

ANALYZING LOW-SPEED ROTOR-FUSELAGE INTERACTIONS: A COMPARATIVE STUDY OF SIMULATIONS AND FLIGHT-TEST DATA ON H175

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Abstract

In this work, comparisons between simulations & measurements in flight are proposed for different low-speed flight conditions out of ground effect on an Airbus Helicopters H175 PT1 rotorcraft equipped with a 5-bladed Spheriflex® rotor. Numerical results have been obtained by full-helicopter unsteady simulations relying on a single-rotor loose coupling approach between the Computational Structure Dynamics & Computational Fluid Dynamics parts, assuming blade elasticity and six degrees-of-freedom trim. One flight condition is tackled with both rigid-blade and elastic-blade modelling so as to highlight the influence of the blade softness on the results.

The paper showcases good agreement between the simulation results & flight-test measurements regarding variations of main-rotor collective pitch, airframe attitude angles, rotor power & rotor loads with true airspeed. Airframe download is also numerically analysed.

1. INTRODUCTION

During low-speed operations, conventional helicopters encounter significant airflow interactions with the airframe. Also, when considering only forward flight conditions, this includes a multitude of phenomena like pitch-up, increase of download, alteration of the tail-rotor inflow, fuselage-induced distortion of the airflow at the rotor etc. [22], that all affect the overall helicopter performance, stability and control [16]. In addition, low-speed flights (in the so-called transitional flight speed regime) can exacerbate rotor-induced vibrations and fatigue on the rotor system components including blades, hub and rotor mast, as well as resonance especially during low-altitude operations. These vibrations can accelerate wear and fatigue, potentially leading to more frequent maintenance operations.

Low-speed flights have already been studied in the past, both experimentally [5][7][10][11] and more recently computationally [1][12]. The goal was either to enhance modern-helicopter blade definitions, along with improved tail-component designs, or to mitigate ground-induced instabilities such as ground resonance — which involves the coupling of the cyclic lead-lag motion of the main rotor blades with the helicopter body motion — with the use of a suitable damping, like inter-connected blade dampers for articulated rotors [15][21].

Improving modeling of the aerodynamic effects of the main rotor wake on the tail unit through Computational Fluid Dynamics (CFD) is another motivation for studying in depth low-speed flights, e.g. to improve the accuracy of helicopter flight-mechanics codes [2] or to better characterize vibrations at tail parts [3]. As an example, the GOAHEAD project carried out extensive wind-tunnel measurements on an instrumented 4-bladed rotor with the ONERA 7AD blades mounted on a 1:3.881 scale NH90 fuselage operating out of ground effect. This database was utilized for various comparisons with CFD simulations for a large scope of flight conditions including a low-speed pitch-up

case (case TC2) [1]. Many advanced numerical approaches consider today a multidisciplinary Computational Fluid Dynamics (CFD) – Computational Structural Dynamics (CSD) coupled toolchain for full-helicopter simulations [8][12][13][17][18][19] in order to take into account complex rotor aerodynamics and multi-physics interactions. We propose in this paper to deploy this kind of approach of single-rotor coupling for concrete industrial cases in low speeds, and compare with in-flight measurements. The starting point is the numerical model comprehensively described in [20], stepping from the isolated main-rotor model to a full helicopter model in this paper.

2. GEOMETRIES AND INTERNAL STRUCTURE DESCRIPTION

2.1. Geometries

2.1.1. Fuselage

The Airbus Helicopters H175 PT1 fuselage is considered in this work. It corresponds to the first prototype version of the H175 airframe that was used to open up the flight envelope (official maiden flight on 17th December 2009). An overview is given in Figure 1.



Figure 1 – Picture of the Airbus Helicopters H175 PT1

This prototype external shape differs from the serial version mainly by a different pylon-fairing design, upper cowlings deprived of butterfly wings at the junction with the tail boom, and by an empennage without end plates and with a different mean chord.

2.1.2. Main rotor (MR)

The fuselage is equipped with the five-bladed serial Spheriflex® H175 main rotor. The H175 blade is a straight blade of radius $R = 7.40\text{m}$, showing two tabs implemented from the radial station $0.60R$ to $0.90R$, as illustrated in Figure 2. A first tracking tab with a chord of 20mm is introduced within the span range $0.60R$ to $0.71R$. The tab slope angle is fixed to 0° . A second tab with a chord of 44mm is then implemented spanwise within the range $0.71R$ to $0.90R$. The tab slope angle is fixed to a value of -8° (i.e., trailing edge to the bottom as measured from the trailing-edge axis). The main rotor is tilted by an angle of 4.5° pointing forwards, and rotates clockwise. More details may be found in [20].

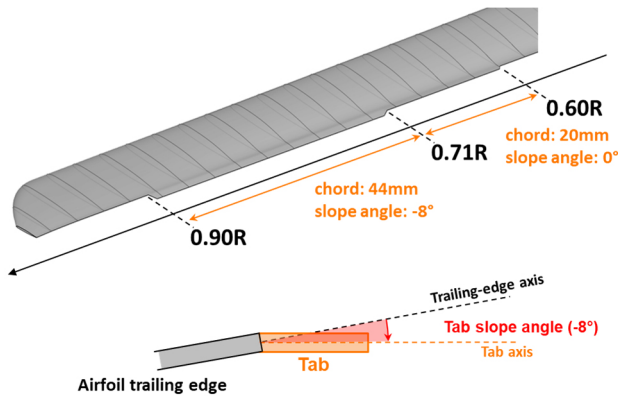


Figure 2 – Characteristics of the H175 blade tab arrangement

2.1.3. Tail rotor (TR)

A pulling articulated tail rotor is fitted on the port side of the vertical fin, as illustrated in Figure 3. It is obviously aimed at generating anti-torque and controlling the helicopter along the yaw axis. It is composed of 3 straight, twisted blades of radius 1.60m canted by 20° and rotates clockwise.



Figure 3 – Overview of the H175 tail rotor

2.2. Structure

The main-rotor elastic blade structure considered in this work is based on the one defined in the blade predesign

phase and includes the reference stiffness-, mass- and inertia-distribution along the blade span.

Tail-rotor blades are assumed to be rigid. The fuselage is considered as purely rigid. It is thus represented from a mechanical point of view only by inertia properties i.e., gross weight & moments of inertia.

3. FLIGHT CONDITIONS

Seven different flight conditions have been investigated in this work, as summarized in Table 1. They all consider a total helicopter mass of 7550kg , along with ISA atmospheric conditions, a pressure-altitude of 350ft (i.e., out of ground effect), and elastic main-rotor blades. A neutral CG position has also been considered as a generic reference. For level flight at 30kt , additional simulations were performed on rigid main-rotor blades in order to highlight the influence of the blade softness.

4. NUMERICAL PROCEDURE AND MODELS

The CFD analysis proposed in this paper is based on Unsteady Reynolds-Averaged Navier Stokes (URANS) simulations using the FLOWER solver developed by the German Aerospace Center (DLR) [14] for the aerodynamic part, coupled with the comprehensive analysis code CAMRADII of Johnson Aeronautics [9], as detailed in [18].

A loose CFD/CSD coupling approach has been adopted, which basically consists in replacing iteratively the low-fidelity aerodynamic loads obtained by CAMRADII from steady aerodynamic polars by the high-fidelity aerodynamic rotor-blade loads and airframe loads computed by CFD (FLOWer), as comprehensively described in [13]. Details on the numerical models along with the coupling procedure are briefly given in what follows.

4.1.1. CSD solver

CAMRADII includes multibody dynamics, nonlinear finite elements, structural dynamics, and low-fidelity rotorcraft aerodynamics relying on steady 2D polars for the airfoils representing the main and tail rotor blades. Aerodynamic modelling of airframe, horizontal and vertical tail plane also relies on tabulated aerodynamic coefficients depending on angle of attack and sideslip angle. The structural rotor blade dynamics, blade deformation and rotor control angles, along with the helicopter (H/C) attitude angles that are required to trim the rotorcraft in regards of target flight conditions are typical outputs of a CAMRADII run.

CAMRADII is used in a 6 degrees-of-freedom (6 DoF) approach with the standard trim strategy of cancelling the total forces & moments that apply on the helicopter. Selected degrees of freedom are classically the main-rotor blade collective pitch (COLL) and the two cyclic components (longitudinal LNGCYC & lateral cyclic pitch LATCYC), the tail-rotor blade collective pitch (COLL_{TR}), along with the airframe roll (Φ) and pitch (Θ) attitudes. Airframe yaw (ψ) is set to 0° . In the current work, the structural dynamics solution for main and tail rotor is sought using a Newton-Raphson algorithm considering 10 blade modes with 10 harmonics for all CAMRADII output quantities, taking into account 30 rotor azimuthal positions per revolution for the main rotor.

CASE ID	NR [%]	ΔISA [°C]	Zp [ft]	TAS [kt]	MR Blade modeling	H/C mass [kg]
HOVER OGE (HOGE)	105%	+0	350 (OGE)	0	Elastic	7550
LEVEL 10kt	105%	+0	350 (OGE)	10	Elastic	7550
LEVEL 20kt	105%	+0	350 (OGE)	20	Elastic	7550
LEVEL 30kt	105%	+0	350 (OGE)	30	Elastic & rigid	7550
LEVEL 40kt	105%	+0	350 (OGE)	40	Elastic	7550
LEVEL 50kt	105%	+0	350 (OGE)	50	Elastic	7550
LEVEL 60kt	100%	+0	350 (OGE)	60	Elastic	7550

Table 1 – List of simulated flight conditions

4.1.2. CSD model

Many details about the CAMRADII model of the H175 Spheriflex® main rotor may already be found in [20]. This model is based on an adaptation of the H175 model extensively used at Airbus Helicopters (AH) but within the STORM environment [4]. The major challenge lies in the modelling of the inter-connected lead-lag dampers of the Spheriflex® articulated main-rotor hub, because the standard process of modelling blade dampers in CAMRADII — which consists in assigning for each blade stiffness and damping properties to the blade articulation joint degrees of freedom — can hardly be used.

Interblade dampers are modelled as rigid body components with joint degrees of freedom. The advantage is to have an adequate kinematic damper model automatically considering the rotor modes in the right manner by mechanical load paths. Geometric non-linearities leading to damper deflections at higher harmonics of the blade root motions are represented accurately. Main drawback is the need to solve the equations of motion for all blades simultaneously thus increasing significantly the computation time due to the large number of degrees of freedom. Furthermore, numerical conditioning tends to degrade due to larger size of the system matrices.

The three-bladed tail rotor model is implemented as a single load path model with swashplate control mechanism rotating clockwise, as for the main rotor. Tail rotor blades are modelled as rigid body components. Aerodynamic discretization of the blade lifting line is based on 17 panels in the spanwise direction. The definition starts with the first panel inboard edge at 0.2875R based on the airfoil tables available and the related airfoil distribution in spanwise direction.

No modal properties are considered for the airframe. The fuselage is thus rigid, and represented only by inertia and aerodynamic properties. Fuselage aerodynamic polars obtained by wind-tunnel tests provide an estimation of the aerodynamic loads as a function of angle of attack and sideslip angle. Geometric information of the fuselage e.g. in view of main/tail rotor locations, center of gravity and aerodynamic reference locations are also important data to build a representative model. An overview of the structural model of the complete H/C is given in Figure 4.

4.1.3. CFD solver

On the CFD side, only the main-rotor blades and the airframe are represented in the numerical model, as the goal was to focus on simulations involving single-rotor coupling (main rotor). This means the tail-rotor loads evaluated in CAMRADII from low-fidelity aerodynamic models are not corrected by CFD and the influence of the

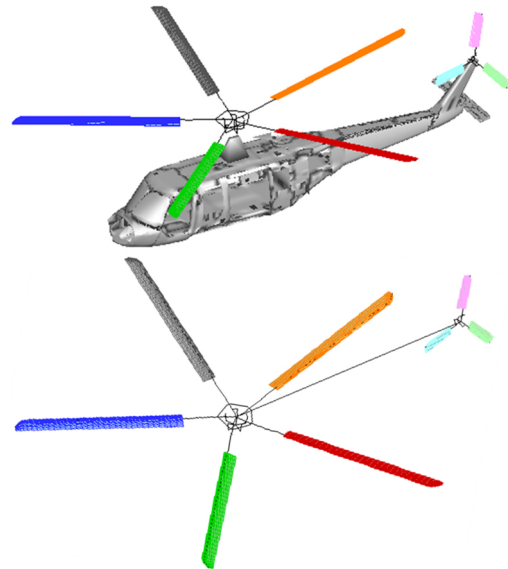


Figure 4 – Structural complete H/C model; top: complete model; bottom: considered model with rigid airframe & tail-rotor blades

tail-rotor downwash onto the airframe (essentially tail parts) is not considered. Main-rotor & tail-rotor heads have been discarded in the numerical model. In addition, air intakes & exhausts do not operate.

The aerodynamic loads on the main-rotor blades and airframe are evaluated using the finite-volume block-structured Reynolds-averaged Navier-Stokes (RANS) CFD code FLOWer. Those high-fidelity loads are then used in replacement of the low-fidelity aerodynamic loads of CAMRADII. The RANS equations have been closed using the Shear Stress Transport k- ω variant of Menter's model. A 5-stage Runge-Kutta central scheme with artificial dissipation has been used to evaluate numerically the Eulerian terms. The time-dependent URANS solution is obtained by integrating the governing equations using an implicit dual time-stepping approach developed by Jameson. The ROT extension of FLOWer has been activated in order to calculate the unsteady flow around the moving and deforming blades.

All the FLOWer simulations have been performed over one complete rotor revolution, i.e. for a reference blade azimuth ψ varying from 0° (backward facing blade) to 360°. The time step has been chosen so as to ensure an azimuthal step of 1° at the considered rotor rotational speed during the convergence process. Blade elastic deformations as predicted by CAMRADII are taken into account in the CFD simulations thanks to the mesh-deformation technique.

4.1.4. CFD model

Multiblock grids have been employed for both the main-rotor blades and the airframe. The tail rotor is not part of the CFD model.

Each blade grid is composed of 64 blocks and 5.9M of nodes. A total of 249 radial stations have been considered in the spanwise direction, including 45 stations to represent the blade root. The body grid extrusion in the wall normal direction is around 1.5 blade chord length. The block topology and resulting structured grid are illustrated in Figure 5 and Figure 6 for the H175 blade with the -8° -oriented tabs. The fuselage is composed of 302 blocks and 89.1M of nodes, reused from [23]. Only one block layer has been considered around the wall (near-field) as the far-field has been discretized with a pure Cartesian background mesh. The block topology and near-field structured grid are illustrated in Figure 5 and Figure 7.

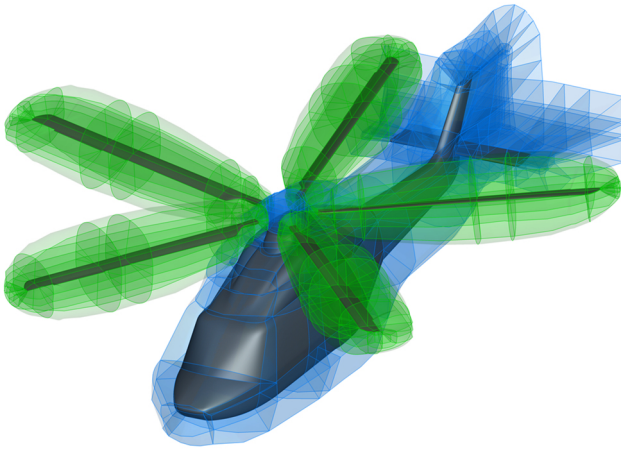


Figure 5 – Blocking of the airframe mesh (in blue) and main-rotor blade meshes (in green)

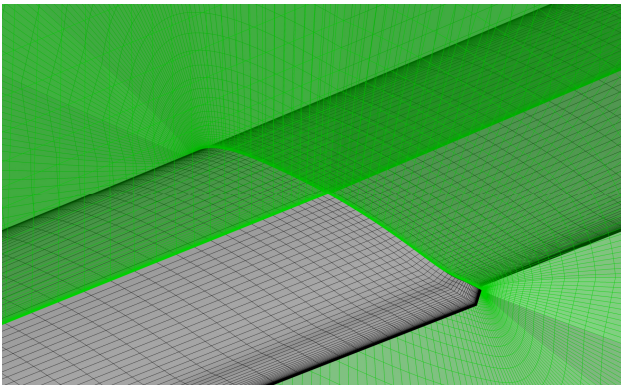


Figure 6 – Overview of the skin grid (in grey) and the volume grid (in green) of the H175 blade incl. tabs

Two background grids have been considered; one in the vicinity of the airframe & blades (inner background), composed of 1440 blocks & 75.9M of nodes and a hollowed one for the far-field (outer background) composed of 134 blocks & 5.8M of nodes, as shown in Figure 8. Airframe and all blade grids are then embedded into the inner background mesh, which spans three rotor diameters in each direction with a prescribed rigid-body motion and a prescribed elastic deformation of the blades along the flap, pitch and lag axes according to the CAMRADII trim solution.

A bi-directional transfer of the flow solution between the grids is ensured using a second-order Chimera interpolation

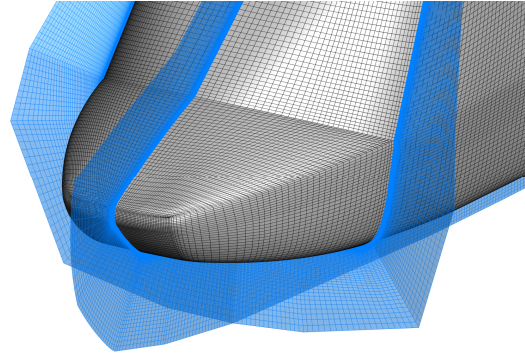


Figure 7 – Overview of the skin grid (in grey) and the volume grid (in green) of the H175 PT1 airframe

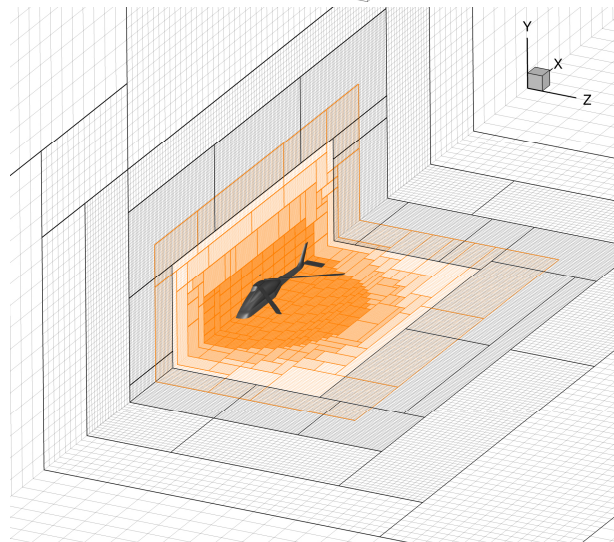
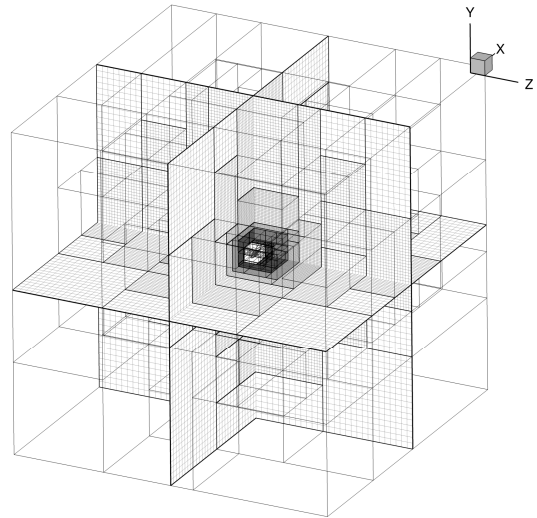


Figure 8 – Overview of the background grids; inner background (in orange); outer background (in black); block edges are represented in bold

technique at the grid overlapping boundaries. Masks have been defined for blades & airframe as illustrated in Figure 9 in order to avoid interpolating too close to the walls, where the cells are very small especially in the wall-normal direction in comparison to the background mesh. The background mesh has been built using a 5-level Octree technique so as to ensure a grid cell size comparable to the cell size of the blade/airframe outer boundaries, where the flow data transfer is performed, while keeping the number

of total nodes reasonable. A grid resolution of 3 cm has thus been applied at the inner background in a large cylinder of radius 10m where the blades operate and in the airframe vicinity. Proceeding so ensures a low dissipative transport of the vortex structures between all the grids and a limited aliasing in the disturbances during the solution interpolations. The outer background mesh is 20 rotor-diameters long in each direction. The overall mesh is composed of 2196 blocks & 187 million of hexahedra.

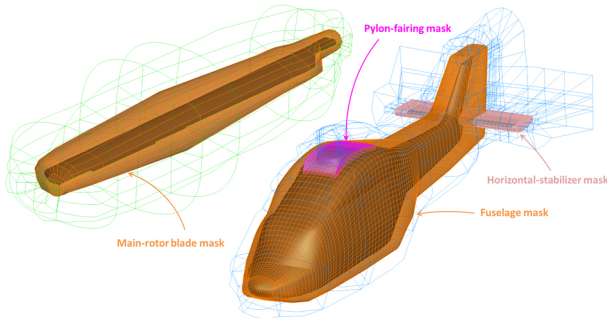


Figure 9 – Mask definitions

4.1.5. CSD/CFD trim procedure

The loose coupling methodology is characterized by the application of a CFD-based load correction term on comprehensive code side (CAMRADII). The so-called delta airloads term is updated sequentially at each iteration of the coupled cycle. In case of the rotor, time-periodic delta loads are exchanged at each iteration. In case of convergence of the coupling scheme, the changes in the delta airloads term become smaller and smaller. After the changes have fallen below a user-defined threshold, the delta airloads can be considered as constant. Due to the formulation of the delta loads as a corrective term, the 2D steady polar based internal aerodynamic loads of the comprehensive codes can be considered as completely replaced with the CFD loads and the comprehensive code's trim will be solely based on the CFD loads.

Each coupling cycle involves four steps which are sequentially executed as follows:

- Execute a CAMRADII run to compute the aircraft trim and the rotor blade motion;
- Prepare position sensor data for FLOWer, incl. main-rotor blade motion & deformation, and airframe;
- Execute a FLOWer computation to get the mean aerodynamic loads on fuselage & periodic main-rotor blade loads;
- Prepare for the next CAMRADII re-trim the delta airloads and map them from the FLOWer sensors (skin grid nodes) to the CII sensors (panels) for blades, and from FLOWer airframe components to the CAMRADII airframe polars. At this stage, drag corrections are typically applied for elements or effects not included in the FLOWer computations.

The preparation of the delta airloads at the main-rotor blade is a critical step that implies the definition of a load-conservative mapping between the radial stations of the CFD blade-skin grid and the CII panels, as comprehensively discussed in [20]. The overall procedure for trim is illustrated in Figure 11. Depending on the flight case, trim convergence is achieved after eight to twenty trim

iterations (especially for hover or very low speeds, which requires more iterations), see Figure 12 where the 40kt case of the present study is shown. Convergence is deemed sufficient when the variation of the control angles, of the elastic blade pitch deformations, and of helicopter pitch attitude between two successive iterations has dropped below 0.05°.

Before being reinjected as inputs into CAMRADII, airframe loads estimated in the FLOWer simulations have been corrected in order to include some effects not taken into account in the CFD numerical model, such as main/tail rotor head drag, air-inlet capture drag, momentum losses, drag from skin roughness & excrescences (wheels, nozzles, etc.) Constant corrections have been applied to this goal. Correction values have been obtained from CFD data on H175 that were generated prior to this work. The drag distribution at the H175 main rotor head is exemplarily shown in Figure 10. It has been calculated from CFD simulations in level flight (TAS 150kt SL ISA) using the DLR's TAU solver on unstructured grids following the methodology described in [6] with a non-rotating rotor head.

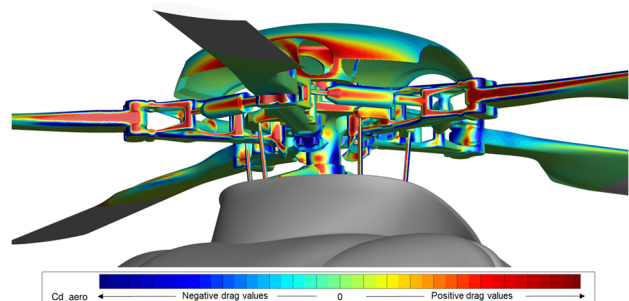


Figure 10 – Drag distribution at the H175 main-rotor head, in level flight (150kt); angle of attack & sideslip set at 0°

Although a trim law with six degrees of freedom is used in CAMRADII, the CFD-CSD coupling does not fully encompass the 6th degree of freedom: Yaw moments on the airframe and from the main rotor torque are transferred from the CFD model to the aeromechanics code, but the tail rotor collective pitch is determined by CAMRADII entirely based on its internal tail-rotor model. The aerodynamic consequences of variations in the tail rotor thrust, such as the fin blockage effect in hover, are not perceived on CFD side. In other words, there is no complete equilibrium between the aerodynamic loads of the CFD model and the helicopter weight, as it would be if there was a fully-fledged 6 DoF coupling for the trim.

5. RESULTS

5.1. Numerical convergence

The numerical convergence of the six degrees of freedom is exemplarily shown for a level flight at 40kt in Figure 12. It shows full-helicopter simulations are well converged after 14 rotor revolutions in this case, whereby the re-trims were effectuated after computing in CFD one main-rotor revolution only at each trim step. The history of the main-rotor thrust as a function of trim iterations is also given in Figure 13. One can verify that mean thrust and the fluctuation magnitudes remains virtually constant after 12 trim iterations, which confirms the correct level of convergence.

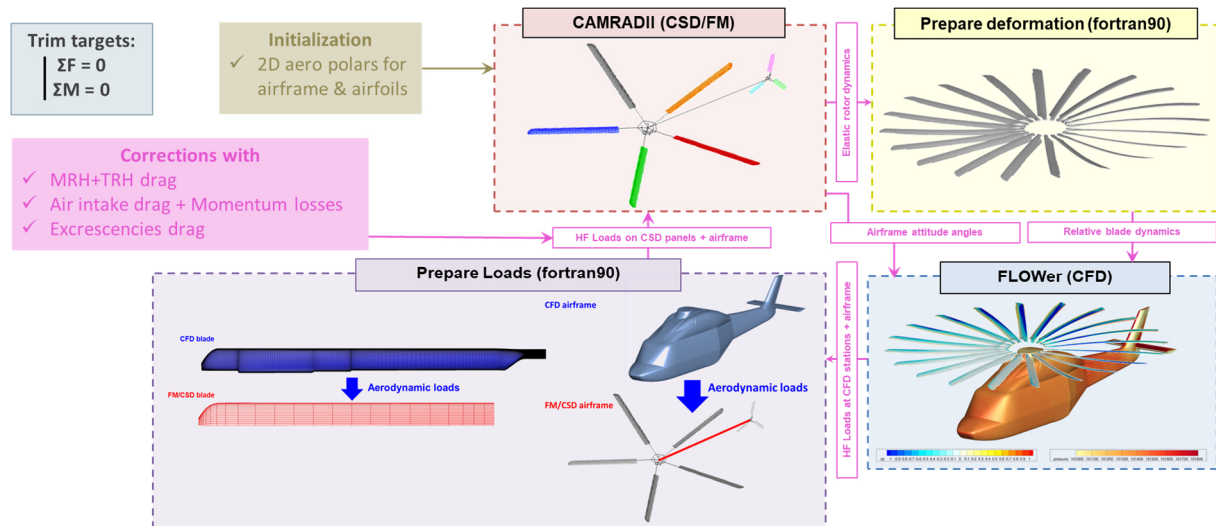


Figure 11 – Overall procedure for 6DoF trim

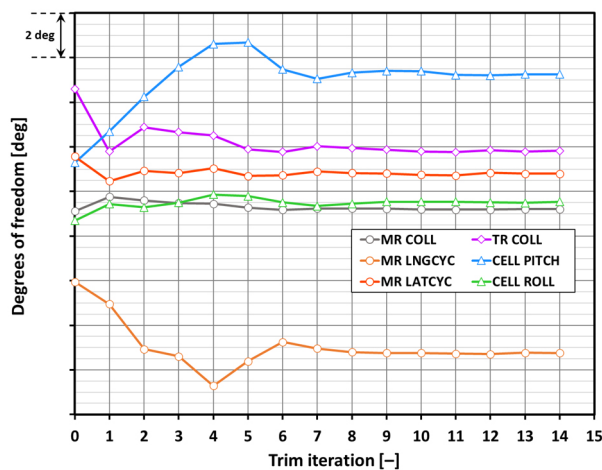


Figure 12 – History of the degrees of freedom as a function of trim iterations; TAS 40kt (CFD)

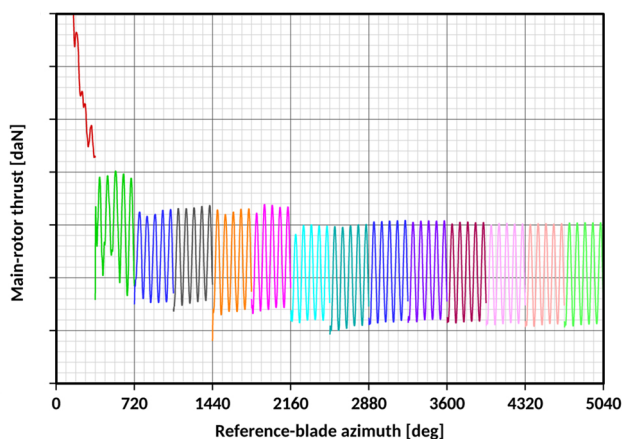


Figure 13 – History of the main-rotor thrust as a function of reference blade azimuth ψ ; TAS 40kt (CFD)

5.2. Flight-test data & simulation projections

The main characteristics representing the H/C trim are now compared with flight data obtained for similar conditions, i.e. a H/C mass of 7.50t~7.55t a temperature of 28°C

(ISA+13°C, i.e. differing from the simulation setup that uses ISA+0°C), a pressure-altitude of 350ft (OGE) and for a range of true airspeeds up to 60kt. The measurements show some dispersion because low-speed flights are tough to stabilize. The averaged values observed in flight are reported in what follows, along with the scattering range.

Since the CG was located more rearwards in the flight tests, the simulations performed for the reference CG position are amended by one additional computation cycle with CAMRADII in order to project the simulation results towards the flight-test weight-and-balance configuration. The delta-loads of the converged CFD-CSD result for neutral CG hence are employed in a CAMRAD-II computation with the CG shifted to match the flight test. For the main rotor state, this extrapolation will not mean much difference, as the rotor disk keeps its orientation in the inertial frame, and thus the delta-loads may be assumed to remain valid. The control vector changes with respect to the helicopter, which assumes a higher pitch attitude upon the rearward shift of the CG, yet the control vector's orientation in space remains nearly unaltered.

Regarding the tail surfaces, the changes in pitch attitude imply a marginal vertical repositioning within the main rotor wake; due to a missing update of the flow field in the CFD simulations, i.e. with further coupling cycles lacking, the situation of the empennage within the wake hence is not entirely representative. To some extent, the vertical offset may be considered as synonymous to a flight speed change: While the stabilizer is positioned lower in the wake in case of the flight test for a given flight speed, the positioning might resemble the simulated situation when looking at slightly lower experimental speeds, where the rotor wake is steeper. In other words, it may be expected that the simulation predicts the peak in mast moments and attitude to occur at slightly higher speeds.

5.3. Main-rotor collective pitch

Flight-test measurements show some dispersion because low-speed flights are tough to stabilize. The averaged values observed in flight are reported in what follows, along with the scattering range. Variations of the main-rotor collective pitch as a function of airspeed are shown in Figure 14. The range of the measurement scattering is

highlighted by the vertical bars. A reduction of the collective pitch with an increase of airspeed is observed, both in the simulations and in the flight measurements. The overall agreement is remarkably good when elastic blades are considered in the simulations.

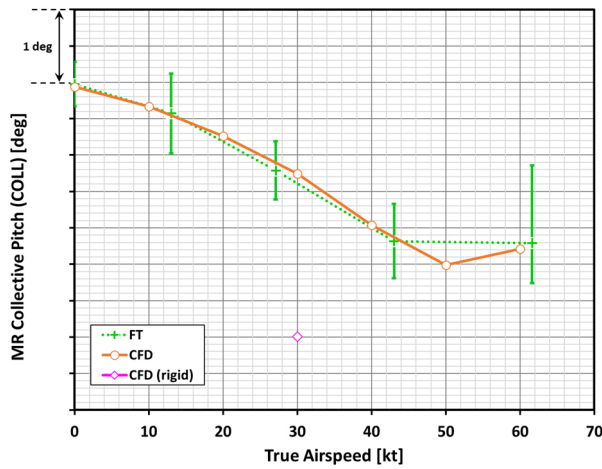


Figure 14 – Main-rotor collective pitch as a function of the true airspeed

The collective pitch appears to be significantly underestimated when rigid blades are considered, as shown for a TAS of 30kt for which a deviation of circa. 2.5° is observed. It may be interesting to look in more detail into the origin of such discrepancy. It is first verified in Figure 15 that the sectional-thrust distribution as a function of the blade azimuth remains rather similar with elastic or rigid blades.

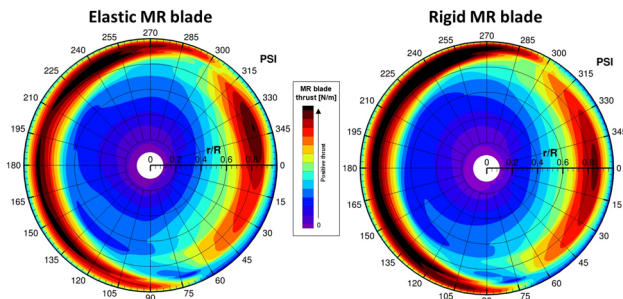


Figure 15 – Sectional thrust at the blade as a function of radial & azimuthal positions, TAS 30kt

The elastic torsional deformation is depicted in Figure 16. An elastic deformation of around -2.5° (i.e. pitch down) is observed in the highly thrust-producing zone, which extends from roughly 70% of the radius up to the tip, as revealed in Figure 15. This value is rather significant, and most certainly comes from the main tab, which generates a strong pitching moment (nose down) on the blade throughout this area, as illustrated in Figure 17.

For rigid blades, this torsional deformation is not possible and is compensated by a collective pitch reduction by circa. 2.5° in order to produce the same thrust. The tabs hence produce a significant increase of blade twist, and the corresponding attenuation of the lift peak near the blade tip is recognizable in Figure 15 for the upstream half of the rotor disc.

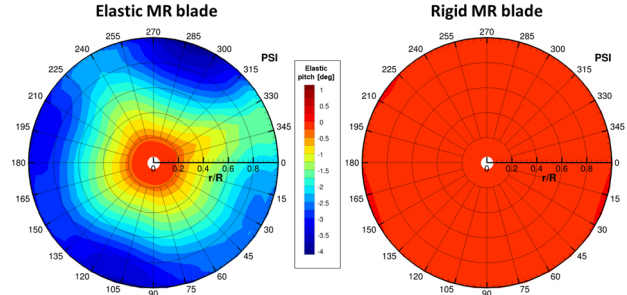


Figure 16 – Elastic deformation about the pitch axis, TAS 30kt

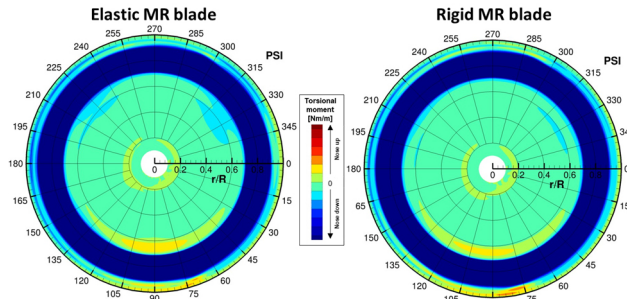


Figure 17 – Sectional moment about the pitch axis, TAS 30kt

This is also consolidated by the rotor mapping of the full blade motion about the pitch axis, as shown in Figure 18, which reports the sum of collective pitch, cyclic pitch and elastic torsional deformation over a complete main-rotor revolution. It shows very comparable azimuthal variations between the rigid case and the elastic case, especially in the highly thrust-producing zone. The small local variations visible at the inner part of the rotor disk that are observed in the elastic case are obviously missing in the rigid case, but the impact on thrust production remains limited given the low speeds involved in this area.

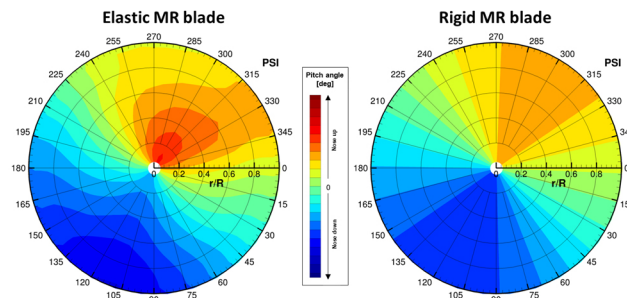


Figure 18 – Blade motion about the pitch axis (rigid + elastic deformation), TAS 30kt

5.4. Main/Tail rotor shaft power

Figure 19 shows the required shaft power at main-rotor & tail-rotor as a function of airspeed. For main-rotor shaft power, numerical results are in good agreement with flight-test data both qualitatively and quantitatively; the rate of decrease of the required power with an increase of airspeed observed in flight is well predicted by the simulations. Remarkably, the rigid blade simulations predict almost the same main-rotor power at the considered flight speed of 30kt, although they slightly differ in radial lift distribution. The overall trend is also well captured for the tail-rotor power, although with some underestimation at low flight

speeds. It is reminded that the tail rotor is modelled by CAMRADII, but obtains, as its effective trim objective, the task to restore the equilibrium with the aerodynamic loads on airframe and main rotor furnished by the CFD model. The CFD model, however, does not comprise the fin blockage effect, and also no estimate of it is made on CAMRADII side.

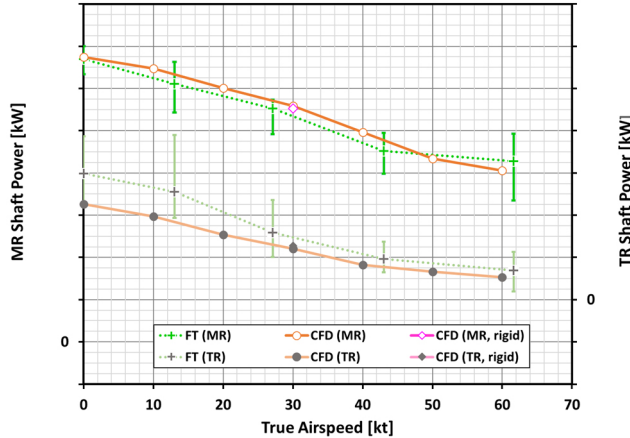


Figure 19 – Shaft power at main rotor & tail rotor as a function of true airspeed

If the fin blockage had been modelled, the torque created by the fin would have to be counterbalanced by more thrust at the tail rotor in order to ensure H/C trim, at a price of a greater required power.

CFD analyses on the H175 tail-unit in HOGE and at 30kt based on steady-state TAU simulations provide additional clues in that direction. In those analyses, the tail-rotor effect is modeled by the Actuator Disc (AD) approach, for which the rotor sectional load distributions have been preliminarily obtained from STORM trim calculations towards the tail rotor thrust of the FLOWER-CAMRADII solution, and using the Drees inflow model. In case of the simulations at 30kts, an AD for the main rotor is part of the setup as well, its load distribution being calculated in STORM with the help of a finite state inflow model (FiSuW). STORM load outputs are expressed in the disc coordinate system, so as to be directly implementable onto the AD.

The pressure distribution on tail elements in HOGE is shown in Figure 20 in delta with the configuration without tail rotor. It highlights the area of the tail-rotor wake impingement on the vertical fin, characterized by the overpressure area, and onto the empennage. However, the net vertical force on those non-rotating elements remains rather small, since portions of the left stabilizer wing also generate an upward force if they are within the influence of rotor suction, and due to suction forces arising along the swept leading edge of the fin. The lift contribution of the inclined tail rotor is thus fully available.

Figure 21 shows the surface pressure differences due to the addition of the tail rotor AD at 30kts. Thereby, the AD for the main rotor remained unchanged. Again, the reduction of fin lateral lift becomes visible in form of the pressure rise over large parts of the left fin surface. The lateral force obtained from interference reaches approximately one third of the effect in HOGE, which corroborates the trend in underestimation of TR power presented in Figure 19.

Lift changes on the fin are less pronounced than in HOGE. The horizontal stabilizer, however, experiences a reduction in download by 10%, such that the net effect of the tail rotor AD is a lift increase on the non-rotating parts. This is largely the consequence of a forward shift of an already existing flow separation on the left lower wing surface upon including the tail rotor, which manifests as the sharply defined area of pressure increase visible in Figure 21. Its effect on the pitch-up is discussed further below.

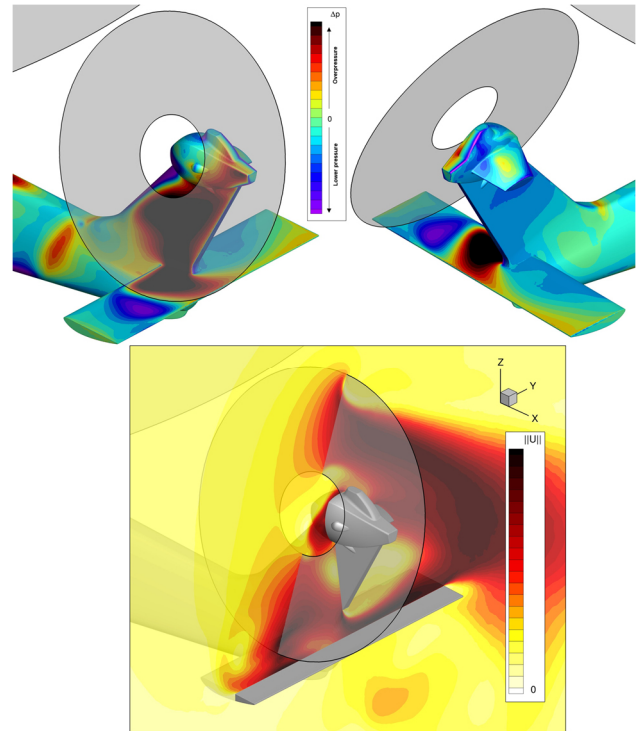


Figure 20 – Top: Pressure distribution over tail parts in HOGE, in delta w.r.t. the configuration w/o tail AD; bottom: Velocity norm in the H/C transversal plane located at the tail-rotor center of rotation for the configuration with tail AD

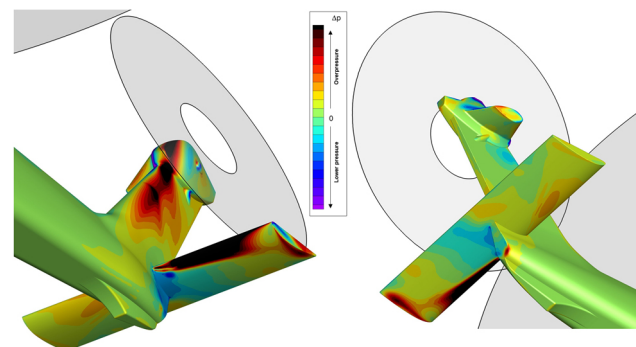


Figure 21 – Top: Pressure distribution over tail parts at 30kts, in delta w.r.t. the configuration w/o tail AD

5.5. Main-rotor pitch-link loads

Dynamic pitch-link loads obtained numerically are first compared to flight-test data for airspeeds of 20kt and 40kt. Time signals are given in Figure 22 and Figure 23, respectively. Harmonic decompositions are also reported. In both situations, agreement between numerical results and in-flight measurements are very good in their trends.

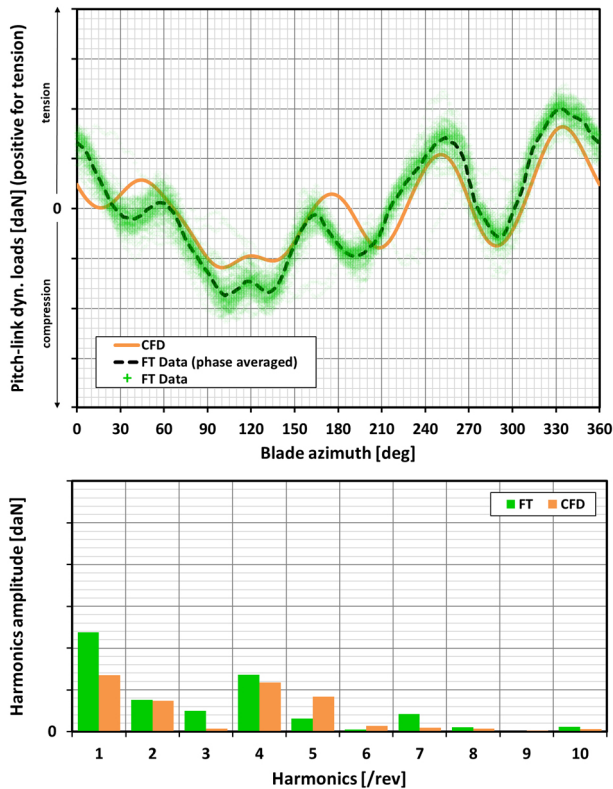


Figure 22 – Top: Dynamic loads at the pitch link as a function of blade azimuth ψ ; Bottom: harmonic decomposition; TAS 20kt

Azimuthal positioning of the peaks and their magnitude match well with the measurements. In particular, the dominant 4/rev component observed for an airspeed of 20kt are well captured in the simulations. Levels of the large 4/rev component is particularly well predicted. The increase of the 4/rev component experienced for an airspeed of 40kt is also well captured by CFD. It is slightly overpredicted by CFD, which becomes apparent particularly during the last quarter revolution.

Simulated dynamic pitch-link loads are reported in Figure 24 for airspeeds ranging from 0kt (HOGE) to 60kt. Harmonic decompositions are also represented. An increase of the peak-to-peak loads are observed for an increase of the airspeed up to 40kt. For larger speeds, the peak-to-peak loads then decrease. Dynamic loads are revealed to be dominated by a 4/rev component which is maximum for an airspeed of 40kt. A 5/rev component emerges for airspeeds greater than 40kt.

It also appears that simulations performed with rigid blades are not able to capture the abovementioned trend. Indeed, for an airspeed of 30kt, the dynamic loads show very limited variations and magnitudes. In addition, the harmonic content appears not to be representative, as the 4/rev component is highly underpredicted. This highlights the important role of considering blade inertia and softness properties for pitch-link load assessments.

5.6. Airframe attitudes

Variations of airframe pitch-and-roll angles as a function of airspeed are given in Figure 25. The airframe pitch angle remains positive in the considered airspeed range, which

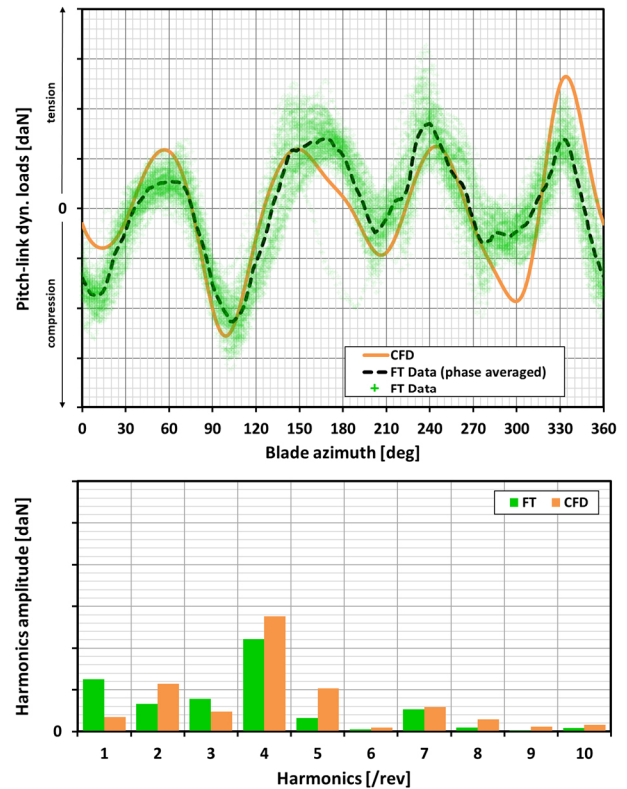


Figure 23 – Top: Dynamic loads at the pitch link as a function of blade azimuth ψ ; Bottom: harmonic decomposition; TAS 40kt

means the helicopter is always in a nose-up position. In addition, the pitch-up phenomenon is well reproduced by the simulations, as an important increase of the airframe pitch angle is observed for airspeeds up to 40kt. The airframe pitch angle then decreases with larger airspeeds. Quantitatively, the numerical results remain in the scatter range of the flight test data. However, a slight 0.5° overestimation for the mean value is observed around the maximal pitch-up conditions (although still acceptable because it remains within the measurement dispersion range). For lower airspeeds, simulations tend to slightly underestimate pitch-up, by 0.5° to 1°.

The missing interactions between tail-rotor and the empennage on the FLOWER side may also modify the observed discrepancy. Indeed, as shown in Figure 20 for HOGE, the tail-rotor sidewash generates strong pressure variations on the left-hand horizontal stabilizer, without however inducing much net vertical loads, according to the simulation. When, hypothetically, the tail rotor thrust was increased to overcome the blockage effect still missing in the simulation, it would generate a supplementary nose-down moment around the CG due to its canted installation. Based on the fin blockage predicted by the AD simulation, this effect is estimated to alter the pitch attitude by circa. -0.5°.

Also, at 30kts (cf. Figure 21), the interaction plays a certain small role for the pitch attitude. The fin blockage is considerably weaker; yet, in combination with the 10% reduction in stabilizer download, the net effect of the TR thrust increase and lift change on the non-rotating parts has a similar impact on pitch attitude; a reduction by circa -0.6° is estimated by STORM computations with accordingly modified lift at the tail elements.

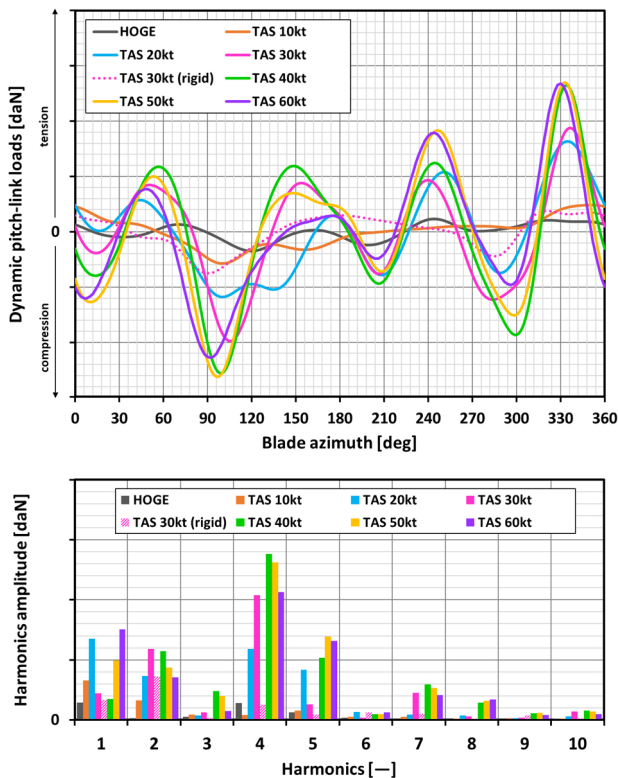


Figure 24 – Top: Simulated dynamic loads at the pitch link as a function of blade azimuth ψ for different airspeeds; Bottom: Harmonic decomposition; (CFD)

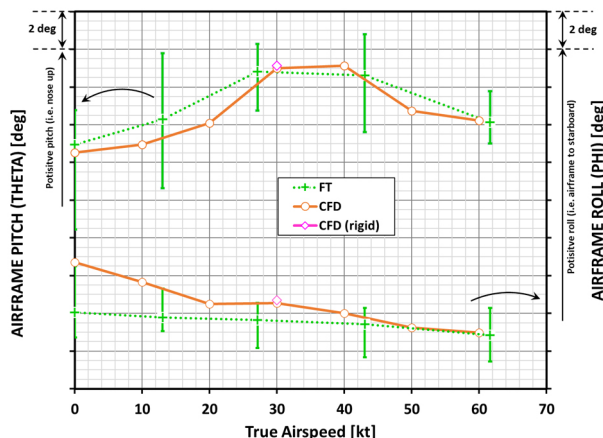


Figure 25 – Airframe pitch & roll as a function of true airspeed

The airframe roll angle also remains positive within the range of considered airspeeds, indicating a permanent roll to the right. The global trend of a decreasing roll attitude with an increase of the airspeed is well captured by the simulations. Quantitative agreement between numerical and flight data are also very good for airspeeds above 20kt. For lower speeds, the roll angle appears to be overestimated in the simulations, by up to 2° (in HOG). The question arises if this can be partly explained by the missing fin blockage effect, as addressed above: Introducing the lateral force from fin blockage will produce a roll-right moment around the center of gravity (CG). However, as the AD simulation suggests, the thrust increase necessary to overcome it has its center of effort at

sufficient height to override the roll-moment produced by the entire fin blockage: A roll-left moment would be the net effect. Based on the AD simulations, this effect can be estimated to produce ~0.20° roll to the left and thus cannot explain the offset in roll. It is reminded that such correction of the missing fin blockage effect does not lead to a change in the lateral force balance, as the anti-torque delivered by the tail rotor in combination with the fin remains unaltered; the lateral inclination of the main rotor disk is hence not affected.

Considering rigid blades has only little effect on the airframe attitude angles. This is because the main-rotor thrust distributions are very similar in the two situations (cf. Figure 15) in spite of different control angles; as a consequence, the main-rotor downwashes are also very similar, as for the overall airframe balance.

5.7. Airframe download

Download is defined as the negative aerodynamic lift created by the flow developing over the airframe, thereby including the effects of the increased static pressure below the rotor disc. In low-speed situations, the flow mainly comes from the induced velocity field off the main rotor. Download has a pressure component which is usually dominant, along with a small friction component.

Contours of surface density of aerodynamic vertical force in the geodesic frame (or simply 'lift' in what follows) are exemplarily shown in Figure 26 for an airspeed of 30kt. The geodesic vertical axis is oriented to the top; areas of download production consequently appear in cold colours (representing negative values of lift). The pressure component of download appears to be the result of direct airflow impingement at the H/C upper parts and static pressure rise during blade passages, along with flow separations at bottom parts that produce suction. In the geodesic frame, download can be directly added to the H/C weight, and thus expressed as a fraction of the H/C gross weight. Contours of lift surface density are given for HOG, TAS 30kt and TAS 60kt in Figure 27. In HOG, cockpit frontal-upper surface and the lower part of the cabin produce most of the downforce, while the tail surfaces contribute very little. The lower part of the tail boom also produces significant download. Rotor swirl gives rise to some lift production at the left tail-boom side.

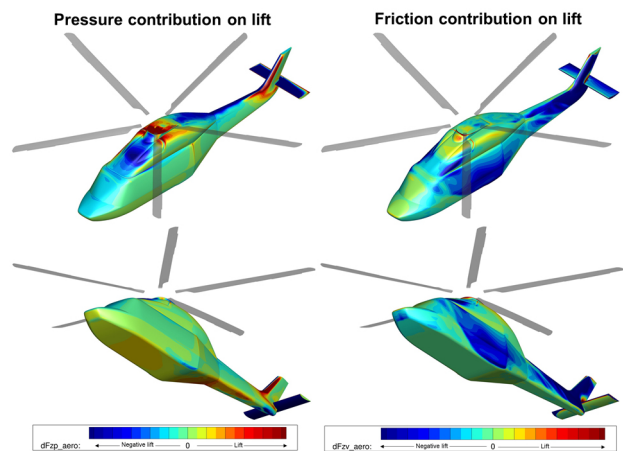


Figure 26 – Snapshots of pressure-based lift & friction-based lift distribution; TAS 30kt

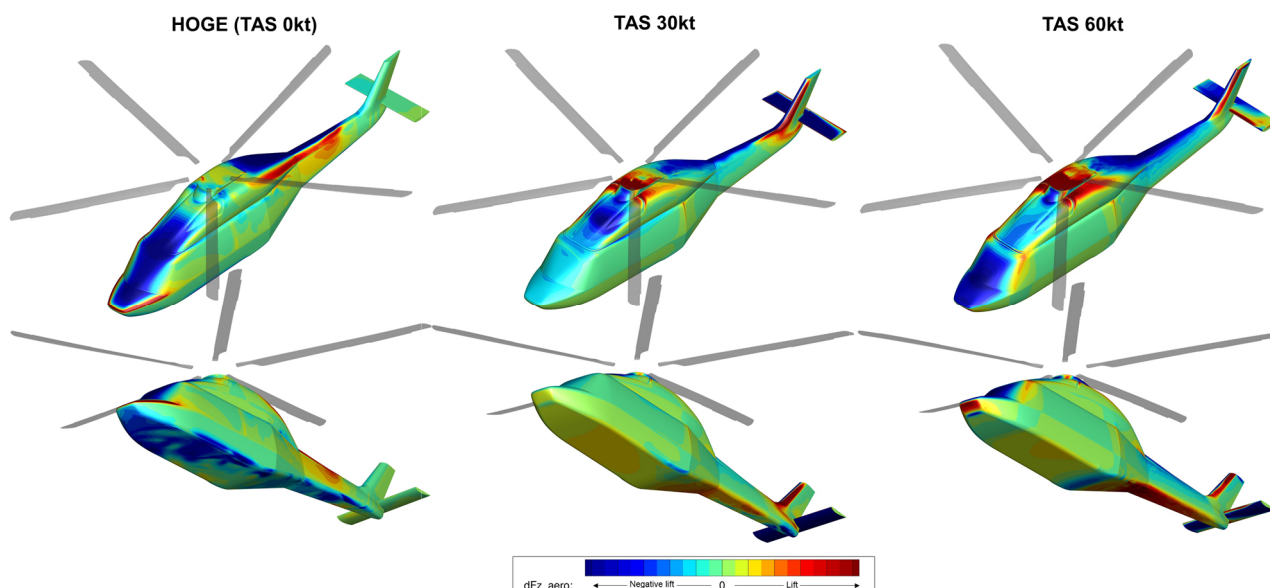


Figure 27 – Snapshots of lift distribution for different airspeeds

The horizontal stabilizer is not in the main-rotor downwash influence and consequently produces almost no aerodynamic forces, in the absence of interactions related to the tail rotor in the simulations.

For an airspeed of 30kt, it is both the lower surface and the upper surface of the horizontal stabilizer which mainly produce download. The front cabin generates much less download as in HOGE. This is because it is no more inside the main-rotor downwash at that speed, and the dynamic pressure associated to the H/C forward velocity is still too small to produce significant download. An important lift contribution stems from suction at the fin leading edge. At 60kt, cabin nose and windshield again produce a large download because the dynamic pressure due to the H/C forward velocity is similar to the dynamic pressure of the main-rotor induced velocity field in HOGE. The two surfaces of the horizontal stabilizer continue to generate negative lift but at lower levels, and with an asymmetry, following the growth of differences between advancing and retreating blade loading with flight speed. An important lift contribution has developed on the convex part of the engine cowling close to the rotor center.

A lift breakdown averaged over a rotor revolution is proposed in Figure 28 for each airspeed considered in this work. Lift values are obtained by surface integrations of the lift surface density on each part mentioned in this figure. It shows very explicitly the transfer of the download main source from the cabin in HOGE (65% of total download) to the horizontal stabilizer around 30kt–40kt corresponding to situations that maximize the H/C pitch-up phenomenon (85% of total download). Then for largest speeds, download is reduced, as a result of less negative angles of attack at the empennage, along with production of lift at the upper deck. The airframe total download variations with airspeed obtained by CFD is illustrated in Figure 29.

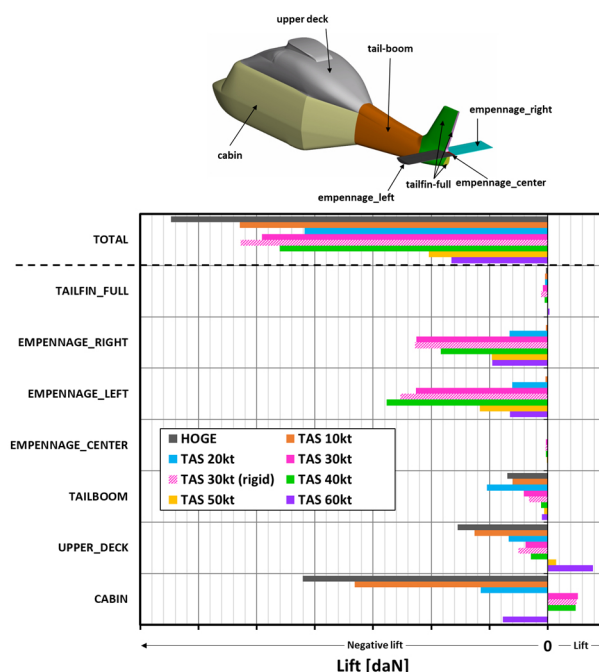


Figure 28 – Lift breakdown (mean) for different airspeeds

The general trend is a download decrease with an increase of airspeed. However, an increase of download is observed when pitch-up is maximal, i.e. for airspeeds of 30 to 40kt. It is remarkable that the asymmetry of the stabilizer download, or its roll moment, changes its sign between 50kt and 60kt; one contributing factor to unloading the left stabilizer wing at the highest speed is the significant antitorque generated by the fin, whose low-pressure field extends over the left stabilizer.

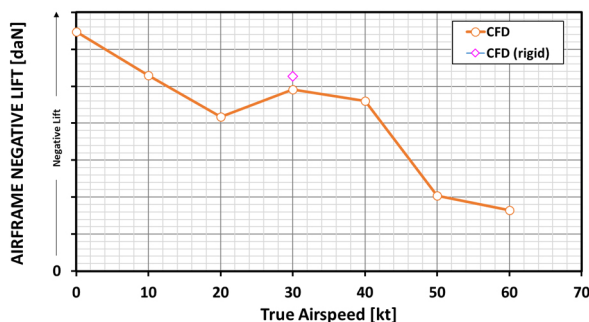


Figure 29 – Airframe total download (mean) for different airspeeds

5.8. Wake visualization

Global wake visualizations are proposed in Figure 30 in HOGE, and for airspeeds of 30kt and 60kt. Iso-surfaces of the Q-criterion of Jeong & Hussain have been considered to represent the vortical structures. The very complex wake, leading to vortex break-up or pairing in HOGE, and arising from strong mutual interactions at the low main rotor advance ratios, is highlighted. In particular, the stabilizer appears to be free of any major interactions with the main rotor in HOGE. Nonetheless, for an airspeed of 30kt, the vertical fin is in the helicoidal wake of the main rotor blade tip vortices, while the horizontal stabilizer is affected by the vortical structures generated at the blade roots (highlighted by the arrows in magenta). For an airspeed of 60kt, the horizontal stabilizer remains in a complex wake originating from blade roots, from flow separations at the cowlings, and from flow separations at the backdoor and aft fuselage.

6. CONCLUSIONS

In the present work, the five-bladed H175 main-rotor mounted on the PT1 fuselage has been simulated in HOGE and for various low-speed conditions with a 6DoF CSD/CFD single-rotor loose coupling. This approach is demonstrated to reproduce well in-flight measurements, provided the main-rotor blade elastic properties are considered in the CSD model. Comparisons have been

conducted on indicators related to H/C performance, aircraft trim, and rotor control loads. Main-rotor collective pitch, rotor shaft power, airframe attitudes and pitch-link loads are indeed well predicted both in trend and levels for airspeeds ranging from 0kt to 60kt. In particular, the pitch-up phenomenon is well captured in the simulations.

Simulation analyses give insight into the mechanisms of rotor/airframe interactions that lead to the production of negative lift at low speeds. Depending on the forward speed, the airframe (accounting for 65% of the total download in HOGE) or the horizontal stabilizer (85% at 30kt) are the main elements contributing to download generation. This is accompanied by a significant variation in the pitch attitude of the aircraft.

Slight discrepancies between simulations and flight data are observed at very low speeds (<20kt) in the tail-rotor power, and airframe attitudes. This is because the sidewash of the canted tail rotor impinges the vertical fin and the left-hand side of the horizontal stabilizer, as evaluated in complementary actuator-disc computations. Those interactions are missed on the CFD side, as no tail-rotor is implemented in the numerical model; aerodynamic loads on the tail unit on the CSD side remains consequently non-corrected. Introducing the tail rotor in the CFD simulations is the next improvement step.

Considering rigid main-rotor blades does not allow to accurately predict the collective pitch or the control loads. However, pitch-up is qualitatively well reproduced, as well as the rotor shaft power at the speed of 30kt. Nonetheless, airframe download remains numerically slightly overestimated, compared to the download assuming elastic blades.

The high-fidelity solutions provided in this work may serve as a reference and thus allows us to glimpse into a more general methodological work concerning medium-fidelity methods (Actuator disks, Actuator lines, Unsteady Panel Methods, wake models etc.) for the performance, loads and airframe attitude assessments at low speeds, with the goal of shortening restitution time while mastering the prediction accuracy.

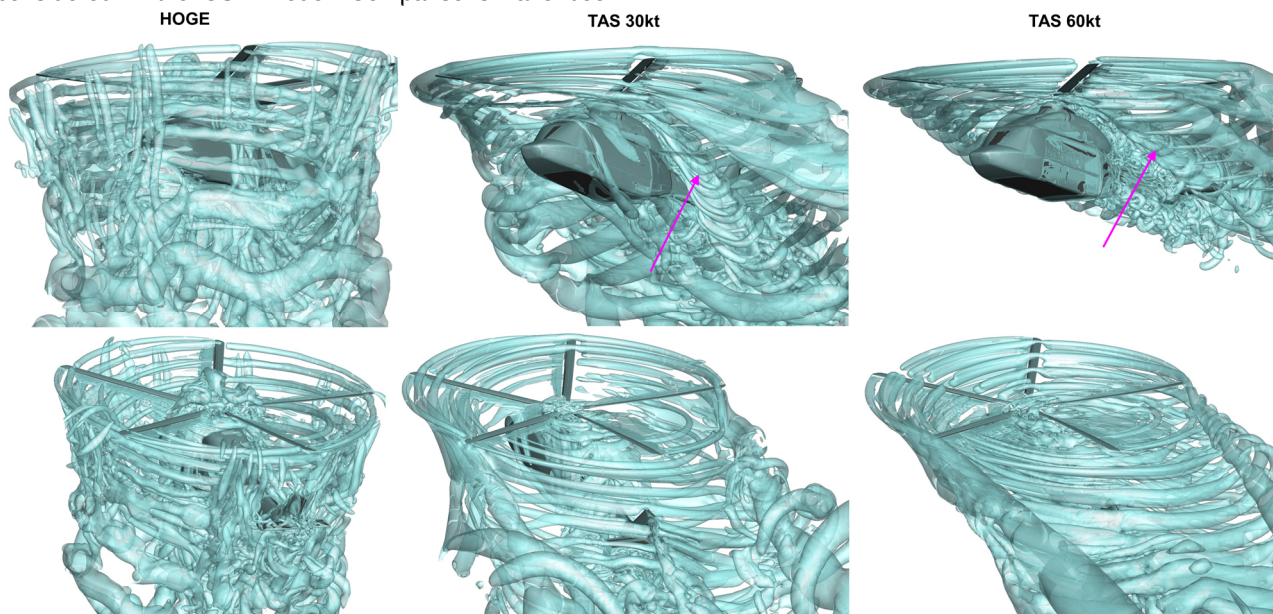


Figure 30 – Snapshots of Q-criterion isosurface for different airspeeds ($Q = 50 \text{ rad}^2/\text{s}^2$); blade-root wake highlighted in magenta

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ABBREVIATIONS

AD	Actuator Disc
AH	Airbus Helicopters
CFD	Computational Fluid Dynamics
CG	Center of Gravity
CSD	Computational Structure Dynamics
CHARME	CHALLENGE AeRoMEchanique
DoF	Degrees of Freedom
GOAHEAD	Generation Of Advanced Helicopter Experimental Aerodynamic Database for CFD code validation
IGE	In Ground Effect
ISA	International Standard Atmosphere
MR	Main Rotor
FT	Flight Test
H/C	Helicopter
HOGE	Hover Out of Ground Effect
OGE	Out of Ground Effect
RANS	Reynolds Averaged Navier Stokes
STORM	Simulation Tools for Overall Rotorcraft Modeling
TR	Tail Rotor
URANS	Unsteady Reynolds Averaged Navier Stokes

SYMBOLS

AoA	Rotor angle of attack	[°]
MR COLL	Main rotor collective pitch	[°]
TR COLL	Tail rotor collective pitch	[°]
MR LATCYC	Blade lateral cyclic pitch	[°]
MR LNGCYC	Blade longitudinal cyclic pitch	[°]
NR	Rotor rotational speed w.r.t. nominal speed	[%]
R	Rotor radius	[m]
TAS	True Air speed	[kt]
Z _p	Pressure altitude	[ft]
θ	Cell pitch attitude	[°]
Φ	Cell roll angle	[°]
Ψ	Cell yaw angle	[°]
ψ	Blade azimuth of the MR ref. blade	[°]

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