

41th European Rotorcraft Forum Munich, 1-4 September, 2015 Paper 46

## CFD-BASED SIMULATION OF HELICOPTER IN SHIPBORNE ENVIRONMENT

C. CROZON, R. STEIJL AND G.N. BARAKOS

CFD Laboratory, School of Engineering University of Liverpool, L69 3GH, U.K. http://www.liv.ac.uk/cfd crozon@liverpool.ac.uk, rsteijl@liverpool.ac.uk, g.barakos@liverpool.ac.uk

## ABSTRACT

The development of High Performance Computing and CFD methods have evolved to the point where it is possible to simulate complete helicopter configurations with good accuracy. CFD methods have also been applied to problems such as rotor/fuselage and main/tail rotor interactions, performance studies in hover and forward flight, rotor design, etc. The GOAHEAD project is a good example of a coordinated effort to validate CFD for complex helicopter configurations. Nevertheless, current efforts are limited to steady flight and focus mainly on expanding the edges of the flight envelope. The present work tackles the problem of simulating manoeuvring flight in a CFD environment by integrating a multi-body grid motion method and the Helicopter Flight Mechanics (HFM) solver with CFD. After a discussion of previous works carried out on the subject and a description of the methods used, validation of CFD for ship airwake flow and rotorcraft flight at low advance ratio are presented. Finally, the results obtained for manoeuvring flight cases are presented and discussed.

#### NOMENCLATURE

$\Psi, O, \Psi$ –	Body attitude angles
$\Phi_{wind}  \Psi_{wind}$	= Wind incoming pitch and yaw angles

- Rody attitude angles

 $\Psi_R$  = Rotor azimuth

AQU

- $\theta_0^M, \theta_0^T$  = Main and tail rotor collective angles
- $\theta_{1s}, \theta_{1c}$  = Main rotor cyclic angles
- A, B, C = Matrices of the linear model
- $F_x F_y F_z$  = Global forces at CG
- L M N = Global moments at CG
- p, q, r = Body rotation rates
- u, v, w = Body velocities
- $x_e, y_e, z_e$  = Body position in earth-fixed FoR
- $\vec{F}_i, \vec{F}_v$  = Inviscid and viscous fluxes
- $\mathbf{R}_{i,j,k}$  = Flux residuals at cell (i, j, k)
- $\vec{S}$  = Source term

$ec{u}_h$	= Local velocity in the rotor-fixed FoR
V(t)	= Time dependent control volume
$\mathbf{w}_{i,j,k}$	= Discretised conserved variables vector
$\vec{\mathbf{w}}$	= Conserved variables vector
ρ	= Air density
$\vec{\omega}$	= Rotor rotational speed

## **1** INTRODUCTION

## 1.1 Background

State-of-the-art Computational Fluid Dynamics (CFD) methods and High-Performance Computing (HPC) facilities have advanced to the point where full helicopter configurations can be simulated with unprecedented levels of detail and good overall accuracy, even for challenging flight conditions [4].

CFD has been used to help understanding a variety of problems: rotor/airframe and main/tail rotor interference, helicopter performance in hover and forward flight, rotor and airframe design. The European project GOAHEAD aimed at

Copyright Statement<sup>©</sup> The authors confirm that they, and/or their company or organisation, hold copyright on all of the original material included in this paper. The authors also confirm that they have obtained permission, from the copyright holder of any third party material included in this paper, to publish it as part of their paper. The authors confirm that they give permission, or have obtained permission from the copyright holder of this paper, for the publication and

distribution of this paper as part of the ERF2014 proceedings or as individual offprints from the proceedings and for inclusion in a freely accessible web-based

providing a high-quality database for validating CFD solvers. The experiments were conducted in the DNW wind tunnel [4]. Various flight conditions were simulated using a scaled model of a helicopter resembling the NH90, with a fourbladed main rotor and a two-bladed tail rotor. This case has since been used to validate numerous CFD codes [19,29,57].

Helicopters are versatile aircraft with capabilities that extend beyond quasi-steady flight: rapid transition from hover to forward flight, operations in confined area and various manoeuvres. The Aeronautical Design Standard performance specification handling qualities requirements for military rotorcraft (ADS-33D-PRF) document provides guidelines on helicopter manoeuvring capabilities required for military operations.

Ship/Helicopter Take-Off/Recovery Operations - also refered to as the Dynamic Interface problem [67] - is a typical example of "worst-case scenario" when characterising the handling qualities of an aircraft. Consequently, expensive and time-consuming campaigns of at-sea trials are conducted to certify every Aircraft/Ship combination and define their operating limitations in terms of admissible wind strength and direction [25]. Extensive experimental and numerical works have been carried out to reproduce the conditions of at-sea trials and expand the range of conditions investigated.

Experimental works include wind-tunnel measurements of the ship airwake [45, 49, 62, 68] and interaction between obstacles and rotor wakes [26, 34, 35, 39, 46, 51, 55, 63, 64, 66] as well as full-scale campaigns [52, 53]. Numerical works include characterisation of ship wakes using numerical models [21, 24, 31, 42, 58, 61], integration of the results into flight simulation environment [14, 28, 47, 48], simultaneous Ship/Aircraft CFD simulations [43, 44] and attempts to couple CFD, flight dynamics and pilot models to capture their interactional effects [2, 13, 22, 32, 33].

Simulating manoeuvring flight requires coupling CFD with flight mechanics methods and tracking or pilot models. With the problem of simulating the Dynamic Interface in mind, the relationships between the components of the simulation are shown in figure 1. The helicopter and ship aerodynamics as well as external disturbances can be modelled directly in the CFD solver while the integrated loads are passed on to the flight mechanics method to determine the helicopter position and attitude. Then, a tracking method or pilot model is added to adjust the helicopter controls and follow a prescribed trajectory. The tracking can be optimal using minimisation methods or realistic, by modelling human behaviour. External information and sensory cues may be used by the pilot model and it includes physiological and environmental feedbacks [37].

## 1.2 Methodology for Dynamic Interface Simulation

A standalone Helicopter Flight Mechanics (HFM) framework was developed based on simplified models (Blade Element Theory, inflow model and aerodynamic tables), and integrated into the CFD solver HMB2 of the University of Liverpool.

A versatile grid motion method was also implemented and the formulation of the CFD solver adapted to use an earthfixed frame of reference, in addition to the wind-tunnel frame of reference used by most CFD solvers. Integrated loads and helicopter state information are passed between the flight mechanics and CFD solvers at every time step. Spatial transformations are applied to account for the fact that HFM and HMB use different frames of reference. The integrated vehicle and component loads are also converted to dimensional values before being used in HFM.

HFM also implements a fuselage polar and Blade Element Momentum (BEM) method with a dynamic inflow model to estimate the blade aerodynamics. Therefore, it can run as a standalone code at a much reduced computational cost in comparison to CFD. The present methodology relies on the approximate models to generate the linear models of the aircraft necessary for the trimming and pilot control methods. Integrated aerodynamics loads from CFD are substituted directly to the approximate ones by HFM during re-trimming and simulated flight. Individual branches of the typical Navy landing manoeuvre serve as test cases for simulating manoeuvring flight, using a Sea King helicopter geometry with 5bladed main and tail rotors. For shipborne manoeuvres, a simplified Halifax-class Frigate geometry is used, known in the literature as the Canadian Patrol Frigate (CPF) [34].

Various comprehensive codes have been developed such as HOST (Eurocopter), CAMRAD II (Johnson Aeronautics), MBDyn (Politecnico di Milano), UMARC (University of Maryland), CHARM/RCAS (US Army). They include blade aero-elasticity, advanced wake modelling, empirical corrections and the low computational cost allows for the simulation of complex flight condition, even in real time. However, some effects are only captured directly by CFD: blade-vortex interaction, main/tail rotor interaction, main rotor/fuselage interaction, dynamic stall, etc.

Typically, analytical tools are used to predict the helicopter and rotor system states that are then used for CFD simulations, although consistency between the two results can be obtained only by coupling the methods. A large amount of work has been done in coupling CFD and analytical tools particularly for accurately predicting the rotor blade motion and deformation. Depending on the objective, different levels of coupling may be used. In the case of a weak/loose coupling, information is exchanged, usually every main rotor revolution. The concept of (very) strong/tight coupling requires that the two problems work with the same time-scales. Typically, data is exchanged at every time step or sub-step of the CFD solver, so as to ensure consistency between the two methods. Weak coupling is sufficient to determine the trim state of a rotor system for a given flight condition but strongly coupled, time-accurate simulations are required if the system has no time-periodicity, such as during manoeuvres.

Rotorcraft blades are highly flexible elements and deformations and these deformations need to be taken into account using dedicated Computational Structural Dynamics (CSD) codes to predict the aircraft performance accurately Numerous studies aimed at including blade aero-elasticity to a CFD solver to account for deformations in flapping and lead-lag. To achieve CFD/CSD coupling, a finite element model is built to match the blades structural properties. The increased complexity of the system usually leads to longer convergence time but the accuracy of the solution is greatly improved.

#### 1.3 Past Works

Ananthan *et al.* [3] interfaced the UMARC code with two CFD codes, OVERTURNS and SUmb, in a looselycoupled fashion and added acoustic predictions to the simulations of the SMART Rotor. Test cases included trailing edge flaps and experimental data was collected by DARPA/NASA/Boeing/Army in 2008. Results showed good agreement, although the study focuses primarily on noise prediction.

The case of the UTTAS pull-up manoeuvre is frequently reported in the literature [1, 10, 59]. The manoeuvre was performed using an instrumented UH60 helicopter and is of great interest as it extends outside of the aircraft flight envelope. During the manoeuvre, the aircraft experiences up to 2.1g acceleration with important stall events and transonic flow regions on the blades. In a key study from Baghwat et al. [10], the 40 revolutions of the UTTAS pull-up manoeuvre were analysed, in terms of blade loading, rotor hub forces and moments, blade flapping and lead-lag behaviour, pushrod and lag damper forces. The standalone RCAS code implementing a lifting line method with dynamic inflow model was compared with the coupled RCAS/OVERFLOW2 method. The coupled method consistently reduces the discrepancy with the experimental data, mainly due to the fact that it is a fast, highly loaded manoeuvre, with stalled and transonic flow regions that are poorly predicted using the lifting line theory. However, it was noted that CFD did not always capture these effects and the improvements it offered may be more or less significant, depending on the flow conditions. Improving the CFD grid and the turbulence models employed were put forward as possible remedies. The paper also concluded that quasi-steady simulations reproducing some specific instants of the manoeuvre offered good results at a much reduced computational cost. However, this was based on the fact that the conditions of the flight were known, and derived directly from the experimental data. In case of a blind-test manoeuvre, the full simulation was still required. The simulations were carried out for the main rotor only: both the fuselage and the tail rotor have been ommited. This simplification has consequences, especially on the prediction of blade flapping at peak loading.

Abishek *et al.* [1] also studied the UTTAS pullup manoeuvre using the UMARC/OVERFLOW2 coupled CFD/CSD method by predicting deformations from measured airloads and using these deformations for lifting-line and CFD analyses. The control angles were determined *a priori* using the lifting line method, in an iterative fashion, to obtain the forces and moments recorded during the campaign. The study focused on capturing and explaining dynamic stall events that occured the high-loading phase of the manoeuvre. Interestingly, the CFD simulations were performed in a non-inertial frame of reference and therefore the inertial effects are added to the Navier Stokes equations as a source term.

Masarati *et al.* [36] developed a multidisciplinary multibody framework designed to handle multi-physics problem by interfacing any external code. The method found applications for rotorcraft studies: modelling of pilot arm dynamics, flapping wing fluid/structure coupling but has not been applied to helicopter rotor systems in manoeuvring flight as of yet.

Yu et al. [65] coupled the CHARM and RCAS analytical

tools to combine the fast lifting surface method, free-wake and panel fuselage models of CHARM with the deforming rotor system of RCAS. More accurate results were obtained using CHARM's advanced methods over simple aerodynamic tables and lifting line theory. The method also benefits from being more computationally efficient than CFD.

Beaumier *et al.* [9] and Servera *et al.* [50] of ONERA coupled the HOST method with the CFD code elsA to include blade motion and aero-elasticity into the simulation. Results were compared against experimental data available for the 7A/7AD rotor. Weak "once-per-revolution" and strong "once-per-time-step" coupling methods were investigated. Similar results were reported in terms of rotor trim condition and the weak coupling is shown to converge more efficiently. However, it was noted that although the weak coupling method was good for periodic conditions, it was not appropriate for non-periodic flights.

A similar method was implemented in the HMB2 solver to couple NASTRAN and HMB [18]. The paper also gives an overview of the literature on CFD/CSD coupling. Results are limited to hover but show reasonable agreement with the experimental data available.

Lee [32] studied the ship-helicopter interaction by performing one-way coupled calculations: the ship wake is calculated prior to the calculation and loaded as a set of look-up tables into the analytical tool to simulate the unsteadiness of the ship wake. The method is similar to what is used in most flight-simulation environments as it uses of simplified models and lacks feedback from the rotor to the ship wake.

Bridges *et al.* [13] used the same approach but performed two-way calculations in which the information from the rotor loading is fed back to the CFD via the use of momentum source terms. Again, the rotor is simulated analytically and suffers from several simplifications. However, simulations include the use of a pilot model and the comparison of the results with a human-piloted maneuver show similar variations of control history.

### 1.4 Objectives of the Current Work

The present work demonstrates coupling of CFD and flight mechanics for the simulation of manoeuvring rotorcraft and applies it for the case of ship/helicopter landing. The CFD method has been adapted to solve the Navier-Stokes equations directly in the inertial "earth-fixed" frame of reference. The Helicopter Flight Mechanics solver HFM was also designed for the study of rotorcraft dynamics and includes a trimming algorithm and a pilot model. The underlying method and its implementation in HMB are then described.

The following section presents elements of validation of the HMB solver for helicopters in forward-flight at low advance ratio and the prediction of ship wakes. Subsequently, a typical ship landing manoeuvre is split into three elements that serve as simpler tests for demonstrating the new coupled method. The paper finishes with conclusions and elements of future work.

#### **2** NUMERICAL METHODS

#### 2.1 CFD Solver

The HMB2 code of Liverpool [8] was used for solving the flow around different ship and rotor geometries. HMB2 is a Navier-Stokes solver employing multi-block structured grids. For rotor flows, a typical multi-block topology used in the University of Liverpool is described in Steijl *et al.* [56]. A C-mesh is used around the blade and this is included in a larger H structure that fills up the rest of the computational domain. For parallel computation, blocks are shared amongst processors and communicate using a message-passing paradigm.

HMB2 solves the Navier-Stokes equations in integral form using the Arbitrary Lagrangian Eulerian (ALE) formulation for time-dependent domains with moving boundaries:

$$\frac{d}{dt} \int_{V(t)} \vec{\mathbf{w}} dV + \int_{\partial V(t)} \left( \vec{F}_i \left( \vec{\mathbf{w}} \right) - \vec{F}_v \left( \vec{\mathbf{w}} \right) \right) \vec{(n)} dS = \vec{S}$$
(1)

where V(t) is the time dependent control volume,  $\partial V(t)$  its boundary,  $\vec{\mathbf{w}}$  is the vector of conserved variables  $[\rho, \rho u, \rho v, \rho w, \rho E]^T$ .  $\vec{F_i}$  and  $\vec{F_v}$  are the inviscid and viscous fluxes, including the effects of the time dependent domain.

The Navier-Stokes equation are discretised using a cellcentred finite volume approach on a multi-block grid, leading to the following equations:

$$\frac{\partial}{\partial t} \left( \mathbf{w}_{i,j,k} V_{i,j,k} \right) = -\mathbf{R}_{i,j,k} \left( \mathbf{w}_{i,j,k} \right)$$
(2)

where w represents the cell variables and R the residuals. *i*, *j* and *k* are the cell indices and  $V_{i,j,k}$  is the cell volume. Osher's [40] upwind scheme is used to discretise the convective terms and MUSCL variable interpolation is used to provide up to third order accuracy. The Van Albada limiter is used to reduce the oscillations near steep gradients. Temporal integration is performed using an implicit dual-time stepping method. The linearised system is solved using the generalised conjugate gradient method with a block incomplete lower-upper (BILU) pre-conditioner [7].

#### 2.2 CFD Grids

A total of four grids have been used to validate the HMB2 solver. The SFS2 ship was meshed using three sizes for a sensitivity study, the finest being around 15 million cells. The GOAHEAD helicopter model contained a total of 90 million cells, including four-bladed main and two-bladed tail rotors, with attention paid to the region of the flow between the rotor and the tail plane and in the near wake, to capture as accurately as possible the shed vortices. Figure 2 shows the grid topology and the details of the mesh on the surface and on the midplane cut in the region above the deck.

Eight structured, multi-block grids are used in this work, for a total of four components: Sea King helicopter fuselage, main and tail rotor, and Canadian Patrol Frigate (CPF). The helicopter fuselage was split in three sections to ease the meshing process; the three elements and the two five-bladed rotors are interfaced using sliding planes. The total number of cells reaches 23.5 million for the complete helicopter grid. A background grid was created to extend the computational domain when the helicopter is isolated. The ship mesh and its background contain a total of 31 million cells. The Sea King and CPF meshes are shown in figures 4 and 3 respectively. The detailed count of the number of blocks and cells in each grid is given in table 1.

# 2.3 Wind-Tunnel vs Earth-Fixed Frames of Reference

The usual approach for CFD simulations consists in choosing a wind-tunnel frame of reference, keeping the aircraft fuselage and rotor axis of rotation fixed. The far-field velocity is uniform and dimensionless  $U_{\infty} = 1$ , the advance ratio is set by applying a non-dimensional rotational speed of  $\frac{1}{\mu R}$  (Figure 6(a)).

This approach is not appropriate for manoeuvring flight as the aircraft is free to translate and rotate in all 6 directions. All simulations were performed in an "earth-fixed" frame of reference. Since this is also an inertial frame of reference, no acceleration terms need to be added to the Navier-Stokes equations. The dimensionless rotational speed of the rotor is  $\frac{1}{R}$  and the advance ratio in each direction are applied through the mesh velocity (Figure 6(b)). The different formulations are summarised in table 2. The table also includes the corresponding dimensional values used by the flight-mechanics solver.

To demonstrate the validity of using the earth-fixed frame of reference and the new grid motion approach, the ONERA non-lifting rotor was used with an advance ratio of  $\mu = 0.5$ . Figure 7 shows the contours of pressure on the blades at different azimuths obtained from the two technique. There is no visible difference between the two sets of results.

#### 2.4 Multi-Body Motion Method

A multi-body motion method was also implemented to allow the relative motion of any grid with respect to another. One or several grids are defined in the absolute frame of reference, and subsequent grids are hierarchised by referring to a parent grid previously defined. The various grids are interfaced using either sliding plane boundaries, the chimera method, or both simultaneously. The rotors are treated separately as they require mesh deformation to allow for pitching and flapping motions, and possibly elastic blade deformations.

In this work, the most complex case is the manoeuvring Sea King above the ship deck. The absolute frame of reference contains the ship and fuselage grid that are allowed to move independently using the chimera method, the main and tail rotors are added, with the fuselage being their parent component. The transformations of each element are calculated at each time iteration. these put the mesh components to their reference position, calculate the loads on each element and position the grids for the next time step. The x-y-z convention is used for the rotation of every component except the blades which articulate according to the hinge order.

$$\begin{cases} \underline{\underline{R}}^{0} = \underline{\underline{R}}_{Z}^{0} \cdot \underline{\underline{R}}_{Y}^{0} \cdot \underline{\underline{R}}_{X}^{0} \\ \underline{\underline{\underline{R}}}^{1} = \underline{\underline{\underline{R}}}_{Z}^{0} \cdot \underline{\underline{\underline{R}}}_{i}^{1} \\ \underline{\underline{X}}^{1} = \underline{\underline{X}}^{0} + \underline{\underline{\underline{R}}}^{0} \cdot \underline{\underline{X}}_{i}^{1} \\ \dots \\ \underline{\underline{\underline{R}}}_{N}^{N} = \underline{\underline{\underline{R}}}_{N-1}^{N-1} \cdot \underline{\underline{\underline{R}}}_{i}^{N} \\ \underline{\underline{X}}^{N} = \underline{\underline{X}}^{N-1} + \underline{\underline{\underline{R}}}^{N-1} \cdot \underline{\underline{X}}_{i}^{N} \end{cases}$$
(3)

The superscript 0...N refers to the grid level: grid 0 is in the absolute frame of reference, subsequent grid n is referenced using the local coordinate system of n - 1. In this way, the global transformation of a grid can be obtained by successively applying each transformation from the grid 0 to the grid n. This method incurs no restriction on the hierarchy, except for the fact that the hierarchy is defined in order of the grid levels.

#### **3** HELICOPTER FLIGHT MECHANICS

#### 3.1 Flight Mechanics Method

The Helicopter Flight Mechanics (HFM) method is a purposebuilt multi-body dynamics solver that was designed specifically for rotorcraft applications. A structural model gives a description of the aircraft and the relationship between the different components, as depicted in figure 8. The fuselage, tail plane and fin are assimilated to singular points where the forces and moments are applied. The fin and tail plane are weightless but contribute separately to the budget of loads.

With the forces and moments written at the center of gravity and the action of gravity added explicitly, the Euler's equations of motion read as follows:

$$\begin{cases} \dot{u} = v r - q w + \frac{F_x}{M} - g \sin \theta \\ \dot{v} = w p - u r + \frac{F_y}{M} + g \cos \theta \sin \phi \\ \dot{w} = u q - v p + \frac{F_z}{M} + g \cos \theta \cos \phi \end{cases}$$
(4)

$$\begin{cases}
\mathbf{I}_{xx}\dot{p} = \mathbf{I}_{xy} p r + (\mathbf{I}_{yy} - \mathbf{I}_{zz}) q r \\
+\mathbf{I}_{yz} (r^2 + q^2) + \mathbf{I}_{xz} p q + \mathbf{L} \\
\mathbf{I}_{yy}\dot{q} = \mathbf{I}_{yz} p q + (\mathbf{I}_{zz} - \mathbf{I}_{xx}) r p \\
+\mathbf{I}_{xz} (p^2 - r^2) + \mathbf{I}_{xy} q r + \mathbf{M} \\
\mathbf{I}_{zz}\dot{r} = \mathbf{I}_{xz} q r + (\mathbf{I}_{xx} - \mathbf{I}_{yy}) p q \\
+\mathbf{I}_{xy} (q^2 - p^2) + \mathbf{I}_{yz} p r + \mathbf{N}
\end{cases}$$
(5)

Where M is the mass of the aircraft,  $I_{ij}$  the matrix of inertia:

$$[I] = \begin{bmatrix} I_{xx} & I_{xy} & I_{xz} \\ I_{xy} & I_{yy} & I_{yz} \\ I_{xz} & I_{yz} & I_{zz} \end{bmatrix}.$$
 (6)

Data is tabulated for a range of Reynolds and Mach numbers and interpolated at the local flow conditions. The Blade Element Momentum (BEM) method is used for the rotors. Each blade is split in 20 segments, each approximated to a 2D section and loads are calculated as functions of the Reynolds and Mach numbers.

To augment the BEM, the 3-state linear dynamic inflow model by Peter and He [41] is implemented to calculate the component of inflow velocity through the rotor disk.

$$[\mathbf{M}] \begin{pmatrix} \lambda_0 \\ \dot{\lambda}_{1s} \\ \dot{\lambda}_{1c} \end{pmatrix} + [\mathbf{L}]^{-1} \begin{pmatrix} \lambda_0 \\ \lambda_{1s} \\ \lambda_{1c} \end{pmatrix} = \begin{pmatrix} C_{\mathrm{T}} \\ -C_{\mathrm{L}} \\ -C_{\mathrm{M}} \end{pmatrix}$$
(7)

In the above [L] the matrix of the linear system, and [M] the apparent mass term:

$$[\mathbf{M}] = \begin{bmatrix} \frac{8}{3\pi} & 0 & 0\\ 0 & \frac{16}{45\pi} & 0\\ 0 & 0 & \frac{16}{45\pi} \end{bmatrix}$$
(8)

and

$$[L] = \begin{bmatrix} \frac{1}{2} & 0 & -\frac{15\pi}{64}\sqrt{\frac{1-\sin\alpha}{1+\sin\alpha}} \\ 0 & \frac{4}{1+\sin\alpha} & 0 \\ \frac{15\pi}{64}\sqrt{\frac{1-\sin\alpha}{1+\sin\alpha}} & 0 & \frac{4\sin\alpha}{1+\sin\alpha} \end{bmatrix}$$
(9)

Table 3 summarises the benefits of using the coupled HFM/CFD method over the simplified models of the standalone HFM. The inflow model and blade aerodynamics, in particular, use first order approximations and a set of lookup tables, and do not take into account the 3D and unsteady effects typical of rotor blades.

For this study, The MK50 Sea King helicopter was chosen. It is a medium-lift transport and utility helicopter designed and widely used for maritime operations, capable of carrying up to 28 troops for a maximum take off weight of about 9700 kg. Information about the MK50 model can be found in a series of DTIC reports [5,6,20]. The main characteristics of the aircraft are collected in table 4

### 3.2 Trimming Method

Trimming the helicopter consists in finding the appropriate pilot inputs and aircraft attitude to maintain the aircraft in a specified steady flight condition. The method builds a jacobian matrix (equation 10) from a chosen set of parameters (equation 11) and variables (equation 12) and uses this matrix to find the values of the pilot inputs that minimise forces and moments applied to the body in the 6 directions. The four pilot inputs and two body attitude angles are chosen as parameters so as to obtain a system of 6 equations and 6 dependant variables.

$$\boldsymbol{J} = \left(\frac{d\boldsymbol{f}_i}{dx_j}\right)_{i,j} \tag{10}$$

$$\boldsymbol{x} = (\theta_0^{\mathrm{M}} \ \theta_{1\mathrm{c}} \ \theta_{1\mathrm{s}} \ \Theta \ \Phi \ \theta_0^{\mathrm{T}})^{\mathrm{T}}$$
(11)

$$\boldsymbol{f} = (F_{\mathrm{X}} F_{\mathrm{Y}} F_{\mathrm{Z}} L M N)^{\mathrm{T}}$$
(12)

The problem then consists in calculating the update value for the parameters  $\delta x$  so that the calculated forces  $\delta f$  are minimised:

$$\delta \boldsymbol{x} = \boldsymbol{J}^{-1} \delta \boldsymbol{f} \tag{13}$$

The matrix is recalculated before each iteration to increase stability and convergence speed. A second trimming method has been implemented in HMB/HFM, referred to as hybrid trimming: it uses a reduced system of four equations, where the parameters  $\Theta$  and  $\Phi$  are frozen to the previously calculated value, and replaces the loads by the ones obtained in the CFD. The reduced Jacobian is calculated around the previous trim

state using the same method as previously, with the following variables/parameters:

$$\boldsymbol{x} = (\theta_0^{\mathrm{M}} \ \theta_{1\mathrm{c}} \ \theta_{1\mathrm{s}} \ \theta_0^{\mathrm{T}})^{\mathrm{T}}$$
(14)

$$\boldsymbol{f} = (F_Z \ L \ M \ N)^{\mathrm{T}} \tag{15}$$

After convergence, the helicopter is trimmed and it is possible to start simulating manoeuvring flight without inconsistencies between the flight mechanics and the CFD.

### 3.3 Manoeuvring Flight

During a manoeuvre, the aircraft is out-of-trim and the global loads applied to the system are not null, furthermore the pilot controls must be in accordance with the objective of the manoeuvre, typically following a predetermined flight path.

To simulate manoeuvring helicopters, controllers were developed and designed to be representative of the behaviour of a real pilot. The SYCOS method has been widely used in the past [12,60] and is based on inverse simulation: an inverse model of the aircraft consists of a set of matrices that allow to compute pilot inputs from a determined flight path. The model is linear and can be solved analytically only for simple cases. The SYCOS method uses an approximate linear inverse model along with a correction method that modifies the problem depending on how accurately the helicopter is following the pre-determined flight path. The SYCOS method proved to be suitable for simulating standard maneuvers described in the ADS33 documentation such as a slalom [60].

To provide good control and trajectory tracking performance for more complex helicopter models, more advanced models are needed. The Linear-Quadratic Regulator [30] is an example of a widely used control method based on leastsquares minimisation. It uses a full linear model of the aircraft to provide control estimates during a manoeuvre, given a prescribed trajectory. The inverse modelling method is presented here as it permits to *a priori* estimate the pilot controls but the LQR method was applied for piloted simulations, with or without CFD.

A typical formulation for inverse modelling is:

$$\dot{\boldsymbol{x}} = A\boldsymbol{x} + B\boldsymbol{u} \tag{16}$$

where *x* and *u* are the state and control vectors respectively:

$$\boldsymbol{x} = (u \, v \, w \, p \, q \, r \, \boldsymbol{\Phi} \, \boldsymbol{\Theta} \, \boldsymbol{\Psi}) \tag{17}$$

$$\boldsymbol{u} = (\theta_0^{\mathrm{M}} \ \theta_{\mathrm{1c}} \ \theta_{\mathrm{1s}} \ \theta_0^{\mathrm{T}}) \tag{18}$$

The output equation is also added that contains the prescribed variables:

$$\boldsymbol{y} = C\boldsymbol{x} \tag{19}$$

The role of the matrix C is to select a set of variables and reduce the system so that A becomes square. The number of parameters is usually four; if the earth-based components of velocity and the heading angle are prescribed, the output vector y is:

$$\boldsymbol{y} = (u_{\mathrm{e}} \, v_{\mathrm{e}} \, w_{\mathrm{e}} \, \boldsymbol{\Psi}) \tag{20}$$

Pilot controls come directly from prescribing  $y^*$  in the inverse problem:

$$\boldsymbol{u}^* = (CB)^{-1} (\dot{\boldsymbol{y}}^* - CA\boldsymbol{x}) \tag{21}$$

By prescribing  $y^*$ , the inverse modelling method allows to predict the pilot controls required to follow the trajectory.

The LQR method [30] is based on a full linear model of the aircraft; the state space and control vectors are modified so that:

$$\boldsymbol{x} = (u \ v \ w \ p \ q \ r \ x_{e} \ y_{e} \ z_{e} \ \Phi \ \Theta \ \Psi) \tag{22}$$

$$\boldsymbol{u} = \left(\theta_0^{\mathrm{M}} \ \theta_{\mathrm{1c}} \ \theta_{\mathrm{1s}} \ \theta_0^{\mathrm{T}}\right) \tag{23}$$

and build the linearised 6-DoF model of the rotorcraft around the trim state  $(\boldsymbol{x}^*, \boldsymbol{u}^*)$  as

$$\delta \dot{\boldsymbol{x}} = A \delta \boldsymbol{x} + B \delta \boldsymbol{u} \tag{24}$$

The nonlinear function f(x, u) describes the evolution of the state space vector from the trim state  $x^*$  to the state x under the action of the fixed input u, and is computed by integrating equation 24 over some revolutions of the rotor to let the flapping motion transient be sufficiently damped.

The aim of an autopilot is to control the position  $(x_e, y_e, z_e)$  of the helicopter in earth reference frame and its heading  $\Psi$ . We recast this trajectory tracking problem into the LQR setting as follows. At each time instant we consider the closest trimmed condition of the helicopter and compute the associated linearised model. Then, if  $\delta x$  is the deviation of the state vector from the desired state, the variation  $\delta u$  of the controls is determined as the LQR optimal feedback due to the deviation  $\delta x$ . The LQR controller will in fact drive  $\delta x$  to zero by minimising the quadratic cost function:

$$J = \int_0^\infty \left( \delta \boldsymbol{x}^{\mathrm{T}} Q \delta \boldsymbol{x} + \delta \boldsymbol{u}^{\mathrm{T}} R \delta \boldsymbol{u} \right) \mathrm{d}t$$
 (25)

where Q and R are weighting matrices that define the "importance" of the states and of the controls in the cost function. The solution to the minimisation problem is

$$\delta \boldsymbol{u}_{\text{LQR}} = -K\delta \boldsymbol{x} \tag{26}$$

where K is the optimal feedback matrix given by

$$K = R^{-1}B^{\mathrm{T}}P \tag{27}$$

and P is the solution of the continuous algebraic Riccati equation:

$$A^{\rm T}P + PA - PBR^{-1}B^{\rm T}P + Q = 0$$
 (28)

As can be seen, the optimal LQR feedback matrix K does not depend on the solution and may therefore be calculated prior to the simulation for the various representative trim states. To achieve better tracking performance the LQR controller has been augmented with a simple PI controller:

$$\delta \boldsymbol{u}_{\mathrm{PI}} = -\operatorname{diag}(K_1^{\mathrm{P}} K_2^{\mathrm{P}} K_3^{\mathrm{P}} K_4^{\mathrm{P}})\boldsymbol{e}$$
<sup>(29)</sup>

$$-\operatorname{diag}(K_1^{\mathrm{I}} K_2^{\mathrm{I}} K_3^{\mathrm{I}} K_4^{\mathrm{I}}) \int_{t-\Delta t}^{t} \boldsymbol{e} \, \mathrm{d}t \qquad (30)$$

where e is the tracking error

$$\boldsymbol{e} = \left\{ \begin{array}{c} \boldsymbol{x}_{\mathrm{e}} - \hat{\boldsymbol{x}}_{\mathrm{e}} \\ \boldsymbol{\Psi} - \hat{\boldsymbol{\Psi}} \end{array} \right\}$$
(31)

and  $x_e$  and  $\hat{x}_e$  are the actual and desired trajectory in Earth reference frame,  $\Psi$  and  $\hat{\Psi}$  the actual and desired heading. The

coefficients  $K_i^{\text{P}}$  and  $K_i^{\text{I}}$  (i = 1, ..., 4) are, respectively, the proportional and integral gains.

The value of the control angles at each time instant is therefore given by their value in the reference trimmed condition plus the feedback given by the LQR and PI controllers:

$$\boldsymbol{u} = \boldsymbol{u}^* + \delta \boldsymbol{u}_{\text{LQR}} + \delta \boldsymbol{u}_{\text{PI}}$$
(32)

#### 3.4 Characterisation of the Linear Model

Linear models give a correct description of the aircraft behaviour under the assumption of small perturbations. Realistic manoeuvres extend beyond the small perturbations assumption where the model may not be accurate. To assess of the accuracy of the model, the response of the aircraft to a single-channel pilot input was calculated. The input chosen is a 2-second sinusoidal input in collective with an integral value of zero. The vertical position and velocity of the aircraft is shown in figure 10, along with the profile of the collective input. The direct response of the linear model and the response of the full non-linear model, with and without the "baseline deviation" due to the inherent instability of the aircraft are plotted.

The linear model response is smooth and non-diverging by nature and predicts a gain in altitude. The full model is diverging due to the unstable nature of the helicopter system and tends to return to its initial altitude.

The overall positive effect of the first half of the manoeuvre translates into a positive overall velocity for the aircraft, which is then cancelled-out during the second half and results in a gain of altitude. In the case of the full model, the first half of the manoeuvre translates into an acceleration, until a new equilibrium is reached, resulting in a given climb velocity and zero acceleration. The opposite effect occurs during the second half and returns the aircraft to its original position. The linear model accurately describes the initial phase of the manoeuvre and as such can be used to design a pilot model, but does not give an accurate approximation of the full manoeuvre.

#### 3.5 Time-Line of a Full Simulation

Ship wake prediction and rotor simulations are two different problems and involve different reference time scales and Mach and Reynolds numbers. Simulations of the isolated ship wakes showed [17] that 100 time steps per beam travel time are usually enough to capture the unsteady characteristics of the wake, while rotor simulations are usually performed with 0.25 to 1 degree of rotor azimuth per step, the ratio between the two time steps being somewhere 10 and 100.

In the first phase of the simulation, the flowfield is calculated using a time step suitable for the ship wake to eliminate the transient flow and reach a converged state (in the statistical sense). The helicopter is then included in the simulation so that the wake of the fuselage is also taken into account. However, the rotor is fixed since the time step chosen corresponds to about 12 degrees of azimuthal resolution for the main rotor - 60 degrees for the tail rotor - and would likely cause the simulation to diverge.

The simulation is then restarted, from the converged flow solution, with the smaller time step that allows to spin the two rotors. Again, the simulation is left to run for about 5 revolutions of the main rotor to allow the rotor wake to clear the airframe and reach a converged state. The loads on the rotor should be reasonably similar from one revolution to the next but are subject to variations caused by the ship wake.

The helicopter uses a trim state that was determined in free air and re-trimming is not attempted since the flow is now constantly varying. Instead, the residual forces and moments are cancelled out at the beginning of the manoeuvre to approximate trimmed flight.

Finally, the fully-coupled simulations of the shipborne manoeuvre is started. The body is frozen in space for a short period of time at the beginning of the simulation to cancel the residual loads and start feeding data into the LQR method. The aircraft is then free to move in all directions and the LQR tracking method is immediately activated to feed back pilot controls.

Figure 11 shows the time-line of the calculation.

## 4 VALIDATION WORK

CFD-based Dynamic Interface simulations require the solver to perform well across a wide range of flow conditions: low speed, low frequency flow at very high Reynolds number around the ship and fuselage, high speed flows around the rotor blades. Validation of the HMB2 solver was therefore carried out using the SFS2 ship geometry [16] and the GOA-HEAD database [11].

#### 4.1 Validation for Ship Airwake

The sharp edges typical of most ship geometries are known to fix the points of separation in the flow and generate large zones of recirculation in the vicinity of the ship superstructure. The wake is typically unsteady, with shedding frequencies in the range of 0.2-2Hz depending on the size of the elements of the superstructure and the wind speed. The Reynolds number based on the ship length is around 100 millions for a frigate while the Mach number is below 0.1.

A campaign of measurements was conducted at the Naval Surface Warfare Center Carderock Division (NSWCCD) [45, 49]. Published results include mean values of streamwise velocity, local flow pitch and yaw angle along 8 vertical lines positioned in the direct vicinity of the ship, above the landing deck (Figure 14(a)). Experiments were conducted at 0 and 60 degrees wind angle.

The numerical simulations used to reproduce the two experimental conditions using Detached Eddy Simulation with Spalart-Allmaras turbulence model (DES-SA) and the Scale-Adaptive Simulation (SAS). Results for each of the two wind angle have a similar level of agreement and only the 60 degrees case is reproduced in this paper.

A grid sensitivity study was conducted using the DES-SA model and results are reproduced in figure 12. No experimental data has been published that help estimate the level of unsteadiness to expect in the flow for this particular geometry. Simulations using DES show that a fine grid containing 15 million cells was required to capture a level of unsteadiness similar to levels reported with in-situ measurements. Mora [38] reported a turbulent intensity of about 25%

behind a scaled frigate in a wind tunnel. The typical shedding frequency is 0.6Hz, with the transient (grey area) removed for the frequency analysis. The frequency analysis in (b) and (c) show that similar levels of unsteadiness are found when using the SAS model with the intermediate and fine grid densities.

At the given flow condition, a clear dominant shedding frequency is found at 0.6Hz, which is within the 0.2-2Hz range typical of ship airwakes [69]. In the region of higher frequencies, it is found that all the grids capture well the -5/3 slope that characterises the Kolmogorov scale with the exception of the SAS model on the fine grid. This quick collapse in higher frequency content is not explained.

The finer grid was used for the rest of the ship wake study and the results were averaged in time from the unsteady solutions and over a converged and significant period of time, statistically. However, For the coupled simulations of the manoeuvring helicopter in the wake of the ship, the SAS model was used as the grid density is closer to the intermediate one and it is a numerically more robust model than the DES-SA.

Figures 14 and 15 show the results obtained using the DES-SA and SAS models respectively. The agreement between experimental and CFD data is good for both models. The DES-SA results show that the recirculation zone is overpredicted by the CFD, with some deficits of velocity, and some discrepancies in terms of downwash angle (pitch).

Considering that the SAS model performs well and is also both numerically more stable and maintain a reasonable level of unsteadiness in coarser regions of the grid, is will be preferred over the DES model in the rest of the study when a ship is present.

#### 4.2 Validation for Helicopter Configuration

The low-speed case "TC2" of the GOAHEAD database is used to validate HMB2 for helicopter configurations at low advance ratio [4].

The advance ratio is close to 0.1 and the aircraft has a nose-up pitch angle of 1.9 degrees. The main rotor pitch and flap harmonics were predicted using HOST and the same values are used here, without re-trimming. This case is characterized by important blade/vortex and vortex/tail interactions due to the low advance ratio. The experimental data available includes recordings of unsteady pressure on the fuselage, fin, tail and main rotor blades, as well as PIV measurements in the region above the tail plane.

Figure 16 shows the distribution of the mean pressure coefficient at 3 fuselage sections and good agreement with the experimental data is found at all regions of the body. Three probes were chosen to show the unsteady pressure signals at key locations on the body: below the rotor, on the side of the fuselage and on the side of the fin. Clear 4-per-rev and 10-perrev peaks in the signals are found that correspond to the main and tail rotor blade passing frequencies. The peak-to-peak values are accurately predicted in most locations, giving confidence in the global load prediction, including the unsteady characteristics.

Pressure levels on the main rotor, figure 17 show reasonable agreement, although they suffer from the uncertainty on the rotor trim values. Agreement is good around the azimuth but inboard loads are better predicted overall.

## 5 DEMONSTRATION OF THE COUPLED CFD/FM METHOD

The strongly coupled HFM/HMB2 method described in section 3.1 is demonstrated in this section for the simulation of manoeuvring rotorcraft aerodynamics. Coupled simulations are carried out by substituting the simplified models used to model the blades, fuselage aerodynamics and inflow by the loads predicted by the CFD. The CFD loads, and the aircraft position and attitude predicted using the multi-body solver are exchanged at every time step of the simulation. The nondimensional time step of  $dt = \frac{2\pi R}{N_{steps/cycle}} = 0.1636$  was chosen, with  $N_{steps/cycle} = 360$  and R = 9.3759. These value size value give one-degree and five-degree azimuthal steps of the main and tail rotor respectively, which is enough to ensure the stability of the CFD solver. The helicopter is trimmed before every attempt to simulate a manoeuvre and the linearised aircraft model required by the pilot model is computed around the trim state. The matrices used by the trimmer and the autopilot model are computationally expensive to generate using CFD if finite differences are used. Instead, the HFM method and simplified aerodynamics models are used and the Jacobian matrices are computed using finite differences.

#### 5.1 Presentation of the Simulations

A model of the Sea King MK50 helicopter was created for HFM from the data made available by the Aeronautical Research Laboratory of the Australian Defence Science and Technology Organisation (DSTO) [5, 6, 20]. Key parameters are presented in table 4.

The helicopter is trimmed before each calculation. If the LQR auto-pilot is used, the required matrices are calculated around the trim state, using HFM, before the manoeuvre and are not recalculated. For CFD calculations, a trim state that best minimises the residual loads on the aircraft was used and the residual loads were removed before starting the manoeuvre.

The case of a shipborne landing manoeuvre was chosen to demonstrate the coupled HFM/HMB2 method. An idealised landing trajectory is shown in figure 18 and consists in three branches:

- **A-B**: Approach and deceleration to come to station keeping at the nominal speed of the ship.
- **B-C**: 15 to 20 meters lateral reposition over the landing point.
- C-D: 10 to 15 meters slow descent and touchdown.

The approach **A-B** is performed on the portside of the ship to give the pilot a good visibility of the deck and ship superstructure. The lateral reposition **B-C** and descent **C-D** are performed at the nominal speed of the ship to maintain a stationary position relatively to the deck. The last two branches are critical as the helicopter must enter the ship wake and descend while maintaining an appropriate position and attitude to touchdown without over-stressing the aircraft or compromising the crew safety. The reported maximum speed for the Halifax-Class Frigate like the CPF is 29 knots and a nominal speed of 10  $m.s^{-1}$ , or 19.4 knots, was chosen. This speed accounts for the combination of wind and ship motion but no variation due to the atmospheric boundary layer profile was taken into account.

A headwind case was considered. First, the **B-C** and **C-D** segments of the idealised landing trajectory were simulated using the standalone HFM code, with the pilot controls predicted using the embedded LQR auto-pilot model presented in section 3.3. Then, the coupled HFM/HMB2 method is demonstrated by simulating a short "single-input" response and comparing the results obtained with the trajectory predicted using the HFM method. Simulations of the shipborne helicopter in station-keeping flight at the first and last positions of the manoeuvre were then performed and the flow-fields are compared. This was carried out to ensure that the Chimera method [27] used to interface the helicopter and ship grids was performing well and to develop the flowfield in the wake of the ship. No flight mechanics model was used for these computations.

The descent manoeuvre was then performed with or without the presence of the CPF. The results were compared to identify the differences in pilot input and aerodynamic loads due to the presence of the ship wake. In both cases, the LQR pilot model was used to track with the best accuracy possible the target trajectory.

## 5.2 LQR Simulation of the Landing using HFM

Figures 19 and 20 show the results of a LQR-piloted simulation of the **B-C** and **C-D** branches of the manoeuvre respectively. The standalone HFM code was used to trim the aircraft, calculate the linearised model required for the LQR pilot model and perform the manoeuvre.

The Aeronautical Design Standard 33 "Handling Qualities Requirements for Military Rotorcraft" (ADS-33E-PRF) document [54] specifies a series of manoeuvres that rotorcraft need to be able to perform and the associated tolerances. Results show that the LQR pilot model accurately maintains stable flight and follows the target trajectories within the tolerance set for similar manoeuvres in the ADS33 document: the lateral reposition and the descent manoeuvres. The tolerances are represented by the shaded area in the figures.

Results for the lateral reposition manoeuvre show some overshoot in the lateral position. To alleviate this problem, some pilot models add a predictive method to "look-ahead" and anticipate on changes in trajectory, as in the Generalised Predictive Control (GPC) method of Hess and Jung [23]. It limits overshoots and gives a behavioural representation of a human pilot, but it is not implemented in the current LQR model.

Moreover, accelerations of the aircraft are typically oscillatory due to the blades rotation. The position, velocities and accelerations are time-averaged over one blade-passing period (one fifth of main rotor revolution). This is done to avoid an oscillatory response of the pilot model but introduces delays in the response.

The target trajectory given to the LQR method only specifies the change in y-position. Other targets in position and attitude angle are kept to their original value. By minimising the overall error in positioning, the LQR method allows for some deviation in every direction. To achieve the repositioning target, the helicopter needs to roll to the right to engage the translation, and to the left to exit the manoeuvre. The two peaks in attitude angle are clearly visible in figure 19(b) with a deviation of about 12 degrees on each side. Forces at the rotor hub clearly show the change in lateral force as well as a high-frequency "blade-passing" signal. The pilot input in the tail rotor collective shows significant variation as a result of the changes in inflow due to the lateral velocity. There are also smaller pilot inputs on the main rotor lateral cyclic and collective to engage and exit the manoeuvre.

The target trajectory for the descent manoeuvre begins after one second of flight and covers a distance of 10 meters in four seconds, while the forward velocity is kept fixed, at  $10 \ m.s^{-1}$ . However, the constraint was that the manoeuvre should be completed in under eight seconds. Results show that the aircraft crosses the 10 meters line six seconds after the beginning of the manoeuvre, reaches  $4 \ m.s^{-1}$  peak descent velocity, and it slows down to about  $0.4 \ m.s^{-1}$  at the seven seconds mark.

The collective inputs were reduced by two degrees to engage the manoeuvre before returning to the initial value. An increase in normal force can be seen at the four-second mark, which is a consequence of the reduced downwash through the rotor disk during the descent. As a consequence, no increase in rotor collective was necessary to slow down the descent and stabilise the aircraft.

## 5.3 Free-Response to Single Pilot Input

The coupled HFM/HMB2 method was first demonstrated by calculating the response of the aircraft to a single-channel pilot input. The command is a simple two-seconds sinusoidal pull-up action that increases the value of the collective by five degrees and then returns it to the original value as shown in figure 21. Other control angles were kept fixed to the initial trimmed condition.

The trimming methods only find a trim state of the aircraft that minimises the average loading. Since the HFM helicopter model is unsteady, it does not maintain steady flight conditions even under those trimmed conditions, and "drifts" if no active control is applied. This response was calculated using HFM and HMB and the resulting trajectory and attitude are shown in figure 22. To characterise the intrinsic response of the aircraft to the pilot input, results are presented with and without the "drift". the results obtained using the standalone code HFM and coupled CFD simulation are shown in figures 23 and 24 respectively.

The HFM results show a clear increase in vertical velocity and a final altitude gain of about 12 meters after six seconds. The aircraft rolls and pitches as a consequence of the change in rotor loading.

The results obtained using the coupled method show a similar behaviour, albeit of lower amplitude. The total gain in altitude is about 7 meters after 6 seconds and the rolling and pitching moments are significantly lower than predicted by the HFM simulation.

#### 5.4 Coupled HFM/HMB2 Simulation in Free Air

Figure 25 presents the test case of the final descent and landing of figure 20 using the coupled HFM/HMB2 method. The LQR pilot model is set to start after three revolutions to allow some time for the flowfield to converge. Any residual load is then removed to start the manoeuvre in trimmed flight, as can be seen in figure 25 (d), at the one-second mark.

The results suggest that the LQR pilot model is able to accurately follow the specified trajectory with minimal deviation in terms of helicopter attitude and lateral and longitudinal positions. The LQR inputs in the main rotor cyclic and collective angles remain lower than 5 degrees, suggesting a mild pilot activity throughout the manoeuvre. It should be noted that by construction the LQR method acts as a filter that limits high-frequency changes in control and provides optimal tracking. It is therefore not representative of the behaviour of a human pilot.

The large excursion in tail rotor collective is caused by a change in moment around the yaw axis at the beginning of the manoeuvre, probably due to a still-converging inflow on the tail rotor and an overestimated tail rotor thrust. The pilot model corrects for the deviation, without affecting the global behaviour of the aircraft.

### 5.5 Coupled Shipborne Simulations

#### 5.5.1 Station-keeping Flight

Because of the two vastly different timescales between ship and helicopter wakes, it is necessary to initialise the simulation with a larger time-step to eliminate the transient flow in the wake of the ship.

- The helicopter and ship speeds were set to  $10 m.s^{-1}$ . A non-dimensional time-step dt = 2.0 was used, and the rotors were kept fixed.
- The time step was reduced to dt = 0.1636 and the rotors were set to rotate at their nominal speed.
- The residual loads were removed to avoid immediate drift from the prescribed trajectory.
- The simulation started with dt = 0.1636 and HFM was used to calculate the aircraft motion.

Results in figure 26 show the flowfield around the helicopter in isolated and shipborne conditions at the beginning of the manoeuvre. The Linear Integral Convolution method initially proposed by Cabral and Leedom [15] was used to visualise the flowfield in the moving frame of reference while the contours show the distribution of streamwise velocity. The topology of the flow around the helicopter is similar and there is a separation between the ship and helicopter wakes, with the helicopter wake being distorted by the ship wake behind the hangar. This suggests a weak effect of the ship wake on the helicopter loading at the beginning of the manoeuvre. Contours of pressure coefficient are based on the main rotor tip velocity.

## 5.5.2 Comparison Between Isolated and Coupled Responses

Results for the landing manoeuvre performed with and without the effect of the ship wake were compared directly to assess the effect of the ship wake. Figure 27 shows the two pilot responses and the subsequent trajectories. As predicted, results show little influence of the ship wake at the beginning of the manoeuvre, when the helicopter is located about 15 meters above the ship deck. The trajectory and pilot controls are similar until the 4th second (3 seconds through the manoeuvre). After 4 seconds, the helicopter rolling angle and lateral position show discrepancies between the two cases.

Overall, the trajectory is followed accurately and the pilot activity is similar in both instances. The rolling angle is larger in the shipborne case and the longitudinal cyclic deviates further, suggesting an increased activity of the pilot. The main rotor collective is comparatively smaller in the shipborne case despite the presence of a downwash behind the hangar. However, this can be partially explained as the main rotor plane is closer to the optimal horizontal ( $\Phi$  closer to zero and  $\Theta$  closer to the shaft angle of 7 degrees) and therefore provides more vertical lift. No calculation could be performed with the helicopter at touchdown altitude because of restrictions imposed by the Chimera method. Results in terms of forces and moments are shown in figure 28. Despite some differences in pitching moments, loads appear very similar throughout the manoeuvre.

Several surges are visible in the loads of figure 28, that appear when restarting the CFD computation. Future work will be carried out to ensure any restart is seamless.

Individual blade loads are shown in figure 29. The pitch angle of the first blade is shown with and without the harmonic content for both cases and the corresponding flapping and lead-lag aerodynamic moments at the hub are plotted. Results show similar values of loading at the beginning of the manoeuvre and discrepancies appear as the helicopter approaches the deck.

The flow visualisations presented previously in figure 26 for the beginning of the manoeuvre are reproduced in figure 30. They correspond to the 8 seconds time mark, with the helicopter close to the deck, and show more clearly an interaction between the two wakes. The development of the rotor wake is confined by the presence of the hangar door and deck, and extends downstream. Vortical structures that emanate from the ship superstructure are clearly visible, although they show signs of dissipation and do not seem to greatly affect the helicopter aerodynamics.

Figure 31 shows the distribution of non-dimensional wvelocity through the rotor disk at four instances during the manoeuvre. After 2 revolutions, the aircraft has just started descending and the isolated and shipborne cases show similar wake topologies. As the aircraft descends, it enters the ship wake and the topology of the global wake shows the presence of vortical structures that characterise the unsteadiness of the flow. The inflow velocity through the rotor disk is more important at 6 and 8 seconds in the shipborne case due to the downwash behind the hangar.

Contours of non-dimensional w-velocity are shown in figure 32 in the ship symmetry plane. Traces of the vortices created in the vicinity of the ship are clearly visible, as well as the fuselage wake below the helicopter. At the four-seconds mark, natural downwash combined with the rotor effect leads to an increased value of w-velocity through the rotor disk At six and eight seconds, the apparent downwash reduces suggesting a partial ground effect caused by the deck. After eight seconds, the upwash velocity of the flow between the nose of the aircraft and the hangar increases as the rotor wake is confined between the helicopter and the deck.

Figure 33 shows the distribution of the pressure coefficient on the fuselage and ship deck, five seconds into the manoeuvre. The pressure coefficient is calculated based on the freestream velocity  $C_P = \frac{P}{\frac{1}{2}\rho U_{\infty}^2}$ . Levels of  $C_P$  show clearly the area where the helicopter wake impinges the deck. The downwash velocity is significantly higher than the freestream, leading to levels of pressure coefficient above one. The downwash over the fuselage constantly changes due to the blades passing in close proximity. Changes in pressure distribution on the fuselage are clearly visible, with high pressure levels on the boom and the roof of the cabin, and low values on the side of the aircraft where the flow accelerates.

#### 5.6 Conclusions on Coupled Simulations

The discrepancies between the results in the calculations of section 5.3 suggests that the Sea King model in HFM that uses approximate aerodynamic models, poorly represents the characteristics of the aircraft obtained using the CFD. Despite the simplicity of the HFM model, it provided matrices for the linear models that proved accurate enough to provide good tracking performance even when using CFD.

A 10  $m.s^{-1}$  headwind case was chosen to ensure that the newly implemented method would not fail to maintain the helicopter position and attitude within a reasonable margin. More challenging flow conditions may require a more accurate linearised model, perhaps directly based on the CFD results. However, it demonstrates that the method is robust and suitable for such calculations.

The time-resolution requirement for rotor blades simulation is about one order of magnitude smaller than for ship wake simulations. It is necessary to choose the smaller timestep to ensure convergence of the solver and one-degree azimuthal steps of the main rotor were chosen to limit the computational time. As a consequence, the time-accuracy for the ship wake was largely exceeding the requirements  $\delta t < \frac{\delta x}{U_{\infty}}$ for the grid density used  $\delta x$ . The region of the deck was meshed with a typical cell size of 0.3 m, giving 50 cells per ship beam. Five newton steps were used per time step to reduce the CPU time required.

The  $k - \omega SAS$  turbulence model used for coupled calculation proved to maintain a more reasonable level of unsteadiness than the baseline  $k - \omega$  model and is more stable than the DES model. However, it only preserved the largest structures over long distances and therefore the ship wake had a minimal impact on the helicopter aerodynamics. A finer helicopter mesh would also be desirable.

#### 6 SUMMARY AND CONCLUSIONS

Previous work on the simulation of ship/helicopter dynamic interface has been presented in the introduction and shows that various levels of accuracy are achieved depending on the methods used and simplifications made. A full-CFD approach for manoeuvring aircraft in ship environment has not yet been considered and this paper represents a first step towards this goal.

Experimental data generated for the Simple Frigate Shape 2 and the GOAHEAD full helicopter configuration was used to validate the block-structured parallel solver HMB2 developed at the university of Liverpool. Results show that the steady characteristics of the ship wake are well predicted and, given a good quality grid, DES and  $k - \omega$ -SAS turbulence models were adequate to maintain the unsteadiness of the flowfield. The SAS model was chosen to carry out the coupled simulations due to the lower grid requirements and its numerical stability. The Test Case 2 of the GOAHEAD campaign was used to validate the performance prediction of HMB2 for helicopters at low advance ratio. Steady and unsteady levels of loading on the fuselage were well predicted, as well as the rotor loading despite the use of an approximate trim state predicted using HOST during the campaign, rather than being measured directly. These results give confidence in the ability of the HMB2 solver to simulate ship and helicopter wakes, and their interaction with a good accuracy.

Ship/helicopter coupled simulations were conducted using the Canadian Patrol Frigate (CPF) geometry as it is a good compromise between geometrical realism and grid complexity. The URANS  $k - \omega$  SAS model was chosen after demonstrating that the URANS and DES models exhibit similar mean flow characteristics and SAS coupled reproduce similar level of unsteadiness as the DES on coarser grids and with a better numerical stability.

The Helicopter Flight Mechanics (HFM) multi-body dynamics solver was then tested as a standalone code and in coupled mode when implemented into the HMB2 environment. HFM builds a model of a helicopter based on first principles of rotorcraft flight and simple aerodynamics models. A linearisation method that computes Jacobian matrices via a second order finite difference method was implemented and used to build a trimming method and a LQR pilot model. The helicopter was trimmed before each calculation and the linear pilot model was generated around the trimmed position. By providing a target trajectory to HFM, it is possible to simulate piloted manoeuvres, whether in standalone mode using simplified aerodynamics models, or in coupled mode using the CFD loads directly. Simulations of the last branch of the shipborne landing manoeuvre were performed using CFD, with and without the presence of the ship. Pilot activity and helicopter attitude show some differences, suggesting an influence of the ship wake on the aircraft.

The feasibility of simulating rotorcraft flight directly into the CFD environment was demonstrated using realistic ship and aircraft geometries, for the challenging landing manoeuvre. The trajectory was tracked with a good accuracy, despite the pilot model relying on an approximate linear model of the aircraft. Coupled simulations of the landing showed interesting results, although the dissipation of the flow solver seems to be a limiting factor. Considering that, given good quality meshes, the solver gave good prediction for both ship and helicopter wakes. it is believed that more realistic simulations of the ship/helicopter interaction can be performed by increasing the spatial and temporal discretisation, as well as increasing the convergence of the flow solver.

#### 7 ACKNOWLEDGEMENTS

The support of this project by AgustaWestland Liverpool Advanced Rotorcraft Center is gratefully acknowledged. The authors would like to thank the N8 High Performance Computing (N8 HPC) centre for the use of the POLARIS system.

#### REFERENCES

- A. Abhishek, S. Ananthan, J. Baeder, and I. Chopra. Prediction and Fundamental Understanding of Stall Loads in UH-60A Pull-up Maneuver. *Proceedings of the American Helicopter Society*, 2010.
- [2] E. Alpman, L.N. Long, D.O. Bridges, and J.F. Horn. Fully-Coupled Simulations of the Rotorcraft/Ship Dynamic Interface. In Annual Forum Proceedings of the American Helicopter Society, volume 63, page 1367. American Helicopter Society, inc.
- [3] S. Ananthan, J. Baeder, B. W. C. Sim, S. Hahn, and G. Iaccarino. Prediction and Validation of the Aerodynamics, Structural Dynamics, and Acoustics of the SMART Rotor Using a Loosely-Coupled CFD-CSD Analysis. *Proceedings of the American Helicopter Society*, 2010.
- [4] A. Antoniadis, B. Zhong, and D. Drikakis. Generation of Advanced Helicopter Experimental Aerodynamic Database for CFD Code Validation. Technical report, GOAHEAD Partners European Commission, 2005.
- [5] A.M. Arney and N.E. Gilbert. A User's Manual for the ARL Mathematical Model of the Sea King Mk-50 Helicopter: Part 1. Basic Use. Technical report, DTIC Document, 1988.
- [6] A.M. Arney and N.E. Gilbert. A User's Manual for the ARL Mathematical Model of the Sea King Mk-50 Helicopter: Part 2. Use with ARL Flight Data. Technical report, DTIC Document, 1988.
- [7] O. Axelsson. *Iterative Solution Methods*. Cambridge University Press: Cambridge, MA, 1994.
- [8] George Barakos, R Steijl, K Badcock, and A Brocklehurst. Development of CFD capability for full helicopter engineering analysis. In 31st European Rotorcraft Forum, Florence, Italy, Sept, 2005.
- [9] P. Beaumier, M. Costes, O. Rodriguez, M. Poinot, and B. Cantaloube. Weak and Strong Coupling Between the elsA CFD Solver and the HOST Helicopter Comprehensive Analysis. *ONERA: Tire a Part*, (186):1, 2005.
- [10] M.J. Bhagwat, R.A. Ormiston, H.A. Saberi, and H. Xin. Application of Computational Fluid Dynamics/Computational Structural Dynamics Coupling for Analysis of Rotorcraft Airloads and Blade Loads in Maneuvering Flight. *Journal of the American Helicopter Society*, 57(3), 2012.

- [11] O.J. et al. Boelens. Aerodynamic Simulation of a Complete Helicopter Configuration. Technical report, Nationaal Lucht- en Ruimtevaartlaboratorium, 2007.
- [12] R. Bradley and G. Brindley. Progress in the Development of a Versatile Pilot Model for the Evaluation of Rotorcraft Performance, Control Strategy and Pilot Workload. *Aeronautical Journal*, 107(1078):731–738, 2003.
- [13] D.O. Bridges, J.F. Horn, E. Alpman, and L.N. Long. Coupled Flight Dynamics and CFD Analysis of Pilot Workload in Ship Airwakes. In *Collection of Technical Papers - 2007 AIAA Atmospheric Flight Mechanics Conference*, volume 1, pages 471–489, 2007.
- [14] J.W. Bunnell. An Integrated Time-Varying Airwake in a UH-60 Black-Hawk Shipboard Landing Simulation. In AIAA Modeling and Simulation Technologies Conference and Exhibit, Montreal, Canada, pages 6–9, 2001.
- [15] B. Cabral and L.C. Leedom. Imaging Vector Fields Using Line Integral Convolution. 20th Annual Conference and Exhibition on Computer Graphics and Interactive Techniques - Anaheim, CA, USA, 1993.
- [16] B.T. Cheney and S.J. Zan. CFD Code Validation Data and Flow Topology for TCCP AER-TP-2 Simple Frigate Shape. *Ottawa, Canada*, 1999.
- [17] C. Crozon, R. Steijl, and G.N. Barakos. Numerical Study of Rotor in Ship Airwake. *Proceedings of the European Rotorcraft Forum*, 2013.
- [18] F. Dehaeze and G.N. Barakos. Hovering Rotor Computations Using an Aeroelastic Blade Model. *Royal Aeronautical Society*, 116(1180), 2012.
- [19] M. Dietz, M. Kessler, and E. KrÃd'mer. Trimmed Simulation of a Complete Helicopter Configuration Using Fluid-Structure Coupling. In Wolfgang E. Nagel, Dietmar KrÃűner, and Michael Resch, editors, *High Performance Computing in Science and Engineering*, pages 487–501. Springer Berlin Heidelberg, 2008.
- [20] R.A. Feik and R.H. Perrin. Identification of an Adequate Model for Collective Response Dynamics of a Sea King Helicopter in Hover. Technical report, DTIC Document, 1988.
- [21] J.S. Forrest and I. Owen. An Investigation of Ship Airwakes Using Detached-Eddy Simulation. *Computers* and Fluids, 39(4):656 – 673, 2010.
- [22] J. R. Forsythe, E. Lynch, and S. Polsky. Coupled Flight Simulator and CFD Calculations of Ship Airwake using Kestrel. *Proceedings of the American Helicopter Soci*ety, 2015.
- [23] Ronald A Hess and Yoon C Jung. An Application of Generalized Predictive Control to Rotorcraft Terrain-Following Flight. Systems, Man and Cybernetics, IEEE Transactions on, 19(5):955–962, 1989.

- [24] S.J. Hodge, S.J. Zan, D.M. Roper, G.D. Padfield, and I. Owen. Time-Accurate Ship Airwake and Unsteady Aerodynamic Loads Modeling for Maritime Helicopter Simulation. *Journal of the American Helicopter Society*, 54(2):0220051–02200516, 2009.
- [25] A. Hoencamp, Th. Van Holten, and J.V.R. Prasad. Relevant Aspects of Helicopter-Ship Operations. *Proceedings of the European Rotorcraft Forum*, 1:578–588, 2008.
- [26] N. Iboshi, N. Itoga, J. Prasad, and L. Sankar. Ground Effect of a Rotor Hovering Above a Confined Area. Annual Forum Proceedings of the American Helicopter Society, 2:1249–1262, 2008.
- [27] M. Jarkowski, M.A. Woodgate, G.N. Barakos, and J. Rokicki. Towards Consistent Hybrid Overset Mesh Methods For Rotorcraft CFD. *International Journal for Numerical Methods in Fluids*, 2011.
- [28] C.H. Kaaria, J.S. Forrest, I. Owen, and G.D. Padfield. Simulated Aerodynamic Loading of an SH-60B Helicopter in a Ship's Airwake. *European Rotorcraft Forum*, 2:1001–1013, 2009.
- [29] W. Khier. Numerical Simulation of a Complete Helicopter Configuration in Forward Flight using Fluid-Structure Coupling. *Notes on Numerical Fluid Mechanics and Multidisciplinary Design*, 121:305–312, 2013. cited By (since 1996)0.
- [30] H. Kwakernaak. *Linear optimal control systems*. Wiley Interscience, New York, 1972.
- [31] S.J. Lawson, C. Crozon, F. Dehaeze, R. Steijl, and G.N. Barakos. Computational Fluid Dynamics Analyses of Ship Air Wakes Using Detached-Eddy Simulation. *European Rotorcraft Forum Proceedings*, 1:502– 523, 2012.
- [32] D. Lee and J.F. Horn. Simulation of Pilot Workload for a Helicopter Operating in a Turbulent Ship Airwake. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, 219(5):445– 458, 2005.
- [33] D. Lee, N. Sezer-Uzol, J.F. Horn, and L.N. Long. Simulation of Helicopter Shipboard Launch and Recovery With Time-Accurate Airwakes. *Journal of Aircraft*, 42(2):448–461, 2003.
- [34] R.G. Lee and S.J. Zan. Unsteady Aerodynamic Loading on a Helicopter Fuselage in a Ship Airwake. *Journal of the American Helicopter Society*, 49:149, 2004.
- [35] R.G. Lee and S.J. Zan. Wind Tunnel Testing of a Helicopter Fuselage and Rotor in a Ship Airwake. *Journal of the American Helicopter Society*, 50:326, 2005.
- [36] P. Masarati, M. Morandini, and P. Mantegazza. An Efficient Formulation for General-Purpose Multibody/Multiphysics Analysis. *Journal of Computational and Nonlinear Dynamics*, 2014.

- [37] M. Mohammad and A.K. Cook. Review of Pilot Modelling Techniques. 48th AIAA Aerospace Sciences Meeting Including The New Horizons Forum and Aerospace Exposition, 2010.
- [38] R.B. Mora. Flow Field Velocity on the Flight Deck of a Frigate. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, page 0954410014524739, 2014.
- [39] Y. Nacakli and D. Landman. Helicopter Downwash/Frigate Airwake Interaction Flowfield PIV Surveys in a Low Speed Wind Tunnel. Annual Forum Proceedings of the American Helicopter Society, 4:2988– 2998, 2011.
- [40] S. Osher and S. Chakravarthy. Upwind Schemes and Boundary Conditions with Applications to Euler Equations in General Geometries. *Journal of Computational Physics*, 50:447–481, January–February 1983.
- [41] D.A. Peters and C.J. He. Correlation of Measured Induced Velocities with a Finite-State Wake Model. *Journal of the American Helicopter Society*, 36(3):59–70, 1991.
- [42] S.A. Polsky. A Computational Study of Unsteady Ship Airwake. Technical report, DTIC Document, 2003.
- [43] S.A. Polsky. Progress Towards Modeling Ship/Aircraft Dynamic Interface. In *HPCMP Users Group Conference*, pages 163–168. IEEE, 2006.
- [44] S.A. Polsky. Computational Analysis for Air/Ship Integration: 1st Year Report. In *High Performance Computing Modernization Program Users Group Conference (HPCMP-UGC)*, pages 109–114. IEEE, 2010.
- [45] E. W. Quon, P. A. Cross, Smith M. J., Rosenfeld N. C., and Whitehouse G. R. Investigation of Ship Airwakes Using a Hybrid Computational Methodology. In Annual Forum Proceedings of the American Helicopter Society, 2014.
- [46] G. Rajagopalan, S. Niazi, A.J. Wadcock, G.K. Yamauchi, and M.J. Silva. Experimental and Computational Study of the Interaction Between a Tandem-Rotor Helicopter and a Ship. In *Annual Forum Proceedings of the American Helicopter Society*, volume 61, page 729. American Helicopter Society, inc, 2005.
- [47] D.M. Roper, I. Owen, and G.D. Padfield. CFD Investigation of the Helicopter-Ship Dynamic Interface. *Annual Forum Proceedings of the American Helicopter Society*, 2:1985–2002, 2005.
- [48] D.M. Roper, I. Owen, G.D. Padfield, and S.J. Hodge. Integrating CFD and Piloted Simulation to Quantify Ship-Helicopter Operating Limits. *Aeronautical Journal*, 110(1109):419–428, 2006.
- [49] N. Rosenfeld, K. Kimmel, and A. J. Sydney. Investigation of Ship Topside Modeling Practices for Wind Tunnel Experiments. *Proceedings of the AIAA Science and Technology Forum*, 2015.

- [50] G. Servera, P. Beaumier, and M. Costes. A Weak Coupling Method Between the Dynamics Code HOST and the 3D Unsteady Euler Code WAVES. *Journal* of Aerospace Science and Technology, 5(6):397–408, 2001.
- [51] M.J. Silva. Wind Tunnel Investigation of the Aerodynamic Interactions Between Helicopters and Tiltrotors in a Shipboard Environment. Technical report, DTIC Document, 2004.
- [52] M. Snyder, H. Kang, and J. Burks. Validation of Computational Ship Air Wakes for a Naval Research Vessel. *Aerospace Sciences Meeting of the American Institute of Aeronautics and Astronautics*.
- [53] M.R. Snyder, J.S. Burks, C.J. Brownell, L. Luznik, D.S. Miklosovic, J.H. Golden, M.E. Hartsog, G.E. Lemaster, F.D. Roberson, J.P. Shishkoff, W.P. Stillman, and C.H. Wilkinson. Determination of Shipborne Helicopter Launch and Recovery Limitations Using Computational Fluid Dynamics. *Annual Forum Proceedings of the American Helicopter Society*, 4:3136–3146, 2010.
- [54] Aeronautical Design Standard. Handling Qualities Requirements for Military Rotorcraft (ADS-33E-PRF). *Redstone Arsenal, Alabama: US Army Aviation and Missile Command, Aviation Engineering Directorate.*
- [55] D. Stargel and D. Landman. A Wind Tunnel Investigation of Ship Airwake/Rotor Downwash Coupling Using Design of Experiments Methodologies. In 50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, Nashville, Tennessee, 2012.
- [56] R. Steijl, G. Barakos, and K. Badcock. A Framework for CFD Analysis of Helicopter Rotors in Hover and Forward Flight. *International Journal for Numerical Meth*ods in Fluids, 51(8):819–847, 2006.
- [57] R. Steijl and G.N. Barakos. CFD Analysis of Complete Helicopter Configurations âĂŞ Lessons Learnt from the GOAHEAD Project. Aerospace Science and Technology, 19(1):58 – 71, 2012. <ce:title>GOAHEAD</ce:title>.
- [58] G.F. Syms. Simulation of Simplified-Frigate Airwakes Using a Lattice-Boltzmann Method. *Journal of Wind Engineering and Industrial Aerodynamics*, 96(6):1197– 1206, 2008.

- [59] S. Thomas, S. Ananthan, and J.D. Baeder. Wake-Coupling CFD-CSD Analysis of Helicopter Rotors in Steady and Maneuvering Flight Conditions. pages 758– 777, 2010. cited By (since 1996)0.
- [60] D. Thomson and R. Bradley. Inverse Simulation as a Tool for Flight Dynamics Research - Principles and Applications. *Progress in Aerospace Sciences*, 42(3):174 – 210, 2006.
- [61] B. Thornber, M. Starr, and D. Drikakis. Implicit Large Eddy Simulation of Ship Airwakes. *Aeronautical Journal*, 114:715–736, 2010.
- [62] J. Van Muijden, O. Boelens, J., Van der Vorst, and J. Gooden. Computational Ship Airwake Determination to Support Helicopter-Ship Dynamic Interface Assessment. Computational Fluid Dynamics Conference of the American Institute of Aeronautics and Astronautics, 2013.
- [63] A.J. Wadcock. PIV Measurements of the Wake of a Tandem-Rotor Helicopter in Proximity to a Ship. Technical report, DTIC Document, 2004.
- [64] G.K. Yamauchi, A.J. Wadcock, and M.R. Derby. Measured Aerodynamic Interaction of Two Tiltrotors. In *Annual Forum Proceedings of the American Helicopter Society*, volume 59, pages 1720–1731. American Helicopter Society, inc, 2003.
- [65] K. Yu, D. A. Wachspress, H-A. Saberi, M. J. Hasbun, J. C. Ho, and H. Yeo. Helicopter Rotor Structural Load Predictions with a Comprehensive Rotorcraft Analysis. *Proceedings of the American Helicopter Society*, 2012.
- [66] S.J. Zan. Experimental Determination of Rotor Thrust in a Ship Airwake. *Journal of the American Helicopter Society*, 47, 2002.
- [67] S.J. Zan. On Aerodynamic Modeling and Simulation of the Dynamic Interface. *Proceedings of the Institution* of Mechanical Engineers, Part G: Journal of Aerospace Engineering, 219(5):393–410, 2005.
- [68] S.J. Zan and E.A. Garry. Wind Tunnel Measurements of the Airwake Behind a Model of a Generic Frigate. Technical report, NRCCNRC report LTR-AA-13, 1994.
- [69] S.J. Zan, G.F. Syms, and B.T. Cheney. Analysis of Patrol Frigate Air Wakes. In *RTO Applied Vehicle Technology Panel Symposium*, pages 7–1, 1999.



Figure 1: Description of the couplings associated with the simulation of the Dynamic Interface.



Figure 2: Simple Frigate Shape grid topology and detail of the mesh above the deck.



Figure 3: Canadian Patrol Frigate grid topology and detail of the mesh above the deck.



Figure 4: (a) Surface blocking and (b) CFD mesh of the Sea King helicopter.



Figure 5: Result of the chimera localisation.

Part	Blocks	Cells (millions)		
SFS2 <sup>1</sup> coarse	566	4.17		
SFS2 <sup>1</sup> intermediate	566	7.96		
SFS2 <sup>1</sup> Fine	566	14.86		
GOAHEAD fuselage	2308	38.65		
GOAHEAD main rotor (per blade)	278	12.15		
GOAHEAD tail rotor (per blade)	188	1.74		
SK <sup>2</sup> Fuselage Front	2146	1.43		
SK <sup>2</sup> Fuselage Middle	1940	0.53		
SK <sup>2</sup> Fuselage Tail	1533	0.39		
SK <sup>2</sup> Main Rotor (per blade)	260	3.39		
SK <sup>2</sup> Tail Rotor (per blade)	230	0.85		
Helicopter Background	34	1.3		
CPF <sup>3</sup> Ship	1026	30.72		
CPF <sup>3</sup> Ship Background	18	0.23		

Table 1: Size of the meshes used for this work. <sup>1</sup> Simple Frigate Shape geometry, <sup>2</sup> Sea King helicopter, <sup>3</sup> Canadian Patrol Frigate geometry.

Non-dimensional variable	Baseline HMB2	HMB2 in vehicle mode	HFM
Tip velocity $V_{tip}$	$V_{tip}=rac{1}{\mu}$	$V_{tip} = 1$	$V_{tip} = \omega R$
Rotational velocity	$\omega = \frac{1}{\mu R}$	$\omega = \frac{1}{R} \left( V_{tip} = 1 \right)$	$\omega = \frac{V_{tip}}{R}$
Time step	$\Delta t = \frac{2\pi\mu R}{N_{steps/cycle}}$	$\Delta t = \frac{2\pi R}{N_{steps/cycle}}$	$\Delta t = \frac{2\pi R}{N_{steps/cycle}V_{tip}}$
Reference length	1 rotor chord length	1 meter	1 meter
Azimuthal step $\omega \Delta t$	$\Delta \Psi^{main} = rac{360}{N_{steps/cycle}}$	$\Delta \Psi^{main} = rac{360}{N_{steps/cycle}}$	$\Delta \Psi^{main} = \frac{360}{N_{steps/cycle}}$

Table 2: Definitions and correspondences between HFM and HMB2 codes.



Figure 6: An earth-fixed frame of reference was chosen in this work to account explicitely for changes in flight condition.



(b) Earth-fixed frame of reference

Figure 7: ONERA non-lifting rotor in forward flight.

Parameter	Standalone HFM	Coupled HFM/CFD		
6DOF fuselage	✓			
Articulated blades				
Atmospheric conditions		1		
Inflow	$\checkmark^1$	✓		
Control surfaces	$\checkmark^2$	✓		
Blade aerodynamics	$\checkmark^3$	1		
Rotor/fuselage interaction	×	1		
Blade-tip losses	×	1		
3D effects	×	✓		
Flexible structures	×	×		

Table 3: Comparison between standalone flight mechanics and CFD coupling approximations. <sup>1</sup> Linear model, <sup>2</sup> Bi-linear model, <sup>3</sup> Blade Element Theory.



Figure 8: Sea King mathematical model.

Variable	Value
All Up Weight (AUW)	8391.46 [kg]
Roll 2nd moment of inertia	19354.3 [kg.m <sup>2</sup> ]
Pitch 2nd moment of inertia	65587.69 [kg.m <sup>2</sup> ]
Yaw 2nd moment of inertia	53080.27 [kg.m <sup>2</sup> ]
Hub coordinates with respect to CG	(0.31,0.0,-2.58) [m]
Rotor radius	9.4488 [ <i>m</i> ]
Blade chord	0.4633 [m]
Hinge offset	0.32 [m]
Blade twist	-8.0 [degrees]
Blade mass	82.1 [ <i>kg</i> ]
Rotation speed $\Omega$	$21.89 [rd.s^{-1}]$
Number of main rotor blades	5
Number of tail rotor blades	5
main rotor airfoil section	NACA0012
tail rotor airfoil section	NACA0012

Table 4: Characteristics of the Sea King MK50 helicopter [5,6,20]



Figure 9: Implementation of the standalone flight mechanics code (HFM).



Figure 10: Aircraft response to a change in main rotor collective input.



Figure 11: Time-line of manoeuvring flight simulation.



Figure 12: Comparison of URANS, DES-SA and SAS models and grid density study. Headwind case,  $Re = 6.5810^5$ .



Figure 13: Position of the eight vertical probe lines, from Quon and Rosenfeld [45, 49]



Figure 14: Time-averaged values of velocity and flow angles along 8 vertical lines. DES-SA model,  $WOD = 60 \ degrees$ ,  $Re = 6.5810^5$ 



Figure 15: Time-averaged values of velocity and flow angles along 8 vertical lines. SAS model,  $WOD = 60 \ degrees, Re = 6.5810^5$ 



(a) Positions of probes



Figure 16: Signal of pressure as function of blade azimuth (mean removed) and FFT decomposition of the signal for 3 different points on the fuselage.

WT data point	WT Mach Number	Fuselage Pitch	$C_T^M$	$M_{tip}^M$	$C_T^T$	$M_{tip}^T$	$C_D$
392	0.059	+1.9	0.071	0.617	0.087	0.563	0.176

Table 5: List of the GOAHEAD test cases with corresponding flow conditions (Reproduced from Antoniadis et al. [4]).



Figure 17: Curves of experimental and numerical pressure coefficient at 0 and 60 degrees for 3 different spanwise locations: 50%, 70% and 82.5%.



Figure 18: Typical landing manoeuvre as performed by the UK Royal Navy.



Figure 19: Aircraft position, attitude, controls history and global forces during a LQR piloted lateral reposition simulation with HFM, compared with the target trajectory. The error in x-position is shown in (a).



Figure 20: Aircraft position, attitude, controls history and global forces during a LQR piloted landing simulation with HFM, compared with the target trajectory. The error in x-position is shown in (a).



Figure 21: Control input used to characterise the aircraft response to a single-channel pilot input.



Figure 22: Aircraft free-response calculated with HFM and HMB if a constant pilot input is applied. This is referred to as "drift".



Figure 23: Aircraft response to a collective input (Fig. 21) with and without the "drift". Position, velocities and attitude calculated using the standalone HFM method.



Figure 24: Aircraft response to a collective input (Fig. 21) with and without the "drift". Position, velocities and attitude calculated using the coupled HFM/HMB2 method.



Figure 25: Aircraft position, attitude, controls history and global forces during coupled CFD simulation with LQR control, compared with target trajectory. Error in x-position is shown in (a).



(b) Shipborne helicopter, t = 0.5 seconds

Figure 26: Flowfield visualised with LIC and pressure on the helicopter at the beginning and the end of the manoeuvre, with and without ship wake. Pressure coefficient was based on free-stream velocity.



Figure 27: Comparison of the pilot and aircraft response during the piloted landing manoeuvre with and without the effect of the ship wake.



Figure 28: Comparison of the global forces and moments on the aircraft during the piloted landing manoeuvre with and without the effect of the ship wake.



Figure 29: Comparison of the blade flapping and lead-lag moments during the piloted landing manoeuvre with and without the effect of the ship wake.



(b) Shipborne helicopter, t = 8 seconds

Figure 30: Flowfield visualised with LIC and pressure on the helicopter at the end of the manoeuvre, with and without ship wake. Pressure coefficient based on free-stream velocity.



(d) Revolution 28 - t = 8 seconds

Figure 31: Distribution of inflow through the rotor plane during the (left) isolated manoeuvre and (right) shipborne manoeuvre.





(a) Revolution 7 - t = 2 seconds







Figure 32: Distribution of inflow in the symmetry plane during the (left) isolated manoeuvre and (right) shipborne manoeuvre.



Figure 33: Distribution of pressure coefficient on the fuselage and deck at 4 azimuthal angle of the main rotor.  $C_P$  scaled with the freestream velocity.