

NUMERICAL INVESTIGATION OF THE FLOW SEPARATION ON A HELICOPTER ROTOR IN DYNAMIC STALL CONFIGURATION

François Richez, francois.richez@onera.fr, ONERA (France)
Biel Ortun, biel.ortun@onera.fr, ONERA (France)

Abstract

Helicopter rotor blades in high thrust forward flight or in stiff maneuvers undergo dynamic stall. This phenomenon is due to complex unsteady three-dimensional flow separation mechanisms on the retreating blade that can lead to structural damage of the pitch links. The understanding and the accurate numerical prediction of dynamic stall are still challenging problems. In the continuity of previous studies focused on simplified configurations of 2D airfoil and 3D finite span wing, the dynamic stall on an isolated rotor in high thrust forward flight is investigated. A particular attention has been paid to the time and space resolution necessary to capture the stall phenomenon. The comparison with experiment in terms of section loads and pitching moments is in satisfactory agreement. The time evolution of the flow separation provided by the simulation is deeply analyzed and a scenario involving different stall mechanisms is proposed in order to explain the occurrence of the strong variations of loads and pitching moments on the retreating blade.

NOTATION

R	Rotor radius, m
c	Blade chord, m
b	Number of blade
S	Rotor disk area, πR^2
σ	Rotor solidity, bRc/S
Ω	Rotor angular velocity, rad/s
U_∞	Freestream velocity, m/s
ρ_∞	Freestream density, kgm^{-3}
a	Freestream speed of sound, m/s
μ	Advance ratio, $U_\infty/R\Omega$
F_Z	Rotor lift in the wind frame, N
F_X	Rotor propulsive force in the wind frame, N
C_L/σ	Rotor lift coefficient, $\frac{F_Z}{\rho_\infty(R\Omega)^2 S \sigma}$
C_X/σ	Rotor propulsive force coefficient, $\frac{F_X}{\rho_\infty(R\Omega)^2 S \sigma}$
$C_n M^2$	Section loads expressed in the local airfoil frame
$C_m M^2$	Section pitching moment expressed in the local airfoil frame
α_q	Shaft angle, deg
θ_0	Collective pitch angle, deg
θ_{1c}	Lateral cyclic pitch angle, deg
θ_{1s}	Longitudinal cyclic pitch angle, deg
θ_t	Torsion angle at blade tip, deg
ψ	Rotor azimuth, deg

r	Radial coordinate, m
τ_w	Wall shear stress, N.m^{-2}
C_f	Skin friction coefficient, $\frac{\tau_w}{0.5\rho_\infty(r\Omega + U_\infty \sin(\psi))^2}$
p	Pressure, Pa
C_p	Pressure coefficient, $\frac{p - p_\infty}{0.5\rho_\infty(r\Omega + U_\infty \sin(\psi))^2}$

INTRODUCTION

Dynamic stall is one of the most difficult aerodynamic problems encountered on helicopter rotors. It is also a very challenging flow phenomenon for the Computational Fluids Dynamics (CFD) community since it involves unsteady and separated turbulent flows. Dynamic stall can occur on the main rotor blades during maneuvers and high thrust forward flights. For these kinds of flight conditions, the equilibrium of the rotor requires to decrease the aerodynamic angle of attack of the advancing blade and to increase the angle of attack of the retreating blade. Thus, very high angles of attack can be reached on a large portion of the retreating blade side of the rotor disk, leading to a massive flow separation. This flow separation induces an increase of the drag, and as a consequence, of the fuel consumption. Dynamic stall also generates large pitching moment oscillations of the blade that are responsible for large pitch link load variations. To prevent any structural damage of the rotor due to dynamic stall, the flight envelope of helicopters is limited.

The complexity of dynamic stall encountered on helicopter rotor configurations led many authors to

first consider 2D airfoils at low frequency pitching motions [1]. Piziali has provided an extensive data base of a 2D NACA0015 airfoil in dynamic stall conditions [2] that has been massively used to assess predictive capabilities of different turbulence models of CFD codes [3][4][5][6]. More recently, several wind tunnel test campaigns have been devoted, at ONERA and DLR, to an OA209 airfoil, providing Particle Image Velocimetry (PIV) and unsteady wall pressure measurements [7][8]. These experimental data have been used in order to validate Unsteady Reynolds Averaged Navier-Stokes (URANS) simulation tools. The 2D OA209 stall case [7] allows some requirements to be defined in terms of turbulence modeling and grid resolutions [9][10]. An extensive analysis of the time resolution has been proposed by Liggett *et al.* for the case of VR7 airfoil in dynamic stall condition [12]. More recently, the configuration of an oscillating finite-span 3D wing has been investigated numerically [13][14][15] and validated with the experimental data of Ref. [8]. The wing is composed of a single OA209 airfoil, has a zero-twist law and an aspect ratio of 2.6. The numerical results showed a fairly good agreement with experiments and provided helpful insights into the dynamics of the flow separation around an oscillating 3D blade. In ref. [13], Costes *et al.* have identified that stall first occurs in the inner part of the blade, in the same way as what is observed in 2D case. A strong spanwise velocity then appears in the confined separated region close to the leading edge. The separation region finally spreads in the spanwise direction and contaminates the outer part of the blade, while the boundary layer close to the blade tip is kept attached during the whole dynamic stall cycle because of tip vortex induced flow.

Based on these 2D and 3D previous studies, this paper proposes to go further into the complexity of stall configuration and to investigate here a helicopter rotor flow in dynamic stall condition. The first experimental analysis of the characteristics of the dynamic stall on a full helicopter was done by Bousman, based on UH-60 flight tests [17]. More recently, some numerical simulations of dynamic stall on rotor configurations were investigated, first in 2006, by Potsdam *et al.* for a UH-60 flight test configuration [18] and more recently by Ortun *et al.* for the wind-tunnel 7A rotor [19]. These activities were mainly focused on the assessment of CFD tools for the prediction of loads. The objective of the present study is first to define requirements in terms of time and space resolutions necessary to accurately capture helicopter rotor stall by means of a coupled aeroelastic simulation, and then, to identify the flow separation mechanisms responsible of the loads and pitching moment oscillations of the retreating blade.

The paper is organized as follows. The flow configuration and the numerical methods are presented in the first section. In the second section, the influence of the time resolution, grid refinement and test-stand is investigated. The comparison with experiments provides the most suitable numerical parameters to capture satisfactorily the stall phenomenon on this rotor configuration. Finally, the numerical results are used in the last section to analyze the dynamics of the flow separation and propose a scenario of stall.

1. FLOW CONFIGURATION AND NUMERICAL METHODS

The flow configuration is taken from the 7A rotor data base, tested in the S1MA wind-tunnel of ONERA, in Modane (France) in 1991 (Fig. 1). This rotor of radius $R = 2.1$ m is composed of four articulated blades of constant chord $c = 0.14$ m. Dynamic stall has been experimentally observed for a forward flight condition at a moderate advance ratio $\mu = 0.3$ and a high lift coefficient $C_L/\sigma = 0.1$. This configuration is retained for the numerical investigation presented hereafter. The propulsive force coefficient is $C_X/\sigma = 0.0045$ and the rotor is trimmed in order to satisfy the Modane flapping law:

$$\beta_{1s} = 0 \text{ and } \beta_{1c} = -\theta_{1s}.$$

The rotor flow condition is summed up in Table 1. Unsteady pressure measurements were performed at four sections located at $r/R = 0.5, 0.7, 0.82, 0.92$ and 0.975 . These data will be used to validate the simulations.

The computations are performed with the *e/sA* solver which discretizes the URANS equations on structured multiblock grids with a finite-volume approach [20]. A Chimera technique is adopted, with near body curvilinear grids around each blade and a background Cartesian grid. The body meshes have an O-grid topology in the chordwise direction and extend over one chord from the blade wall. The Cartesian grid is made of several near matching blocks with different levels of resolution. The blocks closest to the body grids have a grid size length of $10\%c$.

Following the recommendations of the previous 2D [4][9][10] and 3D dynamic stall numerical studies [13][14][15], a $k-\omega$ SST turbulence model is chosen because of its satisfactory capability to capture boundary layer separation. No transition modeling is here involved although this may have an influence of dynamic stall, at least for moderate Mach and Reynolds numbers flows [10][11].

The time derivative is discretized with a second order implicit Gear scheme. At each time step, the non-linear problem is solved by an iterative Newton process.

The blade kinematics and deformations are taken into account by means of a weak coupling strategy between the *e/sA* solver and the HOST comprehensive code [21]. At each rotor revolution, the loads provided by the CFD are used by the HOST code to compute the trim control angles and the kinematics and deformations of the blades, which are, in return, used by *e/sA* to impose the motions and the deformations of the blade grids. The simulations are stopped once the rotor command angles reach an equilibrium state.

2. INFLUENCE OF THE NUMERICAL PARAMETERS

2.1. Temporal resolution

Liggett *et al.* performed a deep investigation of the influence of the time resolution for the prediction of 2D airfoil dynamic stall [12]. In the framework of an implicit second order time scheme, they have shown that the value of the (number of time steps per cycle) $\times$ (number of sub-iterations of the Newton iterative process) should be high enough to capture stall onset and flow reattachment. Other time convergence studies for 2D airfoil in dynamic stall conditions can also be found in ref. [9]. This study shows that temporal convergence can be reached for different number of time steps per period depending on the freestream velocity of the flow configuration. For a low freestream Mach number of 0.16 which is the more critical case considered in this reference, the authors found that 18000 time step per cycle and 20 Newton sub-iterations were necessary to ensure convergence.

The C3003D finite-span wing dynamic stall configuration investigated in references [13], [14] and [15] was performed with 18000 time steps per cycle and 35 Newton sub-iterations for ONERA-*e/sA* simulations, 18000 time steps/cycle and 40 dual-time steps for AFDD-OVERFLOW simulations and 1500 time steps/cycle and 300 inner-iterations for DLR-TAU simulations, with satisfactory agreement with experimental data in each case.

For a rotor configuration, this kind of temporal resolution is not affordable because of computational cost reasons. Based on previous rotor simulation studies [19] where no dynamic stall was involved, the azimuthal time step is set to $\Delta\psi = 0.3^\circ$. As shown in Table 2, this corresponds to 1200 time steps per cycle which is one order of magnitude lower than what was required for the C3003D finite-span wing case.

The influence of the number of sub-iterations of the Newton process has been investigated for the isolated rotor configuration (without test-stand) and using a medium grid defined as M1 in Table 3. Two values of the number of sub-iterations are considered: $N_{sub} = 10$ and $N_{sub} = 30$. For each

case, the *e/sA*/HOST coupling process has been carried on until convergence of the coupling. As shown in Fig. 2, the number of sub-iterations does not change the final trim control angles. Fig. 3.a and Fig. 3.b show the azimuthal evolutions of the sections loads for two radial positions of the blade, while Fig. 3.c and Fig. 3.d show the section pitching moments at the same positions. The experimental curves indicates that stall occurs on these two sections for $220^\circ \leq \psi \leq 330^\circ$. In this range of azimuth angle, N_{sub} parameter has no significant effect on the numerical prediction of section loads (Fig. 3.a and Fig. 3.b). Despite a good agreement on $C_n M^2$, the two simulations give very different predictions of the pitching moment in this azimuthal region of the rotor disk and for both the inner (Fig. 3.c) and outer (Fig. 3.d) sections. This result undoubtedly highlights the strong sensitivity of dynamic stall prediction with respect to the temporal resolution of the simulation. This temporal convergence study has not been investigated further because of the computational cost of such simulations. However, it is considered that the features of dynamic stall in terms of lift and pitching moment variations are satisfactorily captured with $\Delta\psi = 0.3^\circ$ and $N_{sub} = 30$. These parameters are thus set to these numerical values in the rest of this paper.

2.2. Test-stand

In order to quantify the influence of the test-stand on the rotor loads, a simulation has been performed taking into account the geometry of the test-stand that is shown in Fig. 1. The numerical results of this simulation have been published by Ortun *et al.* [19] but with no comparison of the results of the isolated rotor. The section loads and pitching moments obtained with and without test-stand are presented in this section to quantitatively estimate the effect of the test-stand. The body grids, numerical methods, time steps and number of sub-iterations are strictly identical in both cases. The backward Cartesian grid is built in different ways whether the test-stand is considered or not, but the grid size length is imposed to 10%c around the body grids in both cases, so that it is reasonable to assume that the only difference between the two simulations is the effect of the test-stand.

The trim control angles obtained with and without test-stand are compared in Fig. 4. While the shaft angle, collective pitch angle and longitudinal cyclic pitch angle are almost unchanged, the lateral cyclic pitch angle θ_{1c} is significantly increased, from 2.2° to 3.3° , when the test-stand is taken into account. Indeed, the mean effect of the test-stand is to deflect the freestream flow upward on the front side of the rotor disk ($90^\circ \leq \psi \leq 270^\circ$) which increases the angle of attack of the blade. The lateral pitching

angle θ_{1c} is thus increased, in order to decrease the pitch angle at $\psi = 180^\circ$ and then compensate the flow deflection due to the test-stand.

The effect of the test-stand on the section loads are presented in Fig. 5. The evolution of $C_n M^2$ is very similar between the two simulations except on the advancing blade region. The typical drop of lift that occurs around $\psi = 130^\circ$ is underestimated when the test-stand is not taken into account while it is remarkably well-captured in the other case. The test-stand also has an impact on the retreating blade side where stall occurs but well less significantly.

Thus, it is decided to assume that the test-stand does not crucially affect dynamic stall on the retreating blade and can be removed for simplicity in the following of this paper.

2.3. Grid resolution

Stall phenomenon is very sensitive to grid resolution. Grid convergence studies for 2D airfoil [9] [16] and 3D finite-span wing [13][14][15] stall provide some requirements in terms of spatial resolution that are used as reference for the grid generation of the isolated rotor case investigated in this paper. The grid resolution parameters of the C3003D finite span wing taken from ref. [14] are gathered in Table 3. The near-wall grid cell sizes made non-dimensional with respect to the chord are not directly comparable to the ones of the rotor configuration because the flow parameters (Reynolds and Mach numbers) are different. They are however indicated in Table 3 to give an order of magnitude of the number of points in each direction, used in each case. Δx , Δy and Δz denote the near-wall cell sizes respectively in chordwise, wall-normal and radial directions. The superscript + is used when the cell sizes are expressed in wall unit, i.e. made non-dimensional with respect to the turbulent length scale ν/u_τ where ν is the kinematic viscosity and u_τ the friction velocity. Two different blade meshes have been generated for the isolated 7A rotor case. The first one, called M1, is composed of 3.1 million points per blade and the second one, called M2, is composed of 5.7 million points per blade. The total number of points including the body grids of the four blades and the backward Cartesian grid is 22.6 million points for M1 and 43.6 million points for M2.

The first main refinement of M2 with respect to M1 consists in reducing the wall mesh size in the chordwise direction, especially near the leading edge where the adverse pressure gradient is particularly strong when stall is about to occur. The initial M1 mesh was always coarser than the reference C3003D wing by a factor five: $\Delta x/c = 0.23\%$ at the leading edge and 2.6% at mid chord vs. 0.05% and 0.45% for the C3003D. M2 mesh refinement reduces this factor to 2 at the leading edge (0.11% vs. 0.05%) and 3.5 at mid chord (1.6%

vs. 0.45%). The grid chordwise sizes are also expressed in wall unit for a section located at $r/R=0.8$ in Table 3. The refinement of M2 finally reduced Δx^+ from 1300 to 800 at mid chord vs. 300 for the reference C3003D case.

A refinement in the wall normal direction has also been performed with M2 mesh in order to reduce Δy^+ that could reach 1.5 with M1 to a lower value of 0.4. This also allows to slightly increase the number of cells inside the boundary layer (35 vs. 30).

The last refinement concerns the radial direction. M1 mesh keeps constant the cell spacing in the radial direction with a value of $\Delta z = 13\%$. In M2 mesh, Δz is slightly increased in the inboard section ($r/R < 0.5$) and significantly decreased elsewhere in order to reach $\Delta z = 5.6\%$ at $r/R = 0.8$. This allows to reduce Δz^+ by a factor two and reach the requirement of ref. [13], $\Delta z^+ \leq 3000$, at least at mid chord.

The trim control angles obtained with M1 and M2 meshes are first compared to the experiment data and HOST stand-alone results in Fig. 6. As observed for the time convergence study in section 2.1, the grid resolution also has no noticeable effect on the trim control angles.

The section loads and pitching moments with M1 and M2 meshes are compared to the experimental measurements and the HOST stand-alone results respectively in Fig. 7 and Fig. 8. The evolution of $C_n M^2$ is in fairly good agreement with experiments for both meshes except on the advancing blade side. The discrepancy between CFD and experiment in this azimuthal region of the rotor disk is due to the effect of the test-stand, as shown previously in section 2.2. For the region of interest, i.e. the retreating blade side where dynamic stall occurs, the discrepancy between CFD and experiment is weak. The drop of $C_n M^2$ due to dynamic stall is quite well-captured by CFD, while HOST stand-alone simulation completely misses the large amplitude of the lift variations, especially for the most outboard sections. On CFD side, the grid refinement improves the prediction of minimum $C_n M^2$. The agreement between M2 simulation and experiment is almost perfect at $r/R = 0.7$ and $r/R = 0.82$. For sections $r/R = 0.92$ and $r/R = 0.975$, M2 mesh provides lower minimum values than M1, although still overestimated compared to experiments.

On pitching moments (Fig. 8), HOST results give no variation due to dynamic stall. CFD results however provide oscillations of $C_m M^2$ which are more or less in good agreement with experiments depending on the sections. As observed for $C_n M^2$ curves of Fig. 7, the grid refinement improves the prediction of the pitching moment. At mid span ($r/R = 0.5$), the phase when moment stall occurs and its minimum value are better captured with M2. At sections $r/R = 0.7$ and $r/R = 0.82$, both CFD results give poor agreement of the $C_m M^2$ with

experiment, although some variations appear around the azimuthal range where moment stall is experimentally observed. At section $r/R = 0.92$, the pitching moment drop is the most important in both CFD and experiment. The numerical simulation with M1 mesh predicts a delayed moment stall and overestimates the minimum CmM^2 value. The grid refinement of M2 mesh makes stall occur earlier, getting closer to the experimental observation, although a slight delay is still noticeable. The minimum value of CmM^2 reached at stall is significantly reduced with M2 and in good agreement with experiment. On the tip section (Fig. 8.e), the small negative CmM^2 peak that occurs at $\psi = 290^\circ$ is completely missed by M1 simulation. With M2 mesh, this phenomenon is numerically recovered. However, the minimum pitching moment value is reached at a higher azimuthal angle compared to experiment.

Fig. 9 shows the effect of grid refinement on the blade tip torsion angle. M2 mesh provides stronger variation of the torsion angle, especially on the retreating blade side. The maximum peak-to-peak value that is reached for $270^\circ \leq \psi \leq 360^\circ$ is 1.1° with M2 vs. 0.6° with M1. No experimental measurements of the tip torsion are unfortunately available to validate the CFD predictions.

Because of its better prediction of the section loads and pitching moments, the numerical results with M2 mesh will be considered for the analysis of the flow separation of dynamics stall in the next section.

3. FLOW SEPARATION

3.1. Moment and lift stall positions

Following the analysis of the dynamic stall on the UH-60 flight tests of Bousman [17] and the analysis of the numerical simulation of Potsdam *et al.* [18], the positions of moment stall and lift stall occurrences are represented in the rotor disk in Fig. 10. Only the retreating blade side of the rotor disk is shown for clarity reasons. The moment stall (respectively lift stall) is arbitrarily defined as the time when CmM^2 (respectively CnM^2) reaches a local minimum value. The experimental results are shown in red and the numerical results (with M2 mesh resolution) in green. Moment stall is represented with circle symbols, and lift stall with triangles. The stall positions are only indicated in the sections $r/R = 0.5, 0.7, 0.82, 0.92$ and 0.975 where experimental data are available. Iso-contours of CnM^2 and CmM^2 coming from CFD are also shown in grey scale on Fig. 10.a and Fig. 10.b respectively. Moment stall always occurs prior to lift stall whether in CFD or in experiment. This is consistent with most of the non-rotating 2D airfoils and 3D wings dynamic stall investigations that can be found in the literature

(see [9][13] for instance). The position of lift stall is fairly well predicted by CFD. Some discrepancies seem to appear for the most inboard section $r/R = 0.5$, but, when looking at Fig. 7.a, one can see that the simulation is in very good agreement for this section. The discrepancy is due to the fact that the variation of lift is very smooth and that the minimum lift value is reached on a flat region. Thus, the exact azimuth angle where minimum is reached can differ between experiment and simulation at this section although a good agreement is observed.

However, more discrepancies appear on the position on moment stall. In the simulation, the phase difference between moment and lift stall decreases continuously with the blade span position r/R . In the experiment, the phase difference decreases faster than the simulation from $r/R = 0.5$ to $r/R = 0.82$. Then, from $r/R = 0.82$ to $r/R = 0.92$, the phase difference between moment and lift stall first increases, and then decreases from $r/R = 0.92$ to $r/R = 0.975$ where a value of 8° is obtained vs. 3° in the simulation.

This is consistent with the observation of Fig. 8.d and Fig. 8.e discussed in section 2.3. It appears that moment stall is slightly delayed by the simulation in the tip region of the blade, although the grid refinement of M2 improves the prediction of moment stall position compared to M1.

Despite some discrepancies still exist between experimental data and M2 numerical results (mainly a slight phase shift of the moment stall), the complex evolution of sections loads and pitching moments can be considered as fairly well captured by CFD when using the fine M2 grid. Thus, these numerical results will be deeply analyzed in the next section for a better understanding of the flow separation mechanisms that leads to these strong variations of loads.

3.2. The three regions of stall

Fig. 11 aims at making a correlation between the moment and lift stall positions and the extent of the flow separation on the upper side of the blade. The iso-contours of the figure represent the distance x_{sep} between the separation point and the leading edge of the blade. This is computed from the numerical results at each radial section of the blade at each azimuthal angle, thus providing a rotor map of the separation extent. The detection of boundary layer separation when considering unsteady and 3D flow is not a trivial problem. The length x_{sep} has been here simply defined as the chordwise position where the shape factor H_i is greater than a critical value arbitrarily set to 2.7. The rotor map of x_{sep}/c thus obtained is compared to the positions of moment and lift stall in Fig. 11. Three different regions of stall clearly appear on this rotor map:

- The first one concerns the inboard part of the blade ($0.5 \leq r/R \leq 0.8$) and is mainly located in the third quarter of the rotor disk.
- The second one is located in the outboard part of the blade ($0.9 \leq r/R \leq 0.95$) and for $270^\circ \leq \psi \leq 320^\circ$.
- The third one appears on the outboard part of the blade, as previously, but in the azimuthal region $340^\circ \leq \psi \leq 360^\circ$.

The skin friction coefficient and the friction lines are shown in Fig. 12.a on the retreating blade at several azimuthal positions in order to help to the analysis of Fig. 11. The pressure coefficients on the blade at the same azimuth angles are also shown in Fig. 12.b.

In the first stall region, Fig. 11 seems to indicate that the flow separation starts at $\psi = 180^\circ$ in a small radial part located at mid-span. This separation first appears in the trailing edge region and moves upstream in the chordwise direction to finally reach the leading edge at $\psi = 230^\circ$. At the same time as the separation moves from the trailing edge to the leading edge on the section $r/R = 0.5$, it also spreads in the spanwise direction, from root to tip. When separation reaches the leading edge at $r/R = 0.5$ ($\psi = 230^\circ$), moment stall occurs. Then later, moment stall reaches sections $r/R = 0.7$ and $r/R = 0.82$ when the separation region extends up to 30% ($x_{sep}/c = 0.7$). This separation length might appear as small, and is probably underestimated by CFD. This would explain the underestimation of the stall strength for the sections $r/R = 0.7$ and $r/R = 0.82$ observed in Fig. 8.b and Fig. 8.c. Fig. 11 indicates that lift stall occurs where the flow has already started to reattach to the wall. Both skin friction and pressure coefficients of Fig. 12 confirm the conclusion of Fig. 11. A cell of flow separation first appears in the trailing edge region around $r/R = 0.5$. From $\psi = 200^\circ$ to $\psi = 270^\circ$ the separation point moves step by step toward the leading edge. This separation region is not only located around $r/R = 0.5$. It extends up to $r/R = 0.9$ but the separation length progressively decreases when r increases. The section $r/R = 0.92$ seems to be never affected by this first stall region that starts from the inner part of the blade. According to the categorization of stall types than can be found in the literature (for instance in ref. [22]), one can characterize this first stall region as a so-called “trailing edge stall” region, since the flow separation moves progressively from the trailing edge to the leading edge of the blade.

The second stall region visible on Fig. 11 concerns a thin radial region of the blade around $r/R = 0.92$. Unlike the first stall region, the separation seems here to abruptly occur at the leading edge. Indeed, x_{sep}/c discontinuously varies from 1 to 0 as a

function of the azimuth angle. Furthermore, the discontinuity of x_{sep}/c in the radial direction tends to confirm the assumption that this stall region is not a contamination of the inboard stall region but an independent stall phenomenon. This stall region also corresponds to the region where the maximum variations of section lift and pitching moment have been observed both experimentally and numerically (Fig. 7.d and Fig. 8.d). The friction lines of Fig. 12.a confirms that a localized separation cell suddenly appears at the leading of the blade for $0.85 \leq r \leq 0.95$ around $\psi = 294^\circ$. This separation cell leads to a decrease of the pressure in the leading edge region of the blade (Fig. 12.b) that causes moment stall. Following the categorization terminology of ref. [22], this stall can be defined as a so-called “leading edge stall”. This stall mainly affects the section $r/R = 0.92$. This corresponds to the section where the largest variations of pitching moment are observed in Fig. 8. The last section ($r/R = 0.975$) also undergoes variations of lift and pitching moment due to stall but with a lower intensity. Friction lines of Fig. 12.a shows that this last section is contaminated by the massive flow separation that occurs on section $r/R = 0.92$. This contamination only affects the rear part of the blade at $r/R = 0.975$, which explains why $C_m M^2$ variation at $r/R = 0.975$ is lower than the one observed at $r/R = 0.92$ and why the pitching moment is here almost never negative.

Finally, referring to Fig. 11, a third region where separation seems to reach the leading edge appears around $r/R = 0.92$ and in the azimuthal region $340^\circ \leq \psi \leq 360^\circ$. In this region of the disk rotor, the experimental data of Fig. 7.d and Fig. 7.e only show a very small oscillation of $C_n M^2$ while numerical results does not. However, the pitching moment of both experiment and simulation of Fig. 8.e provides some fluctuations for $340^\circ \leq \psi \leq 360^\circ$ than can be associated to this third stall region. A careful look at Fig. 12.a confirms an abrupt change of friction lines direction very close to the leading edge. In this region of the rotor risk, the relative Mach number is high and close to the tip Mach number $M_{tip} = R\Omega/a = 0.646$. Furthermore, the aerodynamic angle of attack is likely to be high because of the action of both the torsion (Fig. 9) and the positive lateral cyclic pitch angle (Fig. 6). Fig. 13 indeed shows that a large supersonic region extending along the chord appears for $340^\circ \leq \psi \leq 360^\circ$, exactly where separation is observed in the rotor map of Fig. 11. Thus, it can be expected that this part of the blade undergoes a so-called “shock stall” where separation is induced by the interaction of a shock-wave with the boundary layer. For this high Mach number, the lift is known to reach a plateau instead of decreasing at the stall angle, which can explain the lack of fluctuations on the $C_n M^2$ in Fig. 7.d and Fig. 7.e.

CONCLUSION

The dynamics stall of the isolated 7A rotor in moderate speed and high thrust forward flight has been numerically investigated. A weak coupling strategy between *e/sA* CFD code and HOST mechanics code has been employed. A deep attention has been paid to the influence of the time and space resolution and to the influence of the test-stand on the numerical results. The numerical parameters in terms of space and time resolution are compared to the requirements of previous numerical investigations of stall phenomena for simpler configurations of 2D airfoils and 3D finite span wings.

The simulation with suitable mesh refinement and temporal scheme parameters provides very satisfactory results by comparison with the experimental data in terms of section loads and pitching moments.

A deep analysis of the dynamics of the flow separation allows assuming the existence of three different stall regions on the rotor disk. The first one concerns the inner part of the blade, occurs in the third quarter of the rotor disk and is of "trailing edge stall" type. The second one occurs close to the blade tip at the beginning of the fourth quarter of the rotor disk and is of "leading edge stall type". The third one is likely a "shock stall" and appears close to the tip of the rear blade.

REFERENCE

- [1] McCroskey, W. J., McAlister, K. W., Carr, L. W., and Pucci, S. L., "An Experimental Study of Dynamic Stall on Advanced Airfoil Sections", NASA TM 84245, 1982.
- [2] Piziali, R., "2D and 3D oscillating wing aerodynamics for a range of angle of attack including stall", Technical Memorandum 4632, National Aeronautics and Space Administration, USA, 1994.
- [3] Srinivasan, G. R. and Ekaterinaris, J. A. and McCroskey, W. J., "Dynamic stall of an oscillating wing", AIAA Paper 93-3403, 1993.
- [4] Ekaterinaris, J. A. and Menter, F. R., "Computation of oscillating airfoil flow with one- and two-equation turbulence models, AIAA Journal, Vol. 32, pp. 2359-2365, 1994.
- [5] Sankar, L., Zibi-Bailly, J., Le Balleur, J.-C., Blaise, D., Rouzaud, O., Rhee, M., "A comparative study of three methodologies for modeling dynamic stall", 28th European Rotorcraft Forum, Bristol, UK, 2002.
- [6] Szydlowski, J. and Costes, M., "Simulation of flow around a static and oscillating pitch NACA0015 airfoil using URAND and DES, ASME Transfer/Fluids Engineering Summer Conference, Charlotte, US, 2004.
- [7] Pailhas, G., Houdeville, R., Barricau, P. Le Pape, A., Loiret, P., David, F., "Experimental investigation of dynamic stall", 31th European Rotorcraft Forum, Florence, Italy, 2005.
- [8] Le Pape, A., Pailhas, G., David, F., and Deluc, J.-M., "Extensive wind Tunnel Measurements of Dynamic Stall Phenomenon for the OA209 Airfoil Including 3D Effects," 33rd European Rotorcraft Forum Proceedings, Kazan, Russia, September 11–13, 2007.
- [9] Richter, K., Le Pape, A., Knopp, T., Costes, M., Gleize, V., Gardner, A., "Improved Two-Dimensional Dynamic Stall Prediction with Structured and Hybrid Numerical Methods", Journal of the American Helicopter Society, Vol. 56, No. 4, October 2011. doi:10.4050/JAHS.56.042007.
- [10] Costes, M., Gleize, V., Le Pape, A., Richez, F., "Numerical investigation of laminar/turbulent transition effects on the dynamic stall of an oscillating airfoil", AHS Specialists Conference, San Francisco, CA, USA, January 2008.
- [11] Richez, F., Mary, I., Gleize, V., Basdevant, C., "Simulation and modelling of a laminar separation bubble on airfoils", IUTAM Bookseries, pp. 457-469, 2009.
- [12] Liggett, N. and Smith, M., "Temporal Convergence Criteria for Time-Accurate Viscous Simulations of Separated Flows, Computers and Fluids, Vol. 66, 2012, pp. 140-156.
- [13] Costes, M., Richez, F., Le Pape, A., Gavériaux, R., "Numerical investigation of three dimensional effects during dynamic stall", Aerospace Science and Technology, Vol. 44, 2015, pp. 216-237.
- [14] Kaufmann, K., Costes, M., Richez, F., Gardner, A. D., Le Pape, A., "Numerical Investigation of Three-Dimensional Static and Dynamic Stall on a Finite Wing", Journal of American Helicopter Society, Vol. 60, No. 3, 2015.
- [15] Jain, R., Le Pape, A., Costes, M., Richez, F., Smith, M., "High-resolution CFD Predictions for Static and Dynamic Stall of a Finite-span OA209 Wing, 72nd AHS Annual Forum, West Palm Beach, Florida USA, May 2016.
- [16] Costes, M., Gleize, V., Szydlowski, J., Sankar, L. Guzel, G., Rhee, M., "Grid sensitivity study for the turbulent viscous flow around a NACA 0015 airfoil at stall", 45th AIAA Aerospace Sciences Meeting and Exhibit Reno, Nevada, January 2007, <http://dx.doi.org/10.2514/6.2007-1082>.
- [17] Bousman, W., "A Qualitative Examination of the Dynamic Stall from Flight Test Data", 53rd AHS Annual Forum, Virginia Beach, VA, USA, May 1997.
- [18] Potsdam, M., Yeo, H., and Johnson, W., "Rotor Airloads Prediction Using Loose Aerodynamic/Structural Coupling", Journal of Aircraft, Vol. 43, No. 3, May-June 2006, pp. 732-742.
- [19] Ortun, B., Potsdam, M., Yeo, H., "Rotor Loads Prediction on the ONERA 7A using Fluid/Structure

Coupling", 72nd AHS Annual Forum, West Palm Beach, Florida USA, May 2016.

[20] Cambier, L., Heib, S., Plot, S., "The ONERA elsA CFD software: input from research and feedback from industry", *Mechanics & Industry*, Vol. 14 No. 3, pp. 159-174, 2013.

[21] Benoit, B., "HOST A General Helicopter Simulation Tool for Germany and France", 56th Annual Forum of the Helicopter Society, Virginia Beach, VA, USA, 2000.

[22] G. B. McCullough and D. E. Gault. "Examples of three representative types of airfoil section stall at low speed", NACA TN2502, 1951.



Fig. 1. Picture of 7A rotor in the S1MA wind-tunnel.

Air density, ρ (kg/m ³)	1.018
Temperature, T (°C)	27.9
Rotor speed, Ω (rpm)	1022
Tip Mach number, $M_{tip} = R\Omega/a$	0.646
Advance ratio, μ (-)	0.3
Rotor lift coefficient C_L/σ (-)	0.1
Rotor propulsive force coefficient C_X/σ (-)	0.0045

Table 1. Rotor flow conditions

	7A rotor	C3003D blade [13]
Number of time steps per period	1200	18000
Number of sub-iterations	30	35

Table 2. Time resolution of the rotor simulation compared to the C3003D blade simulation of ref. [13].

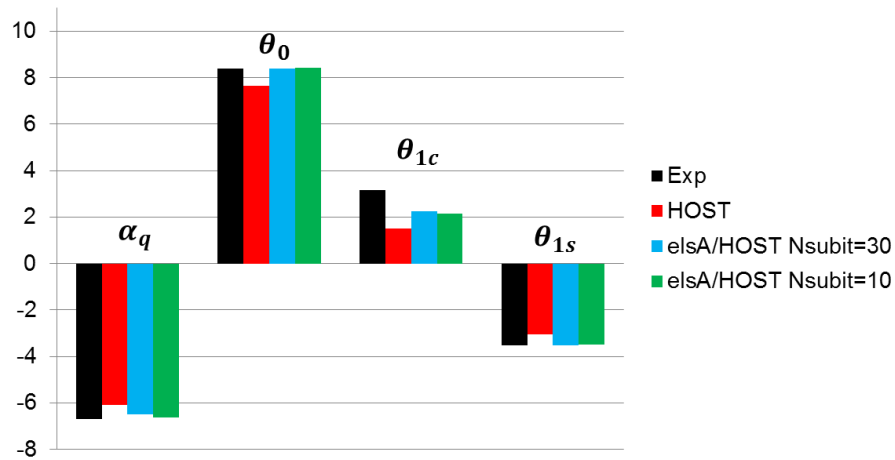
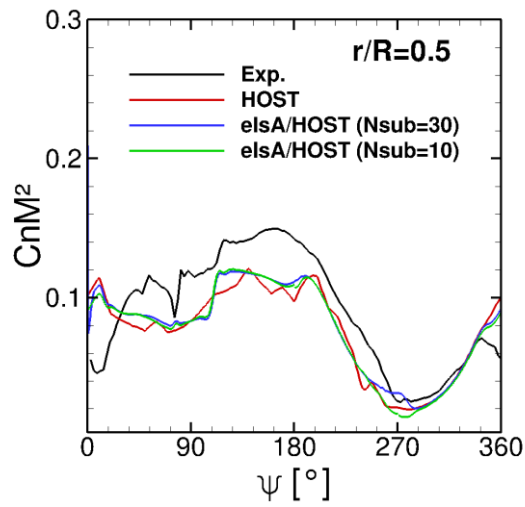
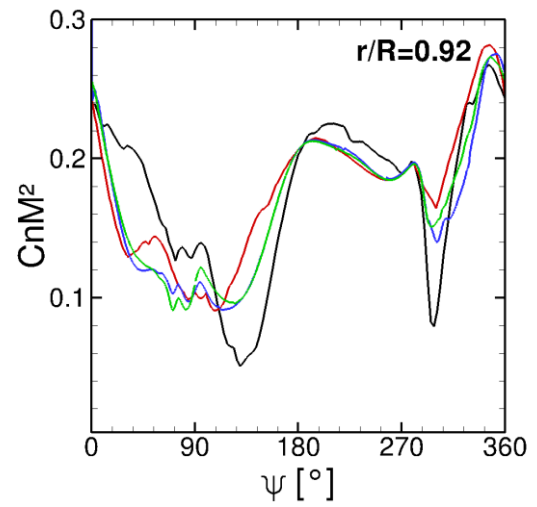


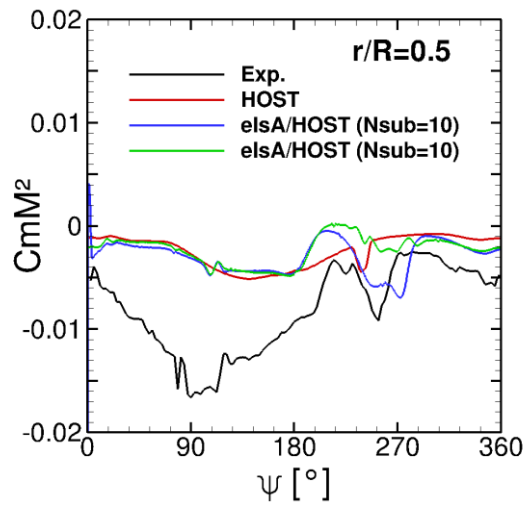
Fig. 2. Influence of the time refinement on the trim control angles (black: experiment, red: HOST, blue: elsA/HOST with 30 sub-iterations, green: elsA/HOST with 10 sub-iterations).



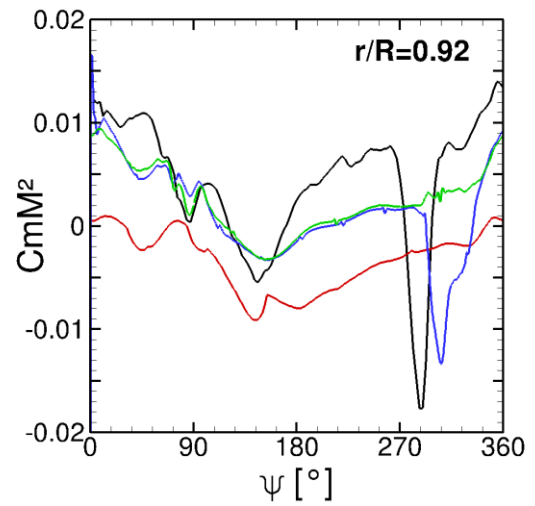
a) Section loads at $r/R=0.5$



b) Section loads at $r/R=0.92$



c) Section pitching moment at $r/R=0.5$



d) Section pitching moment at $r/R=0.92$

Fig. 3. Section loads $C_n M^2$ for the section $r/R=0.7$: Experiments (black), HOST (red), elsA/HOST coupling with 30 (blue) and 10 (green) sub-iterations of the Newton process with a time step of $\Delta\psi = 0.3^\circ$.

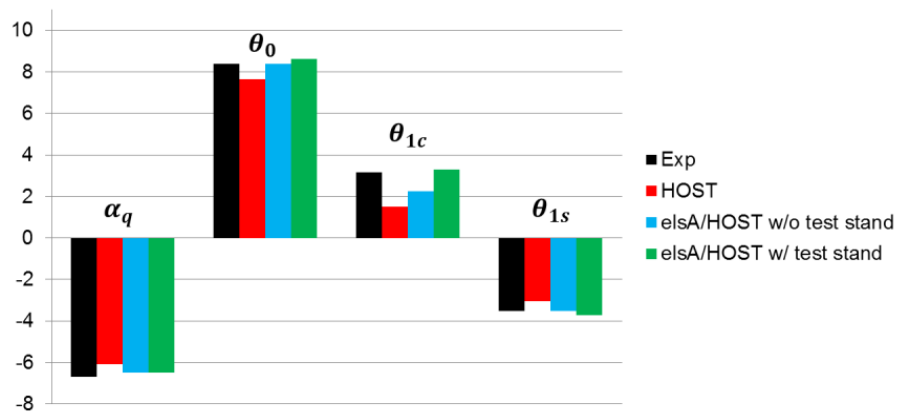


Fig. 4. Influence of the test stand on the trim control angles (black: experiment, red: HOST, blue: elsA/HOST without the test stand, green: elsA/HOST with the test stand).

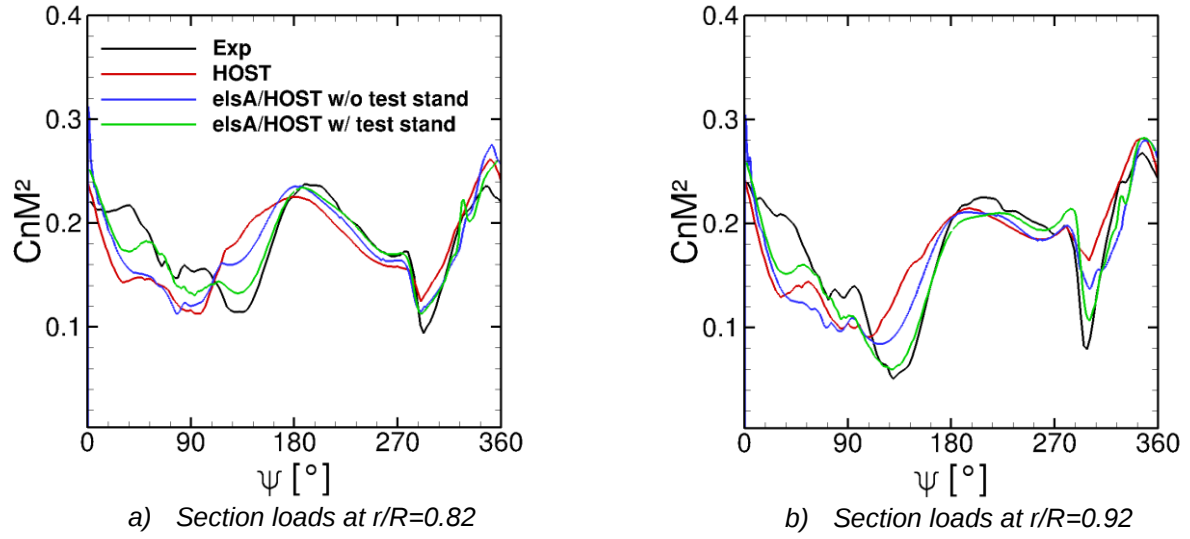


Fig. 5. Section loads CnM^2 : Experiments (black), HOST (red), elsA/HOST coupling with (green) and without (blue) the test stand (medium grid, time step $\Delta\psi = 0.3^\circ$ and 30 Newton sub-iteration).

	7A rotor M1	7A rotor M2	C3003D blade [13]
Number of points per blade grid	3.1 M	5.7 M	
Total number of points	22.6 M	43.6 M	
N around airfoil	217	313	977
N over the blade span	141	155	
$\Delta x/c$ at leading edge	0.23%	0.11%	0.05%
$\Delta x/c$ at mid chord	2.6%	1.6%	0.45%
$\Delta z/c$	13%	5.6%	2.3%
$\max(\Delta y^+)$	1.5	0.4	0.6
N in the boundary layer at mid chord	30	35	35-50
Δx^+ at leading edge	230	130	≤ 300
Δx^+ at mid chord	1300	800	≤ 300
Δz^+ at leading edge	14000	7000	≤ 3000
Δz^+ at mid chord	6000	3000	≤ 3000

Table 3. Comparison of the spatial resolution between the 7A rotor medium mesh M1, the 7A rotor fine mesh M2 and the C3003D mesh of ref. [13].

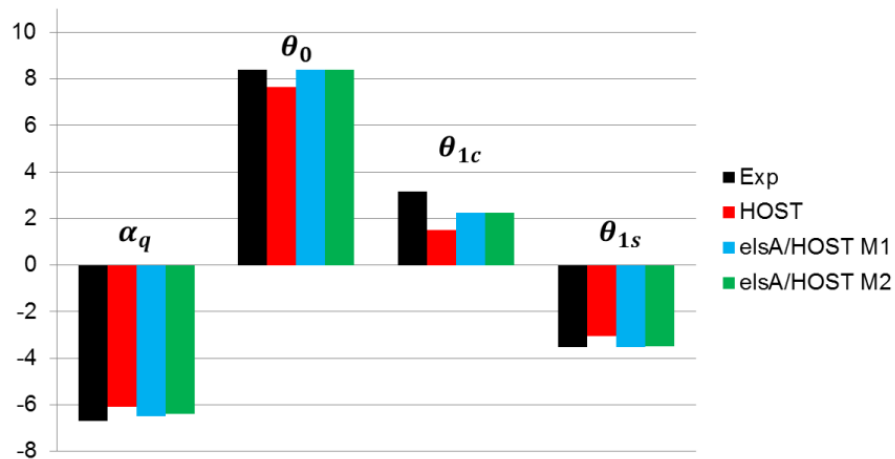
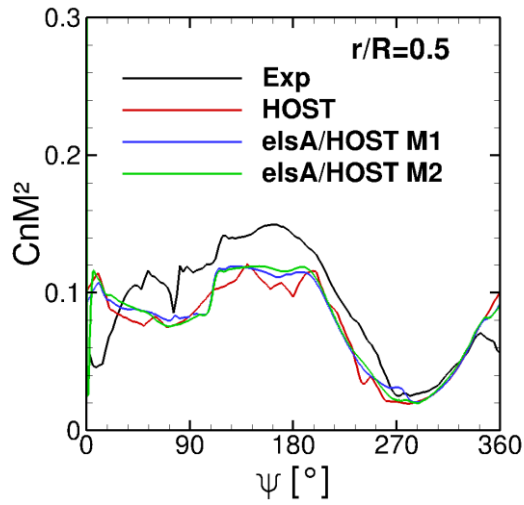
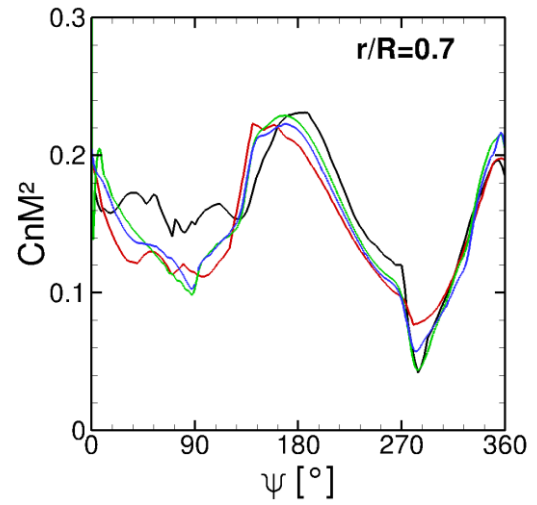


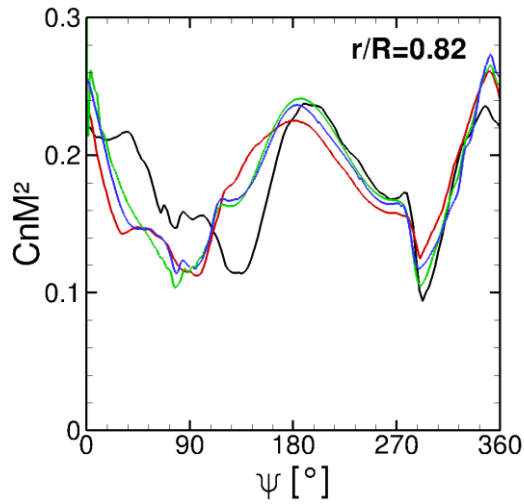
Fig. 6. Influence of the grid resolution on the trim control angles (black: experiment, red: HOST, blue: elsA/HOST with medium mesh M1, green: elsA/HOST with fine mesh M2).



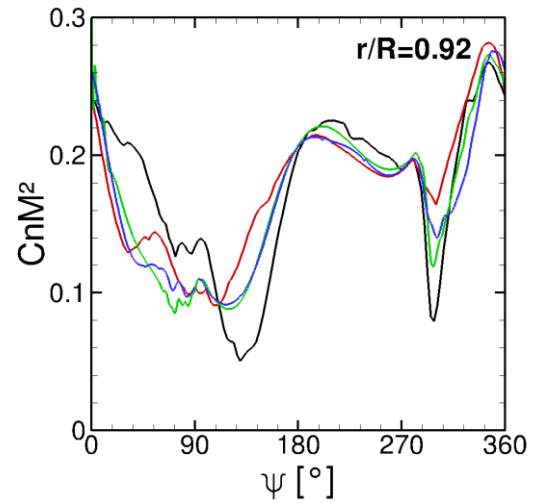
a) Section loads at $r/R=0.5$



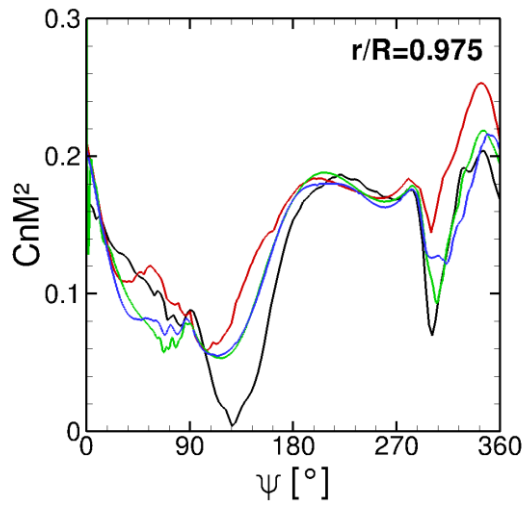
b) Section loads at $r/R=0.7$



c) Section loads at $r/R=0.82$

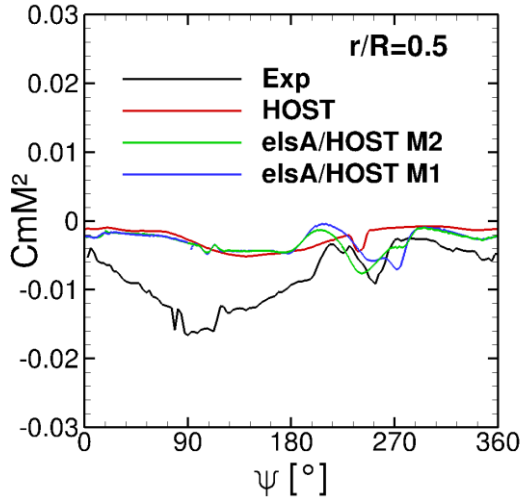


d) Section loads at $r/R=0.92$

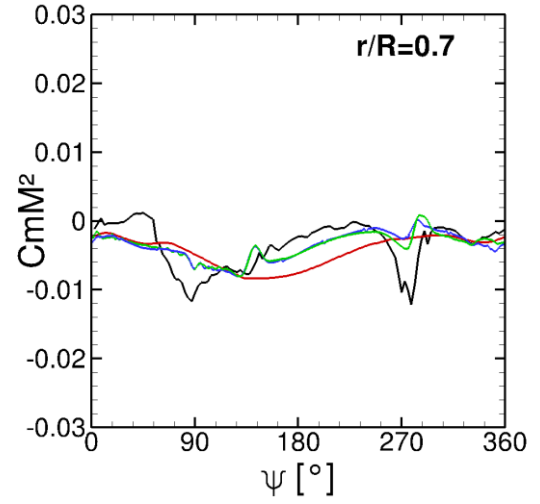


e) Section loads at $r/R=0.975$

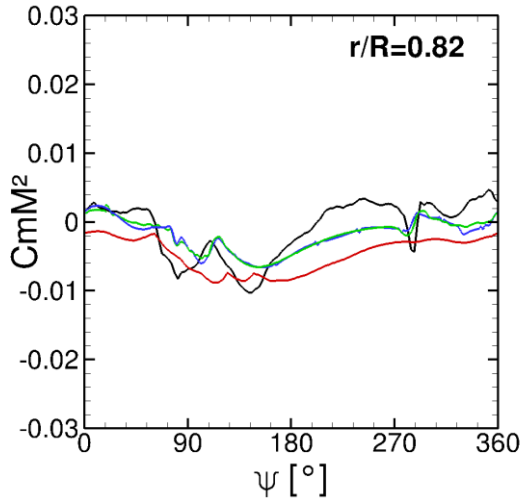
Fig. 7. Section loads CmM^2 : Experiments (black), HOST (red), elsA/HOST coupling on the medium grid M1 (blue) and fine grid M2 (green).



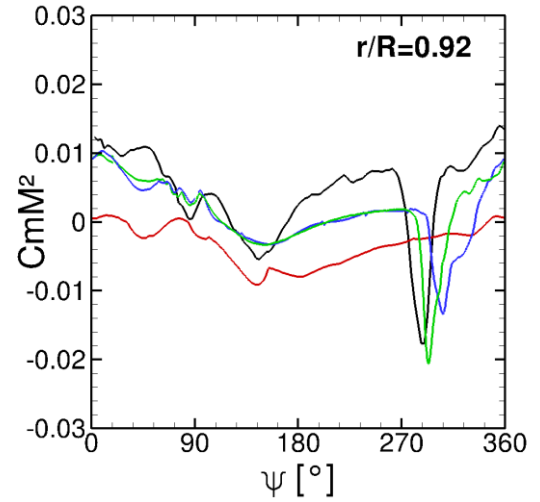
a) Section pitching moment at $r/R=0.5$



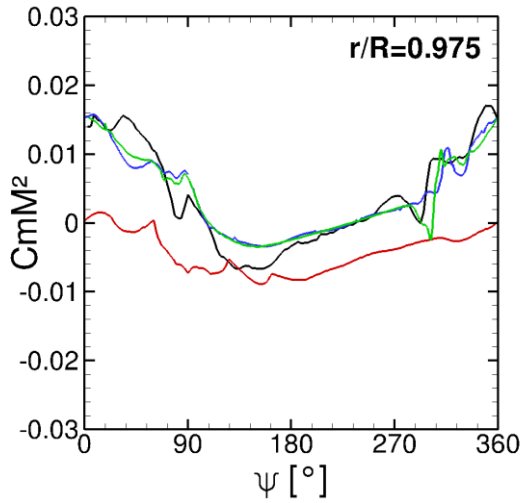
b) Section pitching moment at $r/R=0.7$



c) Section pitching moment at $r/R=0.82$



d) Section pitching moment at $r/R=0.92$



e) Section pitching moment at $r/R=0.975$

Fig. 8. Section pitching moments CmM^2 : Experiments (black), HOST (red), elsA/HOST coupling on the medium grid M1 (blue) and fine grid M2 (green).

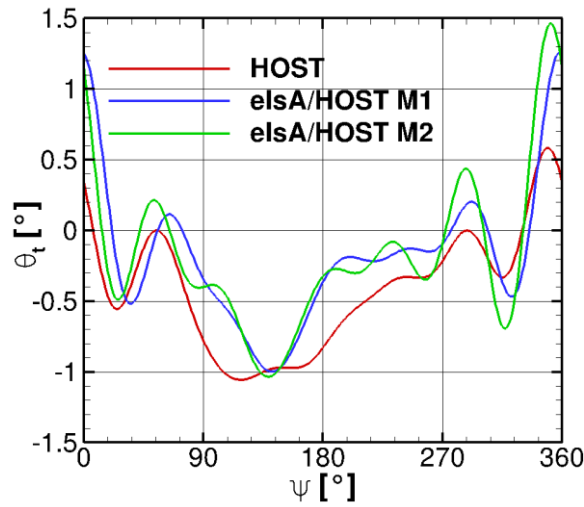


Fig. 9. Blade torsion at tip θ_t as a function of the azimuthal angle ψ (HOST: red, elsA/HOST on the medium mesh M1: blue, elsA/HOST on the fine mesh M2: green).

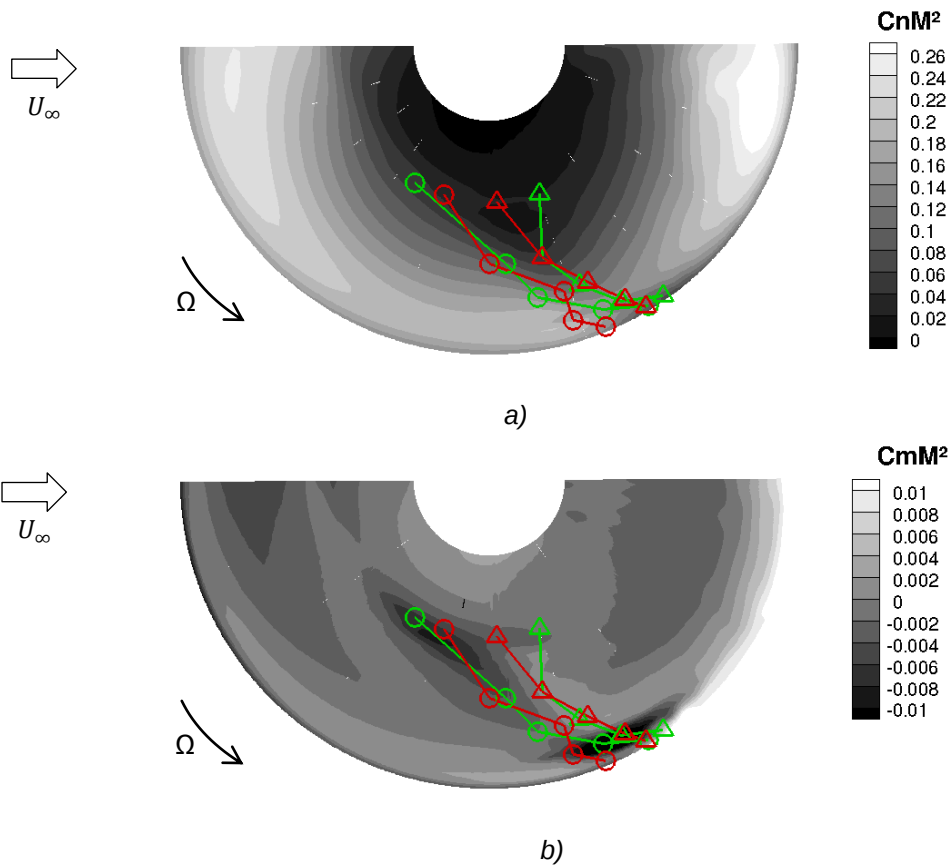


Fig. 10: Locations of the moment stall (circle) and lift stall (triangle) on the section load rotor map (a) and on the pitching moment rotor map (b). Experiment: red, elsA/HOST simulation: green.

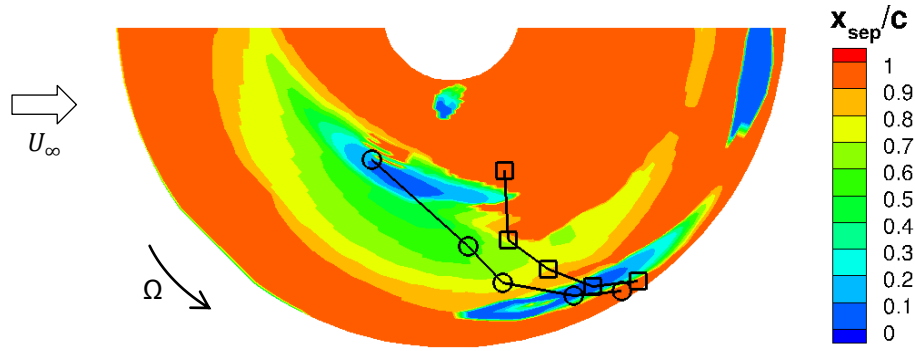


Fig. 11. Chordwise location of the flow separation x_{sep}/c on the retreating blade side (moment stall: circle, lift stall: square).

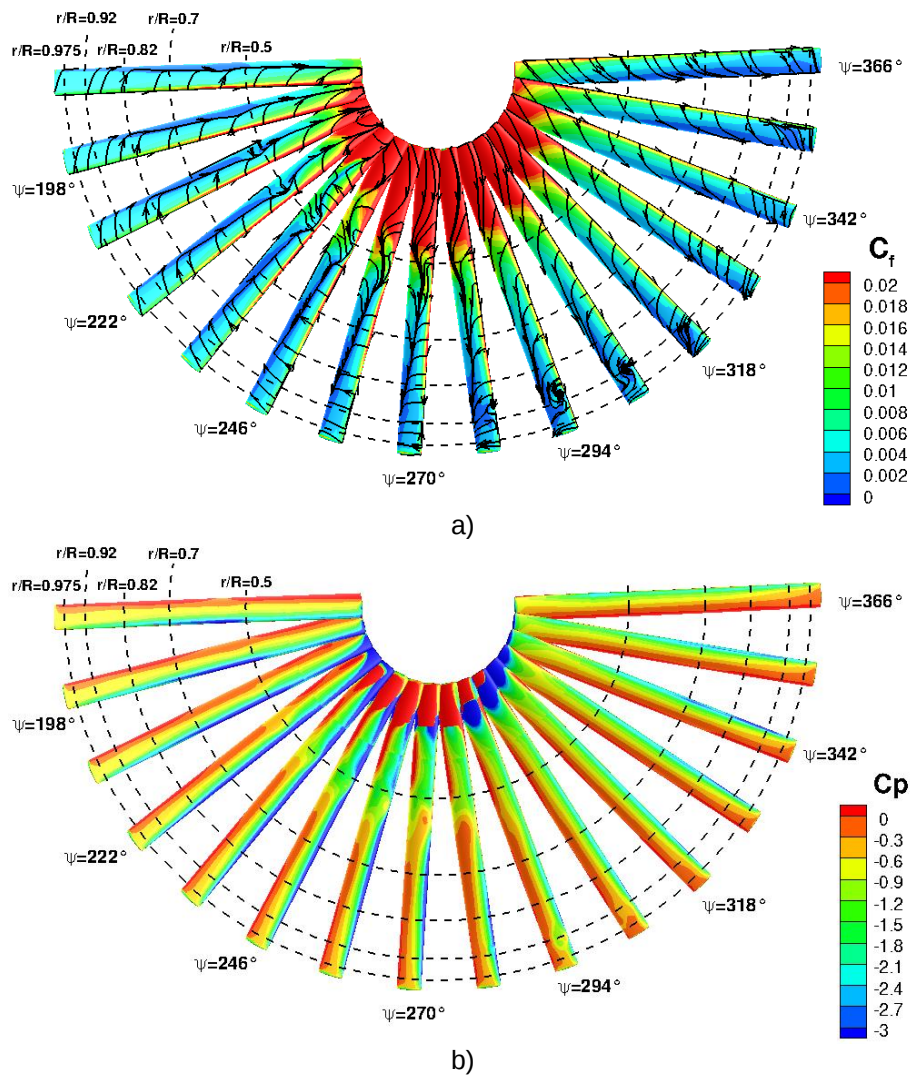


Fig. 12. Wall friction intensity τ_w and skin friction lines (a) and pressure coefficient (b) on the retreating blade at different azimuthal positions ψ . The sections $r/R = 0.5, 0.7, 0.82, 0.92$ and 0.975 are represented in dashed back lines.

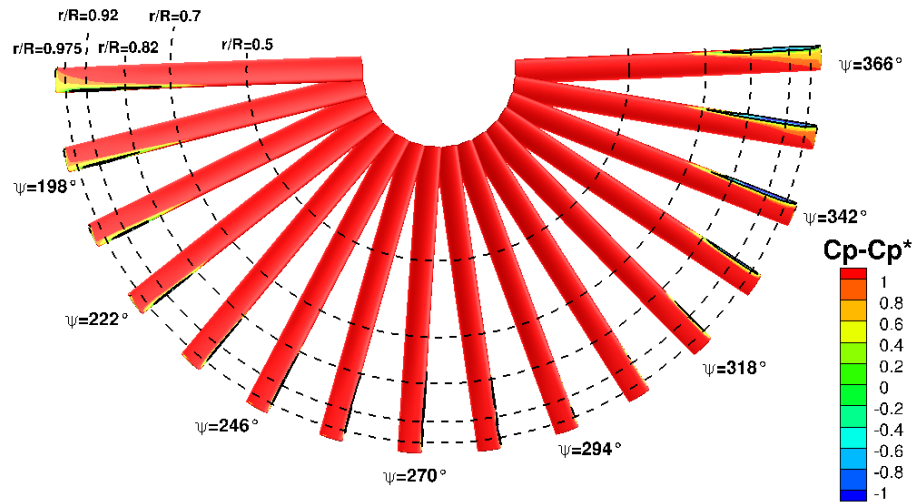


Fig. 13: Iso-contours of $C_p - C_{p^*}$ where C_{p^*} is the pressure coefficient where the local Mach number is equal to 1.