative AoA, which is favorable in the case of high speed flight of the helicopter. No drag reduction could be obtained for a narrow range of AoA around 0° (figure 6). Steady blowing configurations seem to be the most effective, but pulsed jets enable almost the same benefits at half of the required mass flow. The effect of synthetic jets is so far rather limited, with drag reduction only for a limited range of the fuselage angle of attack. These actuators have been slightly modified for another wind-tunnel entry expected in 2012, to achieve higher peak velocities.

Active flow control for helicopter main rotor

This second part is focused on the application of active flow control to rotating blades. Rotor blades encounter a wide range of aerodynamic conditions, from subsonic flow on the retreating blade to transonic flow on the advancing blade, leading to various aerodynamically penalizing phenomena. A first application focuses on dynamic stall. Dynamic stall occurs on the retreating blade for high speed forward flight or highly loaded rotors and it can be studied using the simplified configuration of an airfoil under pitching-oscillation motion. The following section presents the design and application of actively deployable vortex generators for dynamic stall penalty alleviation. Finally, two active blade technologies are discussed: active flap blade and active twist blade. The control principle is based on a more global action of the entire rotor. It not only enhances aerodynamic behavior, but also reduces the noise radiation and the vibratory loads.

Dynamic stall

Dynamic stall has been an intensive area of research over the last decades, to improve the understanding of the complex physics and it remains a very difficult problem in aerodynamics. The alleviation of dynamic stall on rotorcraft blades has also been an area of investigation for many researchers. Since structural problems associated with dynamic stall are due to the negative pitching-moment induced by the shedding of the strong leading-edge dynamic stall vortex, the objective of the dynamic stall control is primarily to reduce the negative pitching moment, while maintaining comparable mean and maximum achievable lift. The reduction of drag due to dynamic stall is generally considered as a secondary objective; any reduction of dynamic stall will lead to an extension of the flight envelope. Many devices have been proposed and experimental validation has been achieved on 2D wind–tunnel models for some of them. The technologies investigated include shape morphing (variable drooping leading-edge), active suction or blowing and passive control using vortex generators or Dielectric Barrier Discharge (DBD) plasma actuators (see for example the review of some devices in [10]).

The most promising studies concern the delay of dynamic stall, or its alleviation, using vortex generators. Significant dynamic stall reductions with leading-edge vortex generators were demonstrated experimentally by Martin et al. [31] and Mai et al.[30]. In the latter study, the devices are small flat cylinders attached to the airfoil leading-edge. However, even if the leading-edge-vortex generators are located near the stagnation point so that the flow is not affected at low and moderate angles of attack, the device may cause penalties for non-stalled flight conditions. Active flow control solves this problem; for example, pulsed-jet vortex generators [29] [42] were successfully applied with one major drawback: the additional air supply required.

In this context, an innovative active device has been proposed and experimentally validated at Onera, in order to alleviate dynamic stall penalties, based on leading-edge vortex generation. The active device is intended to be used only during dynamic stall on the retreating blade; in order to avoid drag penalties on the advancing blade side, an actuation at a typical helicopter rotational frequency (1-per-rev, typically a few Hz) is thus foreseen. The actuator is a row of deployable vortex generators (DVGs) located at the nose of the airfoil (figure 7). The vortex-generators are small blades that conform to the airfoil leading-edge shape so that the airfoil is clean when retracted. The DVGs can be deployed at various heights (from 0.1 mm to 3 mm, with an accuracy of 0.05 mm) and with various deployment motions (sine, square) with respect to the airfoil pitching motion.

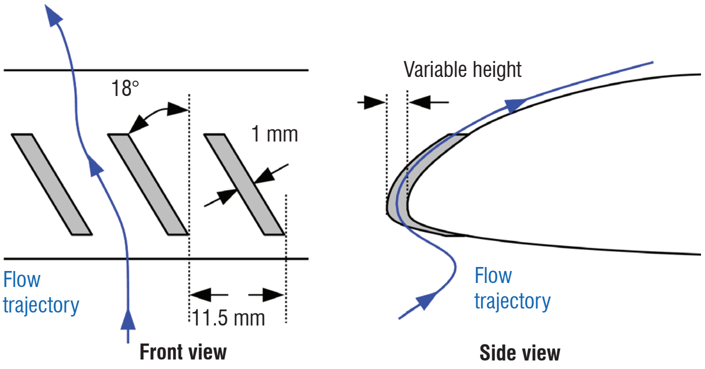

Figure 7 - Sketch of the designed Deployable Vortex Generator system.

The DVGs have been designed and implemented in an OA209 airfoil model and tested in the Onera F2 low-speed wind-tunnel for static and dynamic stall conditions [26]. A delay of up to 3° of the static stall angle of attack is achieved for static stall (figure 8). Results show that static stall delay is obtained for a small DVG height equal to 0.3 mm, but that more significant delays are obtained for hDVG~1.5 mm. This delay is obtained by alleviating the leading-edge stall, while promoting the trailing-edge separation. Therefore, the static stall delay is achieved at the cost of reducing the maximum lift.

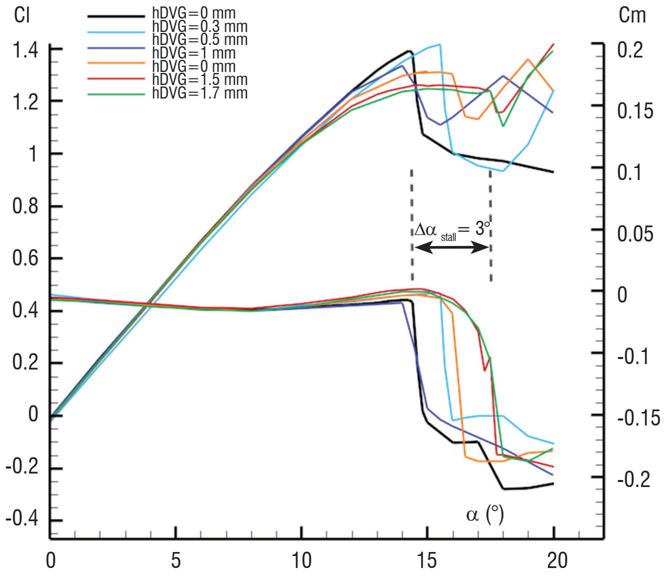

Figure 8 - Static stall delay obtained for various DVG heights

A large reduction in the negative pitching moment is shown for dynamic stall (figure 9). Up to 55% of the negative pitching-moment peak reduction is achieved when DVGs are deployed all over the airfoil oscillation cycle for an optimal DVG height equal to 1.5 mm. A loss of maximum lift of 10% is also observed. The analysis of various DVG deployment schemes shows that various compromises can be achieved between minimum negative pitching moment peak and maximum lift. When DVGs are deployed sufficiently soon before the occurrence of dynamic stall, a very large reduction of the negative pitching moment is achieved but there is also a loss of maximum lift. There is a good compromise for an actuation phase equal to 70°, for which a reduction of 30% of the negative pitching-moment is achieved with a limited loss of maximum lift of 2%. Duty-cycle (ratio of the duration of deployment during the oscillation cycle over the full oscillation cycle duration) optimization is performed and it is shown that these results can be obtained for a duty-cycle of down to 15%, ensuring limited drag penalties due to DVGs. Finally, it is shown that DVGs act primarily in the leading-edge region, where the dynamic stall is prevented from occurring by ensuring an attached flow at the leading-edge during the airfoil entire oscillation cycle.

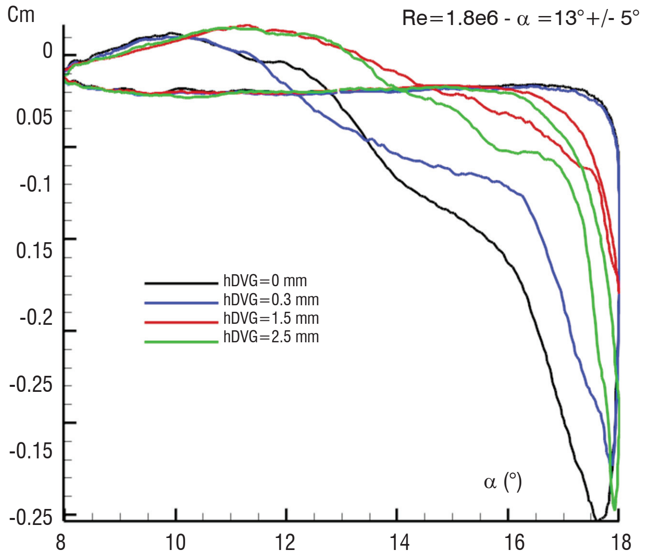

Figure 9 - Pitching-moment hysteresis obtained for various DVG heights

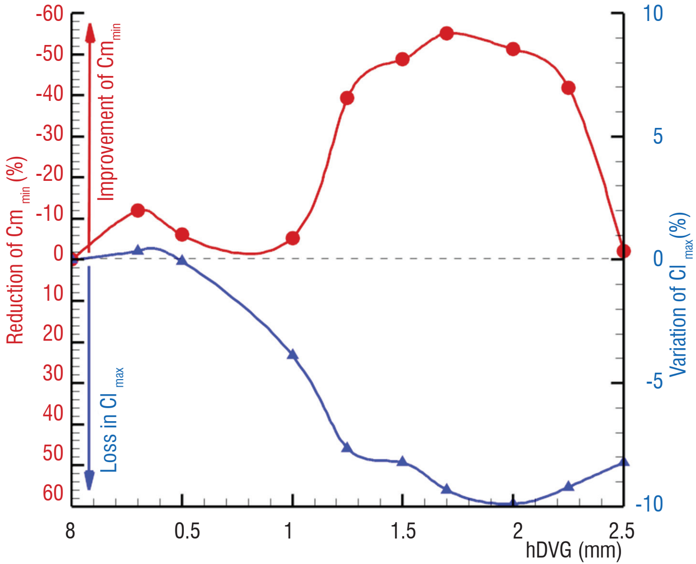

Figure 10 - Summary of DVG effectiveness for various heights

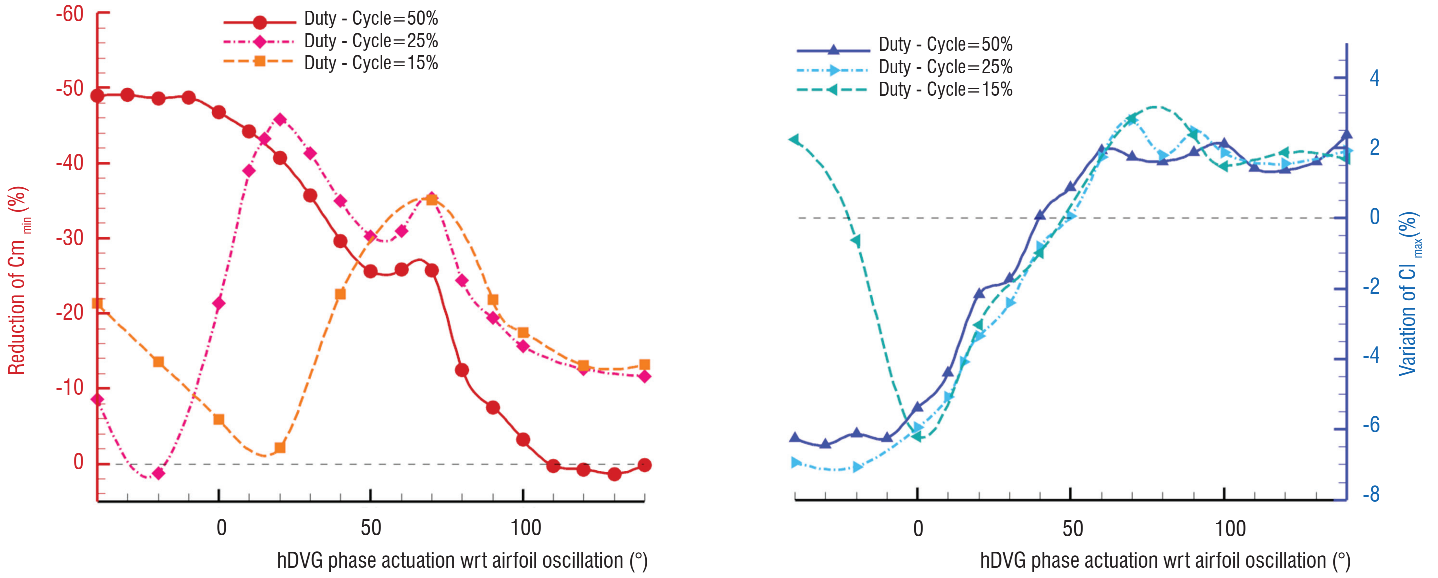

Figure 11 - Summary of DVG effectiveness for hDVG=1.5 mm and several duty-cycle wrt. DVG actuation phase, left: pitching-moment, right: lift

Along with the experimental demonstration of the effectiveness of DVGs for dynamic stall penalty reduction, significant effort has been made in the numerical investigations of this technology. The objective is to establish a computational model, which is validated using the experimental data used to investigate the physical mechanism of the interaction of the vortex emitted by the device and the flow separation at stall. On the other hand, the numerical simulation can also be used to improve the DVG design and optimize its effectiveness. These numerical investigations are presented in detail in [22] and [23]. It is shown that a good agreement with experimental data is obtained for static and dynamic stall, when the DVG device is included in the grid system for static deployment [22]. The analysis based on the numerical results also suggests that the specific aspect ratio of the DVGs is a primary parameter in the control effectiveness. The designed DVG is indeed thicker than the usual vortex generators, to allow mechanical deployment. Computations show that a thinner DVG could improve the static and dynamic stall control.

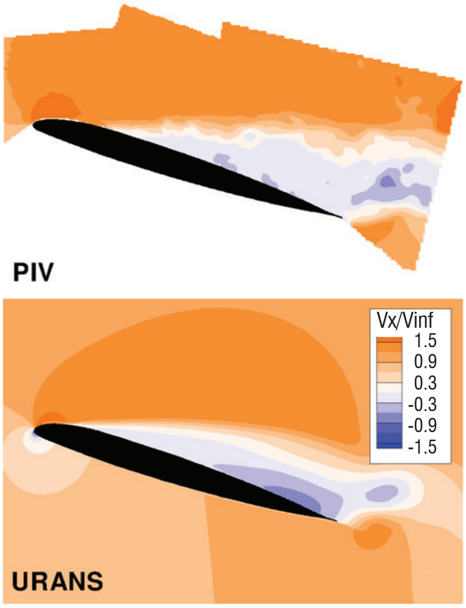

Figure 12 - Comparison of the computational result and the PIV data for dynamic stall control, using DVG

Since the ability of the DVGs to alleviate the dynamic stall penalties for 2D pitching airfoil has been shown, the effectiveness of this device on a helicopter rotor in high speed forward flight must still be estimated. However, including DVG on a rotor blade would require a very fine computational grid, since approximately 650 DVGs should be included to conserve the spacing used during the 2D wind-tunnel test. Time resolution of the single DVG computations is also one or two orders of magnitude higher than what is typically used for helicopter rotor simulations (usually 0.1°, here approx. 0.01°). Even if only a limited spanwise section of the blade is equipped with DVGs, computations of this magnitude remain out of reach with current computational resources and simpler evaluation methods are required. The following section describes active control investigations on rotor blades, based on comprehensive codes that use airfoil look-up tables and lifting-line methods with wake modeling that are simpler than (U)RANS computations.

Active blades

Active flow control on helicopter rotors has been a significant area of research over the last 20 years for active blade studies. The idea is not to add small disturbances in the flow using small actuators, but rather to apply technology that generates a general effect on the entire rotor system. The actuation can be on the rotor control or embedded in the blade to actively modify the blade shape. The expected effect on the flow can be obtained either from a direct local or global influence, or from an indirect influence through a specific aeroelastic response of the blade. Generally, the expected benefits are not only for improved aerodynamic performance, but also for noise and vibratory load reduction. Comprehensive aeromechanic tools are thus used to perform the benefit evaluation computations.

Active rotor studies were initiated at Onera through the HART (1994) and HARTII (2001) international (US Army, NASA, DLR, DNW, Onera) cooperative programs [47]. In these projects, the Higher Harmonic Control (HHC) technology was numerically and experimentally investigated in the continuation of a more industrial application of complex rotor command systems [36]. The objective of HHC is to replace the usual rotor swashplate that provides a 1-per-rev input to the blade motion by an advanced swashplate allowing higher harmonic inputs.

The wind tunnel tests on a 40% Mach-scaled hingeless model rotor showed a maximum reduction of 4dB in descent flight and a maximum vibratory load reduction of approximately 30% [45]. Numerical analysis performed at Onera using the Eurocopter aeromechanic comprehensive code HOST [5] provided good agreement on the trends, as well as other comprehensive codes [47]. Further computational studies focused on the aeroacoustics of the HARTII rotor and the ability of CFD/CSD [43] to accurately capture the rotor wake and the blade vortex interaction (BVI).

In the meantime, other active blade technologies have been studied at Onera, in particular the active flap blade and active twist blade, which are detailed in the following sections.

Active flap

The idea of active flap technology is to include a trailing-edge flap over a given spanwise extension of the blade. The trailing-edge flap can then be actively actuated at various frequencies (harmonic of the rotor rotation frequency are generally used, also noted n-per-rev frequencies) and for various angle of attack amplitude ranges. Preliminary computational studies were performed at Onera to design the trailing-edge flap spanwise extension and chordwise depth. In the comprehensive code used for these computations, the aerodynamic solution is based on a lifting line method and an airfoil property look-up table. To take into account the trailing-edge flap influence, dedicated airfoil polars for various flap deflections are used. The flap deflection airfoil polars are based on 2D wind-tunnel tests and analytical models. The results allowed the design of a model-scaled rotor equipped with trailing-edge flaps, with a spanwise extension equal to 10% of the total blade radius and a chord equal to 15% of the local blade chord. Several spanwise positions of between 70% and 90% of the blade radius were possible (figure 13).

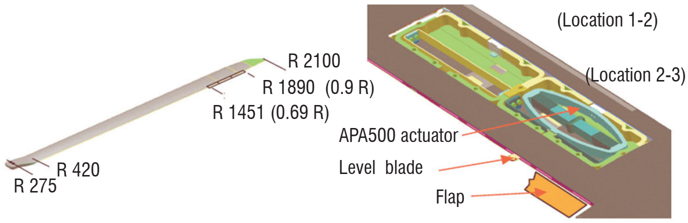

Figure 13 - Sketch of the active flap technology implemented in a helicopter rotor blade

Wind-tunnel tests were performed at Onera for several forward flight conditions [14]. Measurements included blade airloads computed from 168 unsteady pressure transducers, noise emission, blade deformation and rotor hub vibrations. The tests showed a significant reduction of the Blade Vortex Interaction (BVI) noise for a moderate level flight case with 1-per-rev and 4-per-rev actuations. Up to 2.8 dB reduction of the maximum noise measured could be obtained. Measurements of rotor hub vibratory loads were also performed and a closed-loop control of the flap deflection actuation allowed up to 20% of 4-per-rev hub vertical force to be reduced. However, no significant influence on the rotor power consumption was observed.

The wind-tunnel tests also showed that the flap deflection actuation acted in two distinct ways. The flap deflection can locally modify the blade section lift by changing the airfoil camber. In addition, the flap deflection at a given spanwise station and frequency actuation can modify the aeroelastic response of the entire blade and in particular the torsional response (servo-flap effect).

In parallel, Eurocopter Deutschland has developed a full-scaled demonstrator for this active flap rotor technology and has shown similar benefits during flight-tests [44]. Similar activities were also conducted in the US on a full-scale rotor demonstrator in wind-tunnel tests, with similar findings in terms of noise and vibration reduction [35], [28].

Active twist

The general purpose of active twist is to actively modify the rotor blade twist at various frequencies during the rotor rotation. As for the active flap, the flow control effect can be produced by a direct aerodynamic behavior variation with twist modification, or by inducing a modified aeroelastic response of the blade. Over this last decade, Onera developed a specific patented technology [33] based on the TWISCA concept (TWIstable Section Closed by Actuation), whose principle is an open blade section (figure 14) with a slot along the span direction, the two edges of this slot being connected by a Macro Fiber Composite (MFC) actuator located near the 25% of the chord line. Actuating this device induces a relative translation movement in the span direction of the upper and lower edges, resulting in a warping effect of the structure, leading to the twisting of the blade. One of the advantages of this structure is that the actuators, which are located close to the neutral axis, experience low bending stresses.

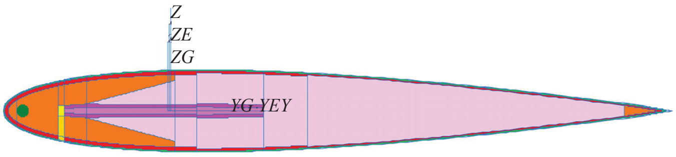

Figure 14 - Lift Demonstrator current section with actuation centered at 25% of the chord and slot at 10% (TWISCA concept)

Benefit evaluation computations, pre-design and wind-tunnel test preparation computations are performed using the comprehensive aeromechanic Eurocopter tools R85 and HOST, similarly to what was performed for active flap studies. Several models have been implemented to include twist modification in the aerodynamic lifting-line model. The first active twist model [6] is based on a direct modification of the local angle of attack of the blade, due to active twist. The active twist angle is included as an additive term of the total incidence angle, defined as the sum of the local pitch angle, the local twist angle and the elastic torsion.

All of the optimized control laws are defined using a harmonic decomposition with a maximum of 5 components, such as:

$$A(t) = A_0 + \sum_{i=1}^{5} A_{ic}\cos(i\omega t) + A_{is}\sin(i\omega t)$$

A_0, A_{ic}, and A_{is} being the fundamental, cosine and sine components of the active twist angle respectively.

Another way to model the active twist is to consider that the actuators create a torsion moment that can be added to the external forces and moments in the same way as the aerodynamic moments, as shown in figure 15. The elastic moment due to active twist must be provided using experimental data. This model implies that two point-sources of opposite sign are considered at each end of the active area of the blade.

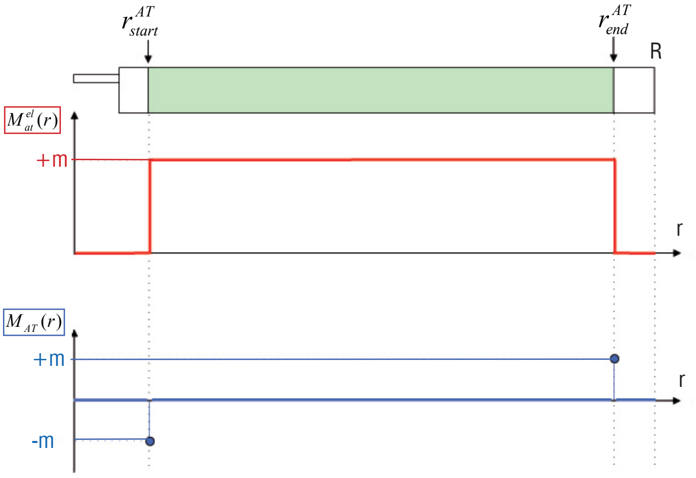

Figure 15 - Active twist model by moment

This model has the advantage of intrinsically containing the elastic response of the blade due to the twist actuation.

A comprehensive code and a genetic algorithm have been coupled to determine optimized active twist actuation laws for improved aerodynamic performance, noise and vibration reduction. The optimization variables are the 5 cosine (A_{ic}) and the 5 sine (A_{is}) components of the active twist angle. The computed configuration is a 4-bladed model-scaled helicopter rotor (2 meter radius). In this optimization process, active twist modeling by angle is applied with a maximum possible twist deflection (defined by technological constraints) of +/-2° at the blade tip. The results allowed the identification of achievable improvements for the various objectives and the useful actuation frequencies. An important result is that each individual objective requires a different type of actuation, as shown in figure 16. It was thus shown that rotor performance in forward flight could be improved using both 4-per-rev and 5-per-rev actuation, leading to up to 2.3% of consumed power reduction. This benefit comes from a reduction of the induced power, related to the modification of the geometric incidence, varying with the active twist angle.

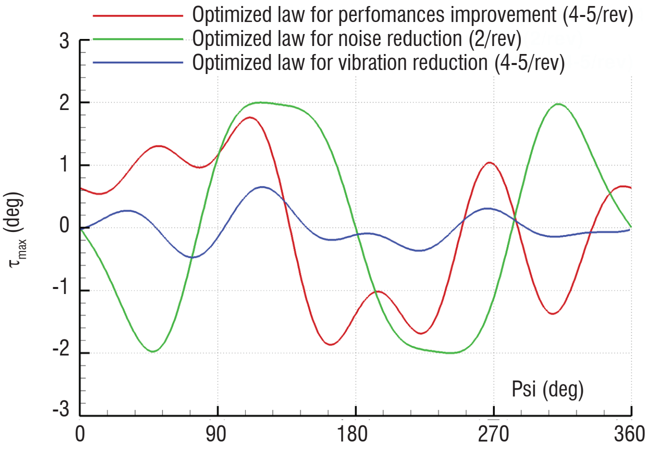

Figure 16 - Examples of active twist actuation laws for the various objectives

Noise reduction was investigated in descent flight for various descent angles. Active twist actuation is used to increase the local convection of the wake, so that interaction with the blade (responsible for BVI noise) is expected to be reduced or even eliminated. It was estimated that large BVI noise reduction could be achieved using 2-per-rev active twist actuations, leading to a noise abatement of up to 7.4 dB, as illustrated in figure 17.

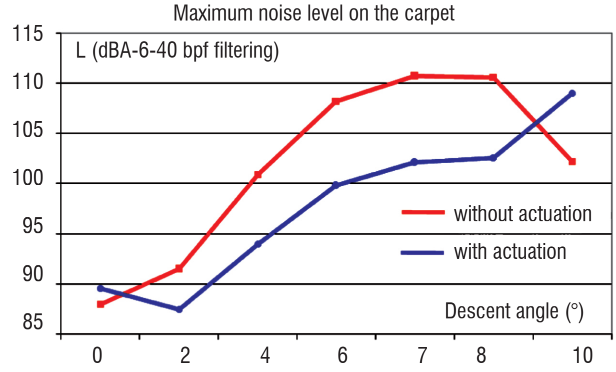

Figure 17 - Effect of actuated laws on maximum noise level

Vibration levels in forward flight estimated through the 3-per-rev in-plane moment and 4-per-rev vertical force (4-bladed rotor) were also be reduced using 3 to 5-per-rev actuations. Up to 100% reduction of the 4-per-rev vertical force was obtained.

These first benefit evaluations and twist actuation laws were demonstrated numerically, identifying the possible improvements achievable and identifying the proper actuation frequencies. The primary conclusion is that significant improvements can be obtained for noise and vibration, however only limited improvements of rotor power consumption can be expected. These improvements were obtained for different n-per-rev frequencies and, unfortunately, the actuation law for noise reduction was not of the same frequency as that required for vibration reduction.

Conclusion

Several applications of active flow control on helicopter airframes and on helicopter rotors have been presented. For non-rotating components, the objective is primarily the alleviation of flow separation region that can appear behind the rotor hub and in the fuselage back-door area, reducing the aircraft drag. This is achieved by applying unsteady blowing through slots. Numerical simulations show that a drag reduction benefit of approximately 15% can be expected. This figure has been confirmed by a wind-tunnel test on a simplified helicopter fuselage configuration. However, the dependence of the separation flow topology on the fuselage angle of attack has been identified, thus resulting in different control effectiveness. Very small time steps had to be used in the numerical simulations, in order to correctly account for the actuator influence. The typical time scales of the actuation are generally one or two orders of magnitude smaller than the time scale of the rotor rotation, which makes complete simulation challenging.

Applications on the main rotor were presented, considering the problem of dynamic stall control. A dedicated actuator based on deployable mechanical vortex generators was designed and tested on a pitching airfoil. Wind-tunnel tests show a very significant effectiveness of the device, with up to 40% of negative pitching-moment reduction. A 1-per-rev frequency actuation was applied to deploy the device on the retreating blade where dynamic stall occurs, while not affecting the flow on the advancing blade. Parametric investigations show that various compromises between maximum lift and minimum negative pitching moment peak can be obtained with a 1-per-rev actuation. Numerical simulations present good agreement with statically deployed VG, but only a small slice of the blade was considered. Taking into account numerous devices on a rotor blade in CFD simulations is a very challenging computational problem, due to the small length scales of the actuators in comparison to the dimension of a helicopter rotor blade. Simpler aerodynamic modeling was thus considered for the evaluation of other active technologies applied to helicopter rotor blades. Active flap and active twist investigations performed at Onera were presented. In these cases, the objective was not only an improvement of the aerodynamic performance, but also noise and vibration reduction. The embedded actuators in the blade influenced the flow by a direct action or through a desired aeroelastic response of the blade. Such technologies are required to account for the aerodynamic properties of the blade, as well as the structural dynamics properties of the rotor. To date, aeromechanic comprehensive codes have been used. Computations show that significant reduction of BVI noise (between -5 and -7dB) and of vibratory loads (20-100%) can be expected. These improvements are obtained by specific n-per-rev actuations with dedicated actuation laws for noise and vibration. Only limited improvements on the rotor power consumption could be obtained. A deeper insight into active blade benefit evaluation will be performed through completed experimental data from the STAR project (international cooperation in continuation of the HART and HARTII programs). Validation of active twist models and CSD/CFD coupling simulations will be required to confirm these benefit evaluations and the rotor aero-elastic behavior.

The helicopter is a favorable platform for the application of active flow control, with significant areas of possible performance improvements. However, the application of active flow technologies on the rotor can be challenging due to the time scales involved and the coupling with the blade motion and elastic response. Long-term research projects are therefore mandatory to improve the active flow control technologies, in order to implement them in a flight demonstrator and verify their effectiveness for certification ■

Acknowledgments

The authors would like to thank all of the Onera teams that have been involved in the activities described and in particular the colleagues who participated in the model design and manufacturing, the wind-tunnel test preparation and execution, and the experimental post-processing. The following colleagues are specifically thanked for the active blade studies: Hugues Mercier des Rochettes for the blade and actuation technology design, Italo Cafarelli and Philippe Leconte for the vibration computations and Yves Delrieux for the acoustics computations.

Acronyms

AoA (Angle of Attack)
BVI (Blade Vortex Interaction)
CFD (Computational Fluid Dynamics)
CSD (Computational Structural Dynamics)
DBD (Dielectric Barrier Discharge)
DVG (Deployable Vortex Generators)
HART (Higher harmonic Aeroacoustic Rotor Test)
HHC (Higher Harmonic Control)
HOST (Helicopter Overall Simulation Tool)
MFC (Macro Fiber Composite)
STAR (Smart Twisting Active Rotor)
TWISCA (TWIstable Section Closed by Actuation)
(U)RANS ((Unsteady) Reynolds-Averaged Navier-Stokes)
VG (Vortex Generator)

References

[1] B. ALLAN, N. SCHAEFFLER - *Numerical Investigation of Rotorcraft Fuselage Drag Reduction using Active Flow Control*. 67th American Helicopter Society Forum, Virginia Beach(VA), USA, 3-5 May 2011
[2] M. AMITAY, A. HONOHAN, M. TRAUTMAN, A. GLEZER - *Modification of the Aerodynamic Characteristics of Bluff Bodies Using Fluidic Actuators*. AIAA paper 97-2004, 1997
[3] S. G. ANDERS, W. L. SELLERS, A. WASHBURN - *Active Flow Control Activities at NASA Langley*. AIAA-2004-2623, 2nd AIAA Flow Control Conference, Portland, OR, June 28 – July 1, 2004
[4] E. ARAD, P. B. MARTIN, J. WILSON, and C. TUNG - *Control of Massive Separation on a Thick-airfoil Wing: A Computational and Experimental Study*. AIAA paper 2006-322, AIAA 44th Aerospace Sciences Meeting and Exhibit, Reno, NV, January 9-12, 2006
[5] J. BAILLY, Y. DELRIEUX, P. BEAUMIER - *HART II : Experimental Analysis and Validation of Onera methodology for the Prediction of Blade Vortex Interaction*. AHS International 61st Annual Forum, June 1-3 , 2005, Grapevine, Texas
[6] J. BAILLY, Y. DELRIEUX - *Improvement of Noise Reduction and Performance for a Helicopter Model Rotor Blade by Active Twist Actuation*. 35th European Rotorcraft Forum, September 22-25, 2009, Hamburg, Germany
[7] J. C. BONIFACE, G. JOUBERT, A. LE PAPE - *Passive Flow Control by Vortex Generators for some Internal and External Aerodynamics Configurations*. 48th International Symposium of Applied Aerodynamics, Saint Louis, France, March 25-27, 2013
[8] L. CATTAFESTA, M. SHEPLAK - *Actuators for Active Flow Control.* Annu. Rev. Fluid Mech., 2011, 43:247-272
[9] L. CARR, K. MCALISTER - *The Effects of Leading Edge Slaton the Dynamic Stall of an Oscillating Airfoil*. AIAA Paper 85-2533, Oct. 1983
[10] M. S. CHANDRASEKHARA - *A Review of Compressible Dynamic Stall Control Principles and Methods*. Proceedings of the Tenth Asian Congress of Fluid Mechanics May 17-21, 2004, Peradeniya, Sri Lanka
[11] M. CHANDRASEKHARA, M. WILDER, L. CARR - *Compressible Dynamic Stall Control Using Dynamic Shape Adaptation*. AIAA Journal, Vol. 39, No. 10, pp2021-2024, October 2001
[12] M. CHANDRASEKHARA, P. MARTIN, C. TUNG - *Compressible dynamic stall control using a variable droop leading-edge airfoil*. Journal of Aircraft, Vol.41, No4, pp 862-869, July-August 2004
[13] D. COLEMANN, F. THOMAS - *Rotorcraft Fuselage Flow Control Using Plasma Streamwise Vortex Generators*. 65th Annual Meeting on the APS Division of Fluid Dynamics, Volume 57, N°17, San Diego, CA, 18-20 November 2012
[14] 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*. AHS International 63rd Annual Forum, Virginia Beach (VA), USA, 1-3 May 2007

[15] M. GAD-EL HAK - *Flow Control: Passive, Active, and Reactive Flow Management.* Cambridge, UK: Cambridge Univ. Press
[16] M. GAD-EL HAK - *Separation Control: Review*. J. Fluids Eng, Vol. 113, Issue 1,5, March 1991
[17] W. GEISSLER, G. DIETZ, H. MAI, J. JUNKER - *Dynamic Stall Control Investigations on a Full Size Chord Blade Section*. 30th European Rotorcraft Forum, Marseille, France, 14-16 September 2004
[18] C. GLEYZES, X. DE SAINT-VICTOR, G. FALEMPIN - *Experimental and Numerical Study of the Flow around an Helicopter Fuselage*. Determination of Drag Coefficient, 15th European Rotorcraft Forum Proceedings, Amsterdam, The Netherlands, September 12-15, 1989
[19] A. GLEZER, M. AMITAY - *Synthetic jets*. Annual Review of Fluid Mechanics, Vol. 34, pp503-529, 2002
[20] D. GREENBLATT, I. WYGNANSKI - *The Control of Flow Separation by Periodic Excitation*. Progress in Aerospace Sciences, Vol.36 (2000), pp487-545
[21] D. GREENBLATT, I. WYGNANSKI - *Effect of Leading-Edge Curvature and Slot Geometry on Dynamic Stall Control*. AIAA 1st Flow Control Conference, St. Louis, MO, June 24-26, 2002
[22] G. JOUBERT, A. LE PAPE, S. HUBERSON - *Numerical Study of Flow Separation Control Over a OA209 Airfoil Using Deployable Vortex Generator*. 49th AIAA Aerospace Sciences Meeting, Orlando, FL, USA, January 4-7, 2011
[23] G. JOUBERT, A. LE PAPE, B. HEINE, S. HUBERSON - *Investigation of Dynamic Stall Control by Deployable Vortex Generator Using Time-Resolved PIV Analysis and URANS Computations*. 37th European Rotorcraft Forum, Italy, 13-15 September 2011
[24] R. D. JOSLIN - *Aircraft Laminar Flow Control.* Annual Review of Fluid Mechanics, Vol30, pp1-29, January 1998
[25] M. KARIM, M. ACHARYA - *Suppression of Dynamic Stall Vortices over Pitching Airfoils by Leading-Edge Suction*. AIAA Journal, Vol.32, N°8, pp1647-1655, August 1994
[26] A. LE PAPE, M. COSTES, F. RICHEZ, G. JOUBERT, F. DAVID AND J. M. DELUC - *Dynamic Stall Control Using Deployable Leading-Edge Vortex Generators*. AIAA Journal, Vol. 50, N°10, pp2135-2145, October 2012
[27] C. LIENARD, A. LE PAPE, C. VERBEKE - *Numerical and Experimental Investigation of Helicopter Fuselage Drag Reduction Using Active Flow Control*. American Helicopter Society 68th Annual Forum, Fort Worth, TX, May 1-3, 2012
[28] P. LORBER, B. HEIN, J. WONG, B. WAKE - *Rotor aeromechanics Results From the Sikorsky Active Flap Demonstration Rotor*. American Helicopter Society 68th Annual Forum, Fort Worth, TX, May 1-3, 2012
[29] J. MAGILL, K. MCMANUS - *Control of Dynamic Stall Using Pulsed Vortex Generators Jets*. AIAA paper 98-0675, 1998
[30] H. MAI, G. DIETZ, W. GEISSLER, K. RICHTER, J. BOSBACH, H. RICHARD, K. DE GROOT - *Dynamic Stall Control by Leading-Edge Vortex Generators*. Journal of the American Helicopter Society, Vol. 53, No1, January 2008, doi:10.4050/JAHS.53.26
[31] P. MARTIN, J. WILSON, J. BERRY, T. C. WONG, M. MOULTON, M. MC VEIGH - *Passive Control of Dynamic Stall*. 26th AIAA Applied Aerodynamics Conference, Honolulu, Hawaii, 18-21 August 2008
[32] P. MARTIN, C. TUNG, A. HASSAN, D. CERCHIE, J. ROTH - *Active Flow Control Measurements and CFD on a Transport Helicopter Fuselage.* 61st American Helicopter Society Forum, Grapevine, TX, June 1-3, 2005
[33] H. MERCIER DES ROCHETTES, D. JOLY, L. BUCHANIEK, P. LECONTE - *A New Concept of Active Twist Blade Applied to Main Rotor of Helicopter.* RTO-MP-AVT-168 Symposium, Paper 25, Evora, Portugal, April 20-24, 2009
[34] M. MC VEIGH, H. NAGIB, T. WOOD, I. WYGNANSKI - *Full-Scale Flight Tests of Active Flow Control to Reduce Tiltrotor Aircraft download*. Journal of Aircraft, Vol.48, N°3, May-June 2011, pp786-795
[35] T. NORMAN, C. THEODORE, P. SHINODA, D. FUERST, U. ARNOLD, S. MAKINEN, P. LORBER, J. O'NEILL - *Full-Scale Wind Tunnel Test of A UH-60 Individual Blade Control System for Performance Improvement and Vibration, Loads, And Noise Control*. American Helicopter Society 65th Annual Forum, Grapevine TX, May 27-29, 2009
[36] M. POLYCHRONIADIS, M. ACHACHE - *Higher Harmonic Control: Flight Tests of an Experimental System on SA 349 Research Gazelle*. American Helicopter Society 42nd Annual Forum, Washington, DC, USA, 2-4 June 1986
[37] M. POTSDAM, A. LE PAPE - *CFD investigations on a NACA0036 airfoil with active flow control*. AIAA 4th Flow Control Conference, AIAA-2008-3869, Seattle, WA, 23-26 June 2008
[38] M. POST, T. CORKE - *Separation Control Using Plasma Actuators: Dynamic Stall Vortex Control on Oscillating Airfoil*. AIAA Journal, Vol.44, No12, pp3125-3135, December 2006
[39] T. RENAUD, D. O'BRIEN, M. SMITH, M. POSDAM – *Evaluation of Isolated Rotor-Fuselage Interaction Using CFD*. AHS International 60th Annual Forum, Baltimore, Maryland, 7-10 June 2004
[40] N. SCHAEFFLER, B. ALLAN, C. LIENARD, A. LE PAPE - *Progress towards Fuselage Drag Reduction via Active Flow Control: a Combined CFD and Experimental Effort*. 36th European Rotorcraft Forum, Paris, France, 7-9 September 2010
[41] J. SEDDON - *Basic Helicopter Aerodynamics*. BSP Professional Books, 1990, p. 78
[42] C. SINGH, D. J. PEAKE, A. KOKKALIS, V. KHODAGOLIAN, F. COTON, R. GALBRAITH - *Control of Rotorcraft Retreating Blade Stall Using Air-Jet Vortex Generators.*Journal of Aircraft, 43(4):pp1169-1176, 2006, doi:10.2514/1.18333
[43] M. SMITH, J. LIM, B. VAN DER WALL, J. BAEDER, R. BIEDRON, D. BOYD, B. JAYARAMAN, S. JUNG, B.Y. MIN - A*n Assessment of CFD/CSD Prediction State-of-the-Art using the HARTII International Workshop Data*. American Helicopter Society 68th Annual Forum, Fort Worth, TX, May 1-3, 2012
[44] D. ROTH, B. ENENKL, O. DIETERICH - *Active Rotor Control by Flaps for Vibration Reduction - Full Scale Demonstrator and First Flight Test Results*. 32nd European Rotorcraft Forum, Maastricht, the Netherlands, September 2006
[45] W. SPLETTSTOESSER, R. KUBE, U. SEELHORST, W. WAGNER, A. BOUTIER, F. MICHELI, E. MERCKER, K. PENGEL - *Key Results from a Harmonic Control Aeroacoustic Rotor Test (HART), in the German-Dutch Wind Tunnel*. 21st European Rotorcraft Forum, St Petersburg, Russia, 30 August – 1st September 1995
[46] R. STROUB, L. YOUNG, R. GRAHAM, A. LOUIE - *Investigation of Generic Hub Fairing and Pylon Shapes to Reduce Hub Drag.* NASA-TM-100008, September 1987
[47] B. VAN DER WALL, C. BURLEY, Y. YU, K. PENGEL, P. BEAUMIER - *The HART II Test - Measurement of Helicopter Rotor Wakes"*. Aerospace Science and Technology, Vol.8 (4), June 2004, pp. 273-284
[48] B. VAN DER WALL, J. LIM , M. SMITH, S. JUNG, J. BAILLY, J. BAEDER, D. BOYD - *An Assessment of Comprehensive Code Prediction State-of-the-Art using the HARTII International Workshop Data.* American Helicopter Society 68th Annual Forum, Fort Worth, TX, May 1-3, 2012
[49] J. S. WILSON - *Turbulence Measurements on a 2D NACA0036 with Synthetic Jet Flow Control*. 62nd American Helicopter Society Forum, Phoenix, AZ, May 9-11, 2006
[50] G. WOO, A. GLEZER, J. BAIN, L. SANKAR - *Rotorcraft Fuselage Drag Reduction Using Combustion Power Actuators*. 49th AIAA Aerospace Sciences Meeting, AIAA-2011-34, Orlando, FL, 4-7 January 2011

Authors

Arnaud Le Pape graduated from the "Ecole Centrale de Nantes" in 2001 and has been working since then in the Applied Aerodynamics Department at Onera on helicopter and wind-turbine aerodynamics. His research includes experimental and numerical activities. Recently he has been leading the Onera/DLR SIMCOS project dynamic stall studies and its control.

Caroline Lienard graduated from the "Ecole Nationale Supérieure de Mécanique et d'Aérotechnique" in 2008. She joined Onera in the Applied Aerodynamics Department to work on helicopter drag reduction using active flow control.

Joelle Bailly graduated from the "Ecole Nationale Supérieure de Techniques Avancées" in 1991. She joined Onera in the Applied Aerodynamics Department and has been working in the helicopter field since then. Her research is focused in particular on numerical optimization methodology and active blade technology evaluation.