Towards a new generation of rotorcraft comprehensive analysis; coupling with CSM and CFD

Biel Ortun*†, Didier Petot*, Khiem-Van Truong*, Roger Ohayon†
*ONERA, Châtillon, France
†Structural Mechanics and Coupled Systems Laboratory. Conservatoire National des Arts et Métiers. Paris, France

ABSTRACT

This paper presents the first activities in the development of a coupling between HOST, a rotorcraft comprehensive analysis code, and 3D Computational Structural Mechanics (CSM) and Computational Fluid Mechanics (CFD) analyses. The objective of this coupling is to introduce 3D finite element based structural dynamics models in rotorcraft aeromechanics analysis. A strong coupling procedure has been adopted, where information is exchanged at each time step. The strong coupling here developed can yield trimmed solutions for steady-flight conditions, thanks to an active trim option developed in HOST. The new coupling has been tested by simulating a high-speed level flight condition for the isolated 7A and ERATO rotors, for which wind tunnel measurements are available. Results for the 7A rotor are compared to a previous HOST/CFD coupling and to experiments. Preliminary results for the ERATO rotor are compared to HOST results and to experiments. The coupling procedure and the active trim are validated. The potential of this new high-accuracy analysis is highlighted.

INTRODUCTION

Important research efforts are being focused on rotorcraft noise reduction, performance enhancement and ride comfort. The master tool to achieve these goals is computer simulation. Current rotorcraft numerical simulation relies mostly on “comprehensive” codes, which owe their name to their capacity to integrate models for structural dynamics, aerodynamics and flight controls in a single simulation in order to perform an aeromechanics analysis. Rotorcraft comprehensive analyses are industrial tools meant to provide engineering accuracy at low computational cost. They achieve this by using relatively simple models. Traditionally, the structure is represented by beam models, while the aerodynamics is based on blade element theory complemented by models for induced velocity and wake computation. Comprehensive analyses give satisfying solutions, yet their accuracy limits are made evident in the most critical flight conditions, such as high-speed, high-thrust or blade-vortex interaction phenomena.

In order to tackle this problem, comprehensive codes have been coupled to the more sophisticated CFD methods, which can solve the 3D Reynolds-Averaged Navier-Stokes (RANS) equations, thus providing a higher-fidelity aerodynamic response. A few of the latest publications on coupled comprehensive/CFD approaches can be found in [1] to [5]. All these works use structural dynamics models based on beam theory of varying refinement. This CFD coupling strategy has brought significant improvements, for the flowfield past a rotorcraft is very complex and worth the computationally intensive CFD. Rotorcraft CFD is a thriving field of research and industry is likely to use it increasingly.

Yet however accurate CFD methods might be, aeromechanics is a coupled problem, where the structure response matters just as much as the aerodynamics. Investing on computationally expensive CFD makes sense as long as the structural dynamics keeps pace with the CFD’s accuracy. So far, the classical comprehensive structural dynamics models based on beam theory have proven reliable enough. But future structural models should embrace arbitrary geometries. In a rotor system composed by blades, hub and control mechanisms, there are many elements unsuitable for a beam representation. The newest bearingless hubs would benefit from three-dimensional structural models. Elastic swashplates would open the way to more accurate studies on pitch control mechanisms. Even the latest blade designs, seeking a lower acoustic signature, feature increasingly complex geometries, which puts a growing strain on beam models for blades. Advanced structural models of the fuselage could also provide new insight into rotorcraft vibration.

The objective of this work is to introduce 3D finite element based structural dynamic models in rotorcraft aeromechanics. This objective will be achieved by coupling HOST, a rotorcraft comprehensive analysis developed by Eurocopter, with 3D Computational Structural Mechanics (CSM) and CFD analyses. This paper presents the first steps in the development of the new coupling. The rotorcraft comprehensive analysis code HOST has been coupled with MSC.Marc, an off-the-shelf non-linear finite element solver, and with *elsA*, ONERA's in-house CFD code. The three codes exchange information at each time-step (strong coupling). Contrary to previous rotorcraft comprehensive/CFD couplings, the strong coupling here developed yields trimmed solutions. HOST evaluates the rotor trim state at each time-step and generates rotor controls in order to match the trim objectives.

The first applications of the new coupling are the simulation of isolated rotors in high-speed level flight.

This study belongs to the SHANEL (Simulation of Helicopter Aerodynamics, Noise and Elasticity) programme, a five-year Franco-German cooperation between ONERA, the DLR, Eurocopter and Eurocopter Deutschland launched in 2006. This work continues the developments of a previous cooperation completed in 2005, the CHANCE project [6], in which a HOST/CFD coupling was developed.

This paper is organized as follows. The first part presents the numerical methods HOST, MSC.Marc and *elsA*. Next the coupling methodology is detailed, first stating the coupling specifications and requirements and then presenting the adopted solutions. A third section presents the active trim for the strong coupling. The last sections are the applications. The coupling has been tested for three different rotors: the 7A rotor, an ADM-like rotor and the ERATO rotor. The 7A rotor had already been studied in 2005 by a coupled HOST/*elsA* analysis and served to validate the new couplings and the active trim. A stiffened version of the ADM rotor was also simulated, though no results are shown due to lack of benchmark measurements. The ERATO rotor, for which a 3D FE model was available from another study, is being tested and preliminary results are presented.

NUMERICAL METHODS

Rotor comprehensive analysis

The rotorcraft comprehensive analysis code HOST has been developed and is used by Eurocopter [7]. This method has the capability to compute the aeromechanics and flight dynamics of the complete helicopter or its isolated components (main rotor, tail rotor). The blade dynamics is described by beam theory with modal projection. For the blade aerodynamics, it uses blade element theory with 2D airfoil tables. Several induced velocity models are available, from simple analytic ones (such as Meijer-Drees model) to vortex wake models (METAR prescribed wake and MESIR free wake), and dynamic inflow models (such as the Pitt-Peters model). Additionally, a set of corrections are available (Theodorsen unsteady theory, Reynolds number effects, dynamic stall).

For computing the rotor, two different approaches can be used in HOST. The trimmed equilibrium search, valid for steady flight conditions of the helicopter, assumes that the response is periodic in time at the frequency of the rotation speed of the rotor multiplied by the number of blades, so that all the rotor parameters can be decomposed into Fourier series in order to reduce the number of unknowns. The rotor solution is then obtained for user-prescribed rotor controls or for any user-prescribed trim conditions, such as rotor lift and propulsive forces and zero first harmonics of the flapping angles. The second approach works in the time domain and is adapted from flight dynamics problems. Starting from a trimmed solution, the aeromechanics problem is time-integrated. The active trim option developed in this study can be switched on to match a trim objective.

CSM method

For the structure model, the MSC.Marc finite element (FE) code is used. The choice of this commercial off-the-shelf code was based on its nonlinear analysis capabilities –it updates the stiffness matrix during a simulation and can account for large displacements and rotations-, its built-in Fortran user subroutines for coupling purposes and past experience at ONERA on its use for the dynamic analysis of helicopter blades [8].

CFD method

The CFD code is *elsA*. The development of this object-oriented software for aerodynamics was initiated by ONERA in 1997. This multi-application CFD software solves the Reynolds-Averaged Navier-Stokes equations for all the aerospace configurations from the low subsonic regime to hypersonic, including fixed wing, rotary wing, turbomachinery, space launcher and missile configurations. It uses cell-centered finite volume discretisation for multi-block meshes, including overset and patched grid capabilities. It has a wide range of numerical techniques available for space and time resolution, as well as for turbulence modeling. In the present work a 2^{nd} order centered discretisation in space with Jameson's artificial viscosity was used. For the resolution in time, the dual time-stepping method or the Gear implicit sub-iterative method was used to converge towards the 2^{nd} order accurate solution. These techniques allow the use of large azimuthal steps: $\Delta\psi$=1.2deg for the present simulations. For turbulence modeling, the low cost algebraic model of Michel is used for the applications presented in this paper.
A recent paper presenting state-of-the-art *elsA* simulations for blade-vortex interaction capture can be found in [9].

METHODOLOGY

The coupling methodology consists in adopting a partitioned approach where HOST provides the flight mechanics, the CSM the structure motion and the CFD the airloads. The three partitions are then coupled with a staggered algorithm that regulates the data exchanges at each time step. This type of coupling is usually referred to as strong or tight coupling in the rotorcraft community. There is another popular approach, called weak or loose coupling, in which the solution is assumed periodic and information is exchanged on a per rotor revolution basis. This second option has not been used for this work because of the difficulty to obtain a structural periodic response from the finite element solver, as argued later in the "FE analysis for rotor aeromechanics" section. Furthermore, the strong coupling is more general, since it can be applied to both periodic and transient flight conditions.

Coupling specification

The coupling framework must fulfill three major requirements. The first one is that HOST's autonomous analysis capacity shall be kept. The couplings are only activated when extra-accuracy is needed. The second requirement concerns the modularity of the coupled models; HOST may be coupled with the CFD, the CSM or both. External models may represent a subcomponent of the HOST model (e.g., HOST performs a complete helicopter simulation yet only the main rotor is CSM/CFD modeled). The third requirement is to produce a general coupling that is not dependent on the CFD and CSM codes currently used at ONERA. The coupling framework shall be compatible with other similar codes.
Another desirable feature of the coupling is the exploitation of the numerous state-of-the-art, open-source, tools that are available today for scientific computing. These include the scripting language Python, public data models or parallel and network distributed computing tools, to name a few.

Coupling framework

In order to match the coupling specification requirements presented in the previous section, the development of the coupling framework adopted the following solutions: (1) a component architecture approach; (2) deployment of a standard format for the coupling data; and (3) use of open-source software and protocols.

The component architecture concept is a programming model. The key idea is that each application participating in the coupling shall be regarded as a component independent of the other applications. Components are designed with standard, clearly defined interfaces which tend to protect them from changes in the software environment outside their boundaries. In a simulation involving several components, the modification of one of them or even its replacement by a similar one should not affect the other components. In the present developments, in which up to three applications run coupled –HOST, CFD and CSM-, each of these applications is considered as a component.

ONERA plans to continue using the public CFD General Notation System (CGNS) [10][11], a standard for fluid data storage and retrieval. The advantages of using CGNS are numerous: it provides a common, consistent and precise specification of the fluid data, together with the libraries and tools needed for manipulation. Furthermore, the CGNS standard is portable because it is platform independent. By having a standard interface, the replacement of the CFD and CSM codes by similar, CGNS-compliant ones will be painless. An extension proposal of the CGNS norm to describe structure data is to be submitted to the CGNS Steering Committee. This proposal is under discussion with the SHANEL partners.

The third feature of the coupling framework is the use of the Python scripting language, an open-source software. Python is a powerful tool for data handling. It includes a network server-client communication system, based on the XML-RPC protocol, which provides an easy and high-level means to distribute the coupling components over a network of computers.

The architecture of the proposed approach, schematically described by Fig. 1, consists of a scaleable, highly-modular set of software tools distributed over various processors. HOST is the keystone of this software assembly. It keeps its current analysis autonomy, based on simple, computationally inexpensive aerodynamics and structural models. But when a high-fidelity representation of a particular system is needed (e.g., the main rotor in a complete helicopter simulation) couplings with the CFD and/or CSM models of that system are activated. In all cases HOST provides the aircraft flight control. The coupling is open to any CSM or CFD solver that is CGNS-compliant.

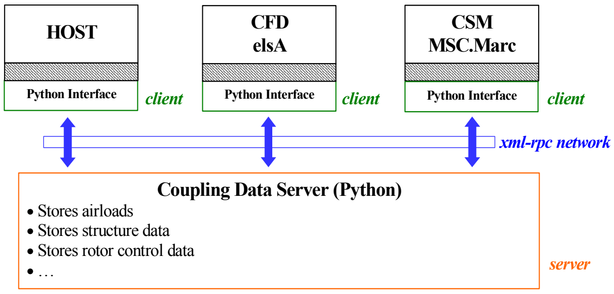

Fig. 1: Coupling architecture

Each component has a Python interface that links it to the coupling framework. This Python interface also acts as a CGNS translator. The components do not communicate directly with each other but rather, they are all clients of a single server. This server is a passive application and executes no commands by its own. It simply stores and delivers CGNS-formatted data upon request from a client. Typically, the server stores only the *n* last iterations in order to bound memory consumption. The server is always activated and available. The user can access the server during the simulation, for debugging purposes for example.

Staggered algorithm

Past research on partitioned procedures for the solution of nonlinear fluid/structure interaction problems has shown that, for strongly coupled simulations in which information is exchanged at every time-step, the algorithm for data exchange has an influence on the accuracy of the results [12][13].

In the present study, HOST, *elsA* and MSC.Marc advance their solutions in time with a common time step that is equivalent to an azimuthal step of $\Delta\psi$=1.2deg. This is also the time step for data synchronizations between codes. In order to minimise the overall simulation time, a parallel fluid/structure staggered algorithm is used. Starting from known fluid and structure states at time t^n, the structure motion at t^{n+1} is predicted using a three-step Adams-Bashforth scheme. The CFD uses this prediction to update its mesh and then integrate in time from t^n to t^{n+1}. The CSM integrates in parallel using the known airloads at t^n and the latest rotor controls generated by HOST.
Albeit practical, parallel staggered schemes have been proven to be less accurate than a serial algorithm in which the fluid and structure computations are offset by half-a-time-step [12][13]. This second scheme will be tested later in the study. The coupling framework is open to any staggered scheme and changes are easy.

The fluid/structure interface (FSI)

The natural interface between the CFD surface mesh of the blade and its 3D finite element model is the wet surface. In such an approach the CSM receives the airloads as a pressure distribution (plus shear for viscous flows) and the deformation of the CFD surface mesh tracks that of the structure. However, this approach involves costly interpolations between non-matching grids. It also requires geometrically rigorous structural models. For this study, it was preferred to start working with simpler fluid/structure interfaces as a previous step to the wet surface approach.
The fluid/structure interface is thus projected on the quarter-chord line. The fluid and structure discretisations are non-matching, but the interpolation functions depend of a single variable, the blade radius. Structure motion is expressed as the coordinates of the quarter-chord line plus rotation matrices defining the orientation of the cross-sections. The CSM nodes deflections are interpolated at the set of spanstations where the CFD expects input to deform its mesh. The CFD returns the six force and moment components of the airloads at a set of spanwise segments. The CFD airloads distribution is then integrated over the CSM segments. Fig. 2 shows the CFD mesh of a generic blade surface. The green and orange nodes at the leading and trailing edges, respectively, represent the CSM nodes. The blue nodes along the blade quarter-chord line are the spanstations where the CFD expects structure deformation.

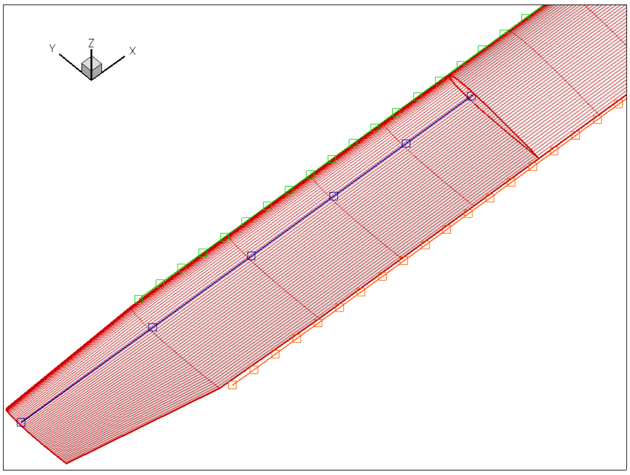

Fig. 2: Fluid/structure interface

FE analysis for rotor aeromechanics

The use of a non-rotorcraft-specific finite element analysis for rotor dynamics has three implications. The first one is that weak or loose coupling analyses, in which the solution is assumed periodic and information is exchanged on a per revolution basis, is hardly achievable. When a rotorcraft comprehensive analysis is loosely coupled with a CFD method, the comprehensive code continues to calculate airloads as a function of the actual blade motion. These airloads are then corrected by the difference between the CFD airloads and the HOST airloads from the previous revolution (delta airloads). The total airloads are equal to the comprehensive airloads plus the delta airloads. Comprehensive airloads are a source of aerodynamic damping, necessary for convergence. Obtaining a periodic response from a finite element simulation that has no comprehensive aerodynamics would require adding some kind of artificial damping or

introducing external, motion-dependent airloads. Even in these cases the periodic response by finite element simulation would demand lengthy and costly runs, mostly due to the slow damping of the lead-lag motion.
A second finite element related issue is the simulation start. The onset of the centrifugal loading triggers high frequency oscillations in the elongation modes. The prescription of the pushrod displacement for setting the initial pitch is a second source of high frequency vibrations, though for torsion modes in this case. These issues are solved by using input ramp functions and temporary element damping. The parameters of the Newmark scheme can also be adjusted to provide some high frequency damping.
The third important difference with respect to comprehensive dynamics is that the finite element solver does not handle the blade angles in flapping, feathering and lead-lag as unknowns. Some post processing of the FE nodal results is necessary to derive these angles.

Trim control in strong coupling

Trimmed solutions enable the comparison between numerical analyses and wind tunnel measurements at the same level of performance and are thus highly desired. Trimmed solutions in strong coupling are usually obtained by manually correcting the commands of a converged solution three or four times so as to end up with the desired trim.
These are unpleasant operations which lead at the very least to a doubling of computation time. In the frame of this work, it was thus proposed to correct the trim during time integration with an option called "active trim".
Just as in the case of manual trims, this active trim option is based on the knowledge of the gradient $\partial O / \partial C$ of the trim objectives *O* with respect to the rotor control commands *C*. This gradient is obtained by an autonomous HOST computation, assuming a linear behavior around the trim state.
For a given trim objectives vector O_0 there is a corresponding control vector C_0, which can be found by

$$C = C_0 + (\partial O / \partial C)^{-1} \cdot (O - O_0) \qquad (1)$$

In order to have a continuous adjustment of the trim, it is proposed to apply a continuous command correction

$$dC / dt = (C_0 - C) / a \qquad (2)$$

This is a well-known differential equation, which introduces the time constant a, which is the delay after which $(e-1)/e$ = 63% of the command is reached. 50% of the desired command is obtained at $t \simeq 0.69a$ (=ln(2)) and 99% at $t \simeq 4.6a$ (=ln(100)).
Replacing the term $(C_0 - C)$ from equation (1) in equation (2) yields the ordinary differential equation

$$dC / dt = -(\partial O / \partial C)^{-1} \cdot (O - O_0) / a \qquad (3)$$

It can be shown that stability of the associated linear system should not be a concern. However, instabilities do develop if too small command delays a are applied. It is not known whether this is due to the explicit time integration method used or to non linear side effects. Convenient values of a were around 1.5 revolution periods.
Examples and results of the active trim in strong coupling are shown in the results section.

APPLICATIONS

This section will present two applications of the strong coupling with active trim: (1) the 7A rotor; and (2) the ERATO rotor.

Test case 1: the 7A rotor

The 7A rotor is a four-bladed rotor tested in ONERA's S1MA wind tunnel. The blades have an aspect ratio equal to 15, with rectangular planform and linear twist. The rotor diameter is 4.2m.
The 7A rotor was simulated in high-speed forward flight (μ=0.4) in order to compare the results with those of the HOST/CFD coupling developed during the CHANCE project (2000-2005). Similar results were expected, since the same CFD method was reused and the CSM model, based on Timoshenko beams, was only slightly better than HOST's, with Euler beams and modal projection.

The trim condition in the wind tunnel is defined by an advance ratio of μ=0.4 (316km/h), a non dimensional rotor lift coefficient, ZB=200.Ct/σ=12.5, a non dimensional propulsive force coefficient of 1.6 and the Modane flapping law. The Modane flapping law is defined by a null first harmonic lateral flapping angle (β_{1s}=0) and a first harmonic longitudinal flapping angle equal and of opposite sign to the longitudinal cyclic control (β_{1c}=- θ_{1s}).

CSM model

The 7A rotor model, shown in Fig. 3, is made exclusively of beam elements for a low computational cost. The model includes a pitch control system by slide elements and lead-lag dampers (not visible in the figure). The blades are clamped and thereby assumed independent.
The Newmark scheme was used. Artificial damping was used during the initial iterations to counter the high-frequency vibrations generated by the centrifugal force onset and the initial pitch input.

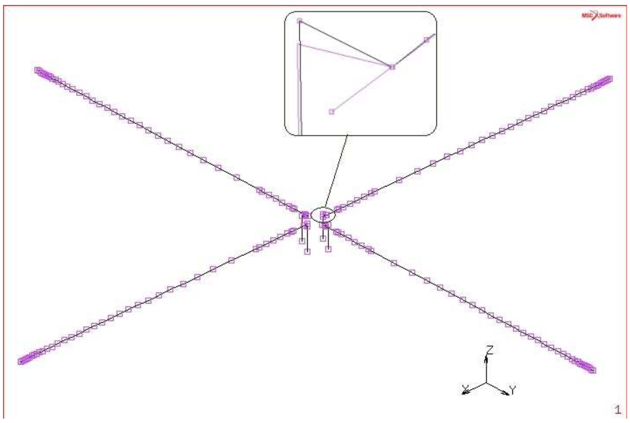

Fig. 3: Finite element model of the 7A rotor with close-up view on the pitch control system

CFD model

The *elsA* model used in the present study was first used by Beaumier *et al.* in [1] but is recalled next. It is a viscous flow simulation, with a rotor grid that is quite coarse compared to other rotor grids in concurrent CSD/CFD coupled analyses. The total number of points for the complete rotor is approximately equal to $2.1.10^6$. There is one C-H block per blade. Each block has 189 nodes along the chord direction, 57 nodes in the spanwise direction (of which 32 over the blade) and 49 nodes in the direction normal to the rotor plane.
A 2nd order centered discretisation in space with Jameson's artificial viscosity was used. The resolution in time is achieved by the dual time-stepping method. The algebraic model of Michel is used for turbulence.

Results

Nine rotor revolutions were simulated. During the first three revolutions the airloads were given by HOST. They were used to initialize the rotor dynamics at a low computational cost. After the third revolution the airloads were provided by *elsA*. The rotor controls were generated by HOST during all the revolutions.
Results are first presented for the convergence of the trim and rotor controls. Then sectional airloads are presented and compared to experiment and previous HOST/CFD strong coupling results from the CHANCE programme. In that strong coupling the trim was adjusted by stopping the simulation and correcting manually the rotor controls before relaunching it again.
In the wind tunnel the rotor trim was defined by four variables (lift coefficient, propulsive coefficient and flapping law) depending on four rotor control variables (collective pitch, lateral cyclic pitch, longitudinal cyclic pitch and rotor shaft angle). However, the rotor shaft angle cannot be modified yet in *elsA* during run-time. Loosing one control variable constrained to suppress a trim variable. The propulsive force coefficient was chosen to be left out of the trim objectives. The rotor shaft angle set in e*lsA* for the entire simulation was previously obtained by a HOST trim calculation.
The evolution of the non dimensional lift coefficient ZB and of the collective control is shown in Fig. 4. The evolution of the Modane flapping trim condition and cyclic controls is shown in Fig. 5. In both figures a perturbation of the trim variables is observable at the start of the fourth revolution. This is due to the switch from HOST airloads to *elsA* airloads. A fair

convergence to the trim objectives is attained after six rotor revolutions. Another revolution is yet necessary for the controls to start stabilizing. In the last revolution, the relative error of the rotor lift coefficient, ZB, with respect to its trim objective is 0.77%. The absolute error of the Modane flapping trim variables is 0.027deg for the first lateral flapping harmonic, β_{1S}, and 0.023deg for the variable $\theta_{1s}+\beta_{1c}$. The absolute variation of collective control during the last revolution is -0.008deg. For the lateral control this variation is of 0.003deg and for the longitudinal control, -0.004deg. The rotor propulsive force coefficient (not plotted), although left out of the trim, stays satisfyingly close to the trim target.

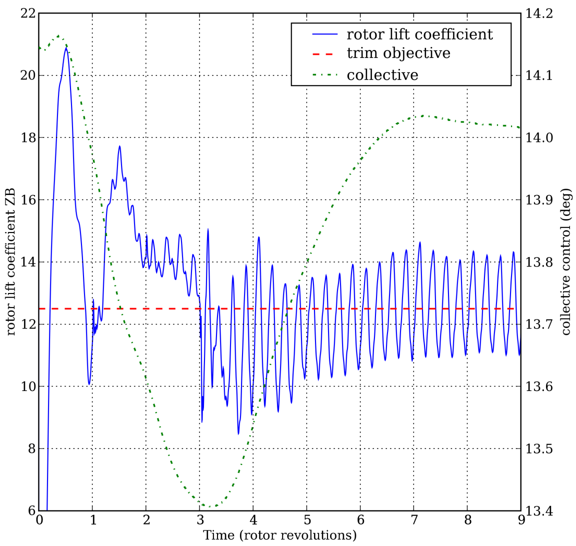

Fig. 4: Collective control and rotor lift coefficient

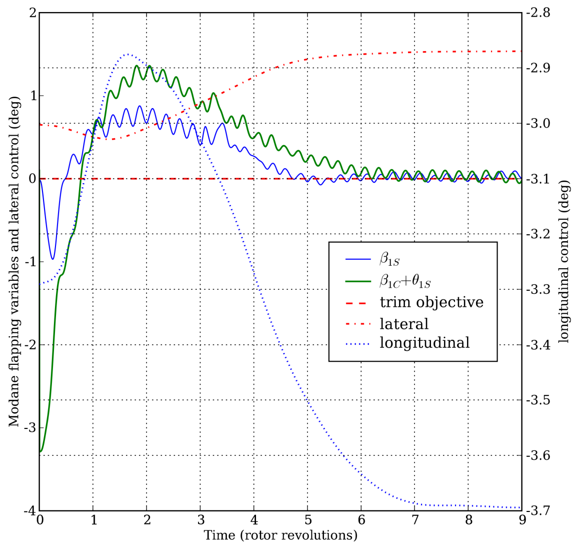

Fig. 5: Cyclic control and Modane flapping trim

The section normal force, Cn, and pitching moment, Cm, coefficients (times M^2) are presented at two spanstations: r/R=0.70 and r/R=0.975. The results are compared with measured data and with the results of a HOST/*elsA* strong coupling [1]. The section normal force coefficient distributions over the last revolution at r/R=0.70 and r/R=0.975 are shown in Fig. 6 and Fig. 7, respectively. The pitching moment coefficients at r/R=0.70 and r/R=0.975 are shown in Fig. 8 and Fig. 9, respectively. As expected, the previous HOST/*elsA* coupling results have been successfully reproduced, which validates the first developments of the new CSM/CFD/HOST coupling.

Although the amplitude of the negative peaks in the advancing blade remains poorly predicted, it is recalled that the objective of this simulation was to validate the new coupling and the active trim. The CFD model of a past HOST/*elsA* coupling was used instead of taking advantage of the state-of-the-art capabilities in *elsA*. The prediction of the amplitude of the negative peak of pitching moment coefficient can be improved by simply switching to the Gear method for the time integration in *elsA* (instead of the dual-time stepping method), as shown in [1]. Further improvement of the airloads prediction would probably require finer CFD grids.

.

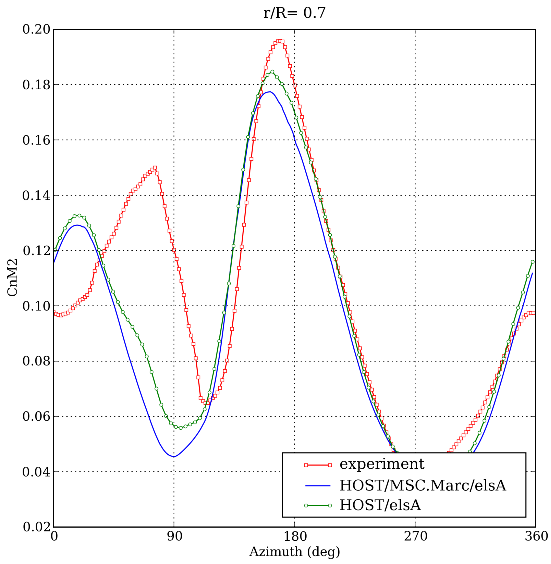

Fig. 6: 7A. Normal force r/R=0.70

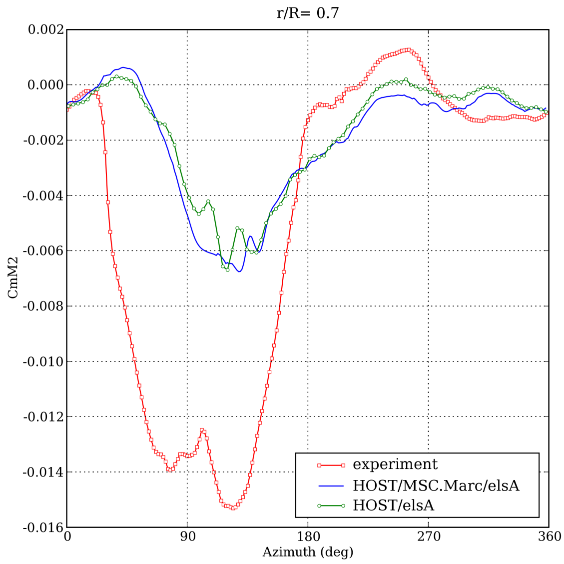

Fig. 8: 7A. Pitching moment r/R=0.70

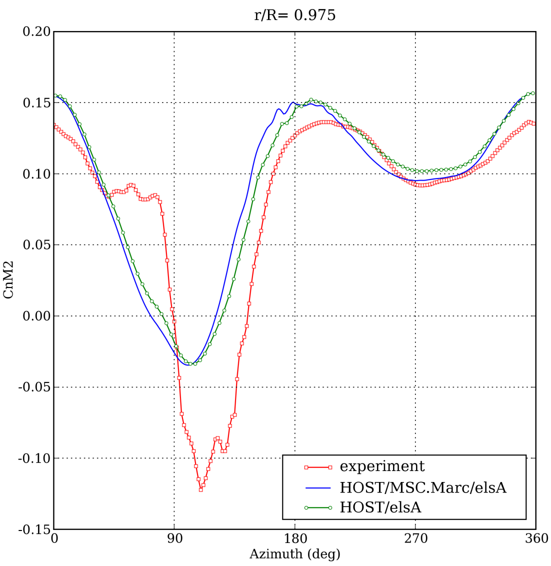

Fig. 7: 7A. Normal force r/R=0.975

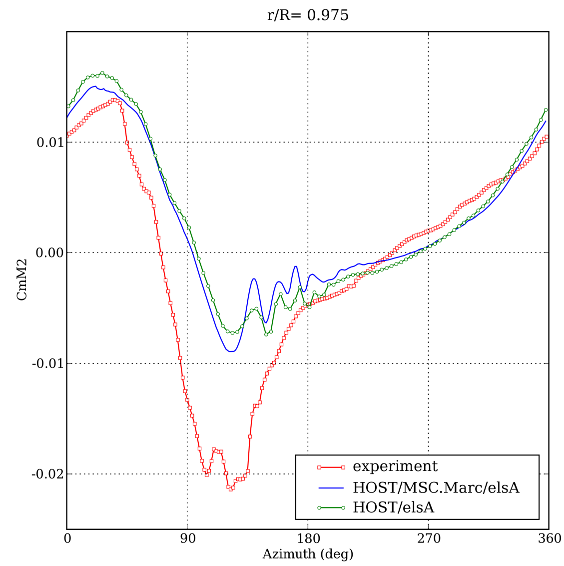

Fig. 9: 7A. Pitching moment r/R=0.975

Test case 2: The ERATO rotor

The ERATO rotor is the outcome of a research project seeking to design a blade with lower acoustic signature. Its four blades feature a complex chord and twist distribution, forward and backward sweep and a profile evolution including up to four different profiles. Like the 7A rotor, it has a rotor diameter equal to 4.2m.

The simulations in this study reproduce a high-speed level flight (advance ratio equal to μ=0.423) tested in wind tunnel. The trim

condition in the wind tunnel is defined by an advance ratio of μ=0.423, a non dimensional rotor lift coefficient, ZB=200.Ct/σ=12.5, a non dimensional propulsive force coefficient of 1.6 and the null first flapping harmonics piloting law ($\beta_{1s}=\beta_{1c}=0$).
The use of advanced structure models for this blade is interesting because HOST's structure model underpredicts the torsional response, which is critical to an accurate aeroelastic analysis. This fact is illustrated in Fig. 10, where the measured torsion component of the third rotating flap mode is compared to a prediction done with the 3D finite element model and with HOST's model. The latter underpredicts the amplitude of the torsion component.

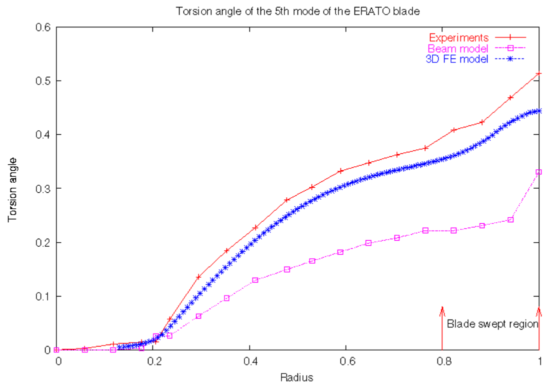

Fig. 10: Torsion component of the third flap mode of the rotating ERATO blade.

CSM model

The 3D finite element model of the ERATO blade is shown in Fig. 11. The model was built with a minimum number of elements, but reproduces the measured modal frequencies. Used elements include beams, shells and cubic hexahedra. Each blade is equipped with a pitch control system and a lead-lag damper.
In order to trim the computation costs of the four bladed rotor, two MSC.Marc applications run in parallel, each containing two blades, see Fig. 12. This is possible because the blades are assumed mechanically independent (rigid hub). Running parallel CSM applications is easy thanks to the modularity of the coupling framework.
The fluid/structure interface is composed by the nodes spanning along the leading and trailing edges. The CFD mesh is deformed from the motion of these two sets of nodes and the CFD airloads are distributed between the leading and trailing edges.

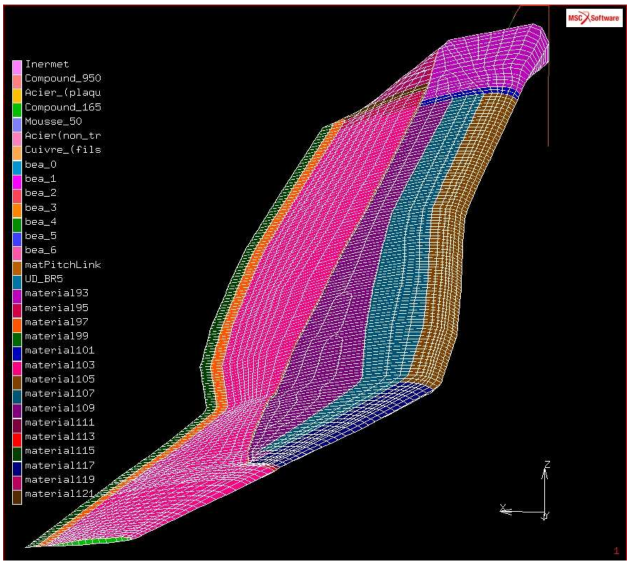

Fig. 11: 3D finite element model of the ERATO blade

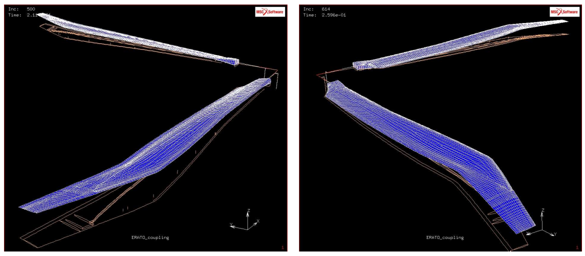

Fig. 12: Two finite element models run in parallel

CFD model

The first simulations have been carried out with an inviscid Euler model, in order to lower the computation costs. Multi-block grids (one C-H block per blade) are used for the simulation of the isolated rotor, see Fig. 13. Each block has 141 nodes along the chord direction, 40 nodes in the spanwise direction (of which 26 over the blade) and 26 nodes in the direction normal to the rotor plane, resulting in a total number of nodes for the complete rotor over $5.8.10^5$.
A 2nd order centered discretisation in space is used. The time integration is done with the implicit Gear method. The azimuthal step is equal to $\Delta\psi$=1.2deg.

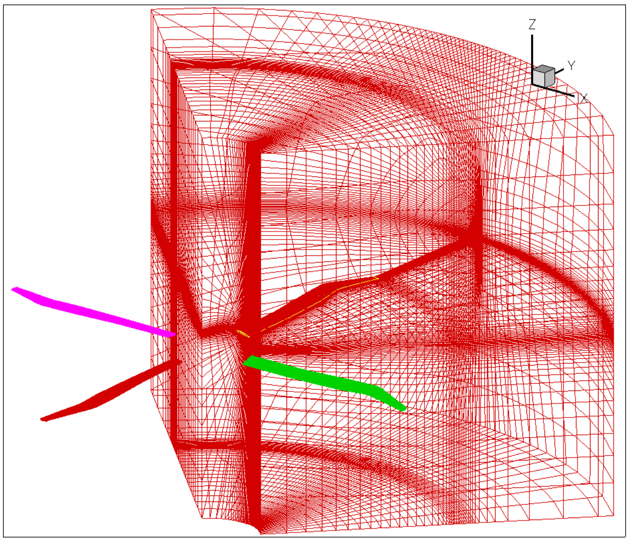

Fig. 13: Multi-block grid used for Euler simulations of the isolated ERATO rotor

Results

This paper presents the very first results of the ERATO rotor. Thereby these results should be regarded as preliminary. Further adjustments are still necessary.

The simulation ran over more than eight revolutions. No HOST airloads were used. The trim controls are fairly stabilized. A small error in the input frame of the airloads in MSC.Marc probably delayed the trim convergence.

The MSC.Marc simulation takes longer than the CFD because it runs on a desktop computer, whereas the CFD runs on a high-performance vectorial computer. A parallel staggered scheme reduces the overall simulation to that of the CSM. A rotor revolution takes approximately eight hours (wall clock). A full convergence of the simulation might require up to eight or nine revolutions.

The convergence of the non dimensional rotor lift coefficient, *ZB*, towards the trimmed state is shown in Fig. 14. The same figure includes the evolution of the collective pitch control. It appears that the active trim was too amplified. As a result, the response has a mild overshooting tendency. The same trend is observed in the convergence of the first flapping harmonics, β_{1C} and β_{1S}, see Fig. 15.

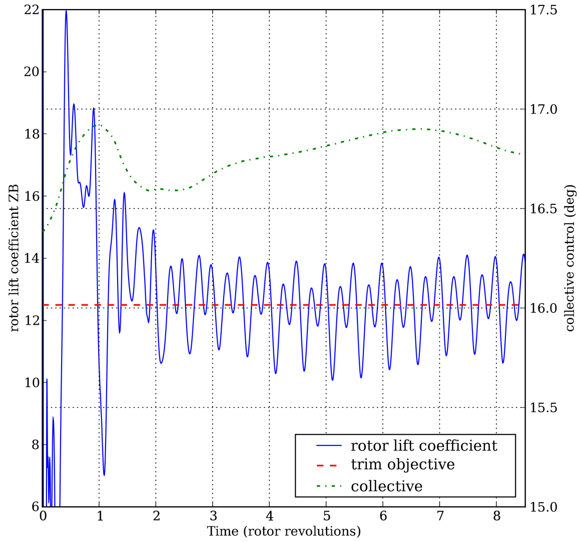

Fig. 14: Collective control and rotor lift coefficient

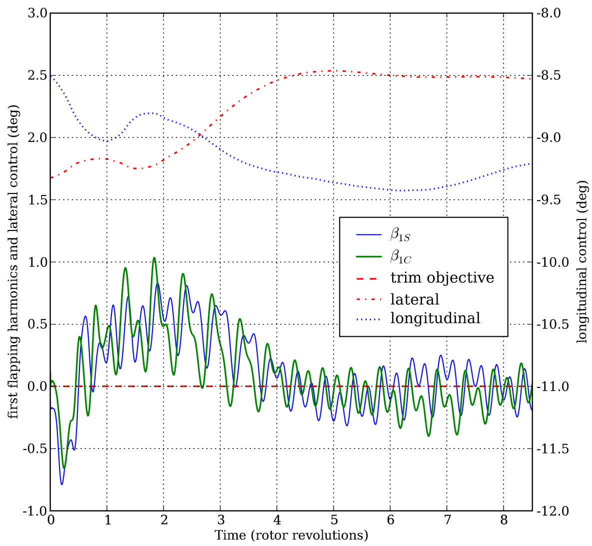

Fig. 15: Cyclic control and American flapping trim

Fig. 16 to Fig. 19 show the normal force and pitching moment sectional airloads at two spanstations, r/R=0.75 and r/R=0.975. All these figures include the measured airloads, the airloads predicted by the HOST/MSC.Marc/*elsA* coupling and the airloads from an autonomous HOST analysis. The HOST results were obtained by running a trim computation, with the METAR wake model and Theodorsen unsteady corrections. The METAR wake model is a prescribed-position wake method.

At the r/R=0.975 spanstation, the azimuth of the negative lift and pitching moment peaks in the advancing blade (ψ=90deg) is slightly better predicted by the CFD than HOST (Fig. 18 and Fig. 19). The amplitude of the negative peak in pitching moment is however underestimated. As a consequence, the blade tip does not twist enough and thereby the negative peak in normal force is also underestimated.

In high-speed level flight, blade vortex interaction is not a dominant phenomenon because the rotor wake is quickly convected behind the rotor, which is strongly tilted forward. But the surge in pitching moment at Ψ=75deg in Fig. 19 could nevertheless be due to a vortex perturbing the advancing blade. Naturally, the inviscid Euler grid cannot capture such phenomena

At the r/R=0.975 section the ERATO blade is strongly tapered. This favours a dynamic stall in the retreating blade, corresponding to the second negative pulse in the experimental pitching moment in Fig. 19 and minor lift perturbations in Fig. 18, shortly after the 270deg azimuth. Neither HOST nor the CFD capture the dynamic stall.

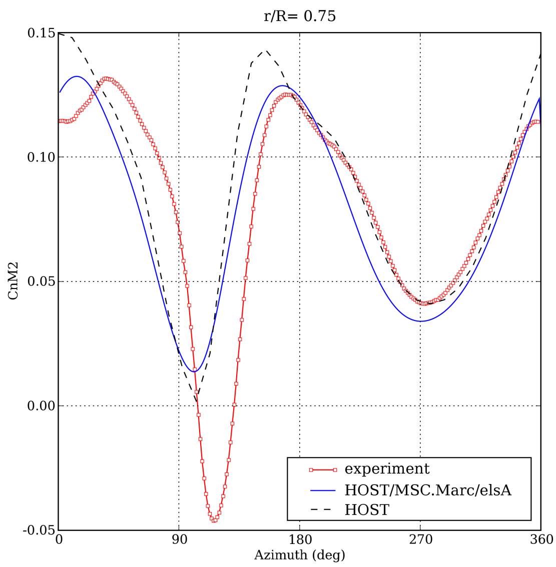

Fig. 16: ERATO. Normal force r/R=0.75

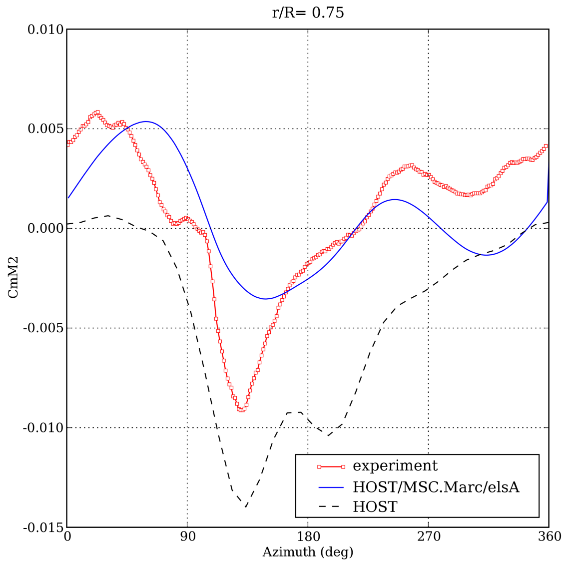

Fig. 17: ERATO. Pitching moment r/R=0.75

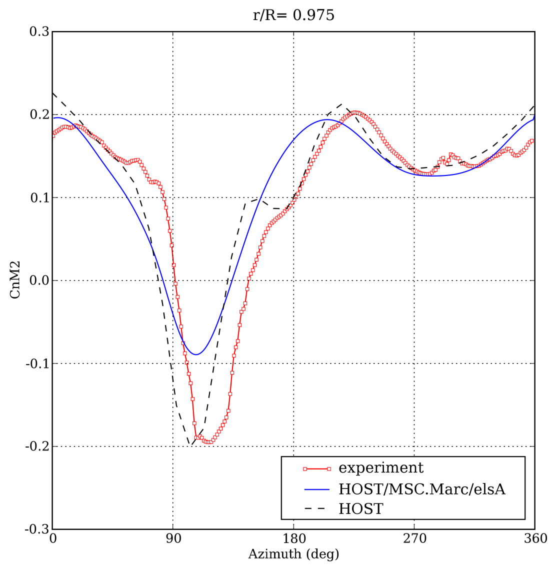

Fig. 18: ERATO. Normal force r/R=0.975

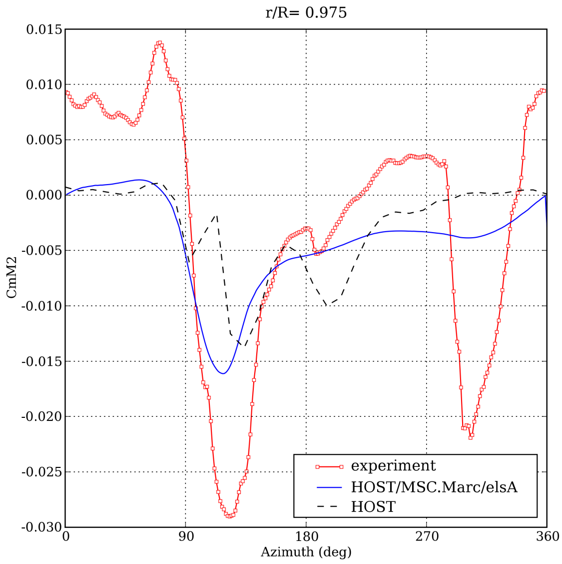

Fig. 19: ERATO. Pitching moment r/R=0.975

Finally, the elastic torsion of the blade tip is presented in Fig. 20. The backward sweep of the ERATO blade leads to minimum torsion when the blade tip of the advancing blade (ψ=90deg) undergoes transonic speeds. The aft-swept blade tip, pulled down by negative lift, acts as a lever introducing pull-up pitch to the rest of the blade. The frequency of the measured torsion is 5/rev, whereas both HOST and the coupling results yield a 4/rev frequency.

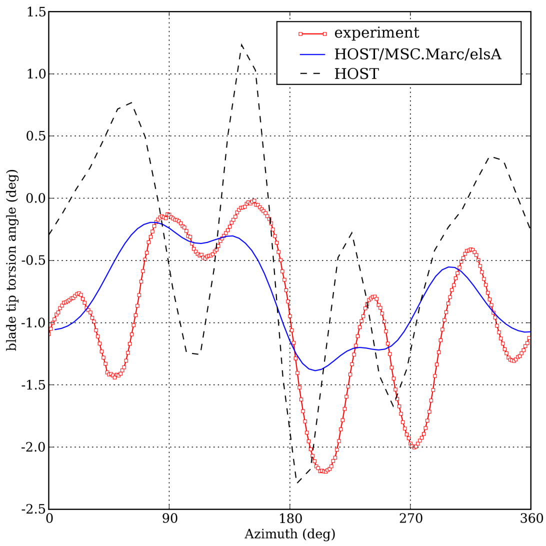

Fig. 20: ERATO. Blade tip elastic torsion

The coupled HOST/CFD/CSM results will certainly be improved. Additional accuracy may be gained by substituting the parallel staggered scheme by a serial scheme with half-a-time-step between the fluid and structure integrations. Finally, a viscous flow RANS CFD analysis will substitute the present Euler analysis used for the first tests.

CONCLUSIONS

The rotorcraft comprehensive analysis HOST has been successfully coupled with 3D Computational Structural Mechanics (CSM) and CFD analyses by a tight or strong coupling procedure, in which information is exchanged at each time-step. An active trim has been implemented in the strong coupling. The developments have been tested on the 7A and ERATO rotors in high-speed level flight.

From the 7A application it can be drawn that:

- The first HOST/CSM/CFD developments have been validated by reproducing previous HOST/CFD analyses.
- The active trim yields a trimmed solution of the strongly coupled analysis.
- Accounting for shear in the 7A blade structural model does not seem to improve the agreement with experiments

From the ERATO test it can be concluded that:

- 3D finite element structure models have been successfully introduced in rotorcraft aeromechanics analysis.
- The modularity of the coupling framework has been shown by splitting the computationally intensive FE model of the rotor into two models, each containing two blades.
- The presented results are not final results. More accurate results are expected from the use of finely tuned viscous RANS CFD methods and higher-accuracy staggered schemes.

More generally, this work achieves its objectives:

- It lays the foundations in the development of a new, high-accuracy, generation of comprehensive rotorcraft analyses by code coupling.

- A prototype of highly-modular coupling framework has been setup.
- The new coupling is open to any CSM or CFD solver compliant with the CGNS public standard.
- High-performance computing is achieved through network distributed analysis.

Future work will include:

- An assessment on the influence of the staggered scheme (parallel, serial, collocated, non-collocated) on the accuracy of the aeroelastic simulation.
- Refinement of the herein presented results.
- Evaluation of the beam models in HOST by comparison with the CSM models.
- Using the 3D CSM for new exciting applications, such as bearingless rotor hubs or tiltrotor gimbal hubs.

ACKNOWLEDGEMENTS

This work is funded by the the DPAC (Direction des Programmes Aéronautiques Civils) and by ONERA internal funding.
The data on the ADM blade were obtained thanks to the MOA collaboration between the Aeroflightdynamics Directorate (AFDD, U.S.) and ONERA.

REFERENCES

[1] Beaumier, P., Costes, M., Rodriguez, B., Poinot, M. and Cantaloube, B. *Weak and Strong Coupling between the elsA CFD solver and the HOST helicopter comprehensive analysis*, 31st European Rotorcraft Forum, September 2005.

[2] Bhagwat, M.J. and Ormiston R.A. *Examination of Rotor Aerodynamics in Steady and Maneuvering Flight Using CFD and Conventional Methods*, American Helicopter Society Specialists' Conference on Aeromechanics, Jan. 2008.

[3] Bhagwat, M.J., Ormiston, R.A., Saberi, H.A. and Xin, Hong. *Application of CFD/CSD Coupling for Analysis of Rotorcraft Airloads and Blade Loads in Maneuvering Flight*, American Helicopter Society 63rd Annual Forum, May 2007.

[4] Nygaard, T.A., Saberi, H., Ormiston, R.A., Strawn, R.C. and Potsdam, M. *CFD and CSD Coupling Algorithms and Fluid Structure Interface for Rotorcraft Aeromechanics in Steady and Transient Flight Conditions*, American Helicopter Society 62nd Annual Forum, May 2006.

[5] Potsdam, M., Yeo, H. and Johnson, W. *Rotor Airloads Prediction Using Loose Aerodynamic/Structural Coupling*. Journal of Aircraft, Vol. 43, No. 3. May-June 2006.

[6] Costes, M., Pahlke, K., D'Alascio, A., Castellin, C. and Altmikus, A. *Overview of Results Obtained during the 6-year French-German CHANCE Project*, American Helicopter Society 61st Annual Forum, June 2005.

[7] Benoit, B., Dequin, A.M., Kampa, K., Grunhagen, W., Basset, P.M. and Gimonet, B. HOST, *A general helicopter simulation tool for Germany and France*, American Helicopter Society 56th Forum, May 2000.

[8] Truong, V.K, *Dynamics Studies of the ERATO blade, based on Finite Element Analysis*, 31st European Rotorcraft Forum, September 2005.

[9] Renaud, T., Perez, G., Benoit, C., Jeanfaivre, G. and Peron, S. *Blade-vortex interaction capture by CFD*, 34th European Rotorcraft Forum, September 2008.

[10] Poinot, M., Costes, M. and Cantaloube, B. *Application of CGNS software components for helicopter blade fluid-structure strong coupling*, 31st European Rotorcraft Forum, September 2005.

[11] Poinot, M., Rumsey, C. and Mani, M. *Impact of CGNS on CFD workflow*, 34th AIAA Fluids Dynamics Conference, July 2004.

[12] Farhat, C., van der Zee, K. and Geuzaine, P. *Provably second-order time-accurate loosely-coupled solution algorithms for transient nonlinear computational aeroelasticity*, Comput. Methods Appl. Mech. Engrg., 2006, 195, pp 1973-2001.

[13] Piperno, S. and Farhat, C. *Partitioned procedures for the transient solution of coupled*

aeroelastic problems – Part II: energy transfer analysis and three-dimensional applications, Comput. Methods Appl. Mech. Engrg., 2001, 190, pp 3147-3170.