SIMULATION OF TILTROTOR MANEUVERS BY A COUPLED MULTIBODY–MID FIDELITY AERODYNAMIC SOLVER

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Abstract

The present work proposes a new aeroelastic solution applicable to rotors and tiltrotors configuration by joining the multibody software MBDyn and the mid-fidelity aerodynamic tool DUST. The coupled MBDyn-DUST simulation environment is aimed to be used for the evaluation of the loads and of the vibratory levels of a tiltrotor aircraft during some critical transient maneuvers. The coupling is first validated by modelling the XV-15 equipped with metal blade rotors in hover configuration. Firstly, the dynamic behaviour of the rotor is tested by comparing the MBDyn Campbell collective diagram with the corresponding CAMRAD II and RCAS diagrams. Secondly, the rotor performances in hover are evaluated by using the coupled approach. The structural dynamics is taken from MBDyn whereas the aerodynamic loads are calculated by DUST. This coupled approach shows a good agreement in terms of polar curve and figure of merits when compared to experimental results. These preliminary results encouraged the use of this novel coupled tool for the simulation of tiltrotor flight dynamics and aeroelasticity.

1 INTRODUCTION

Tiltrotor design is a rather challenging activity due to the diverse missions and configurations in which the aircraft operates. In particular, tiltrotors must be able to take-off and land as helicopters and, once completed the conversion maneuver, carry on the flight as an airplane. To control these vehicles, several control surfaces and actuation systems are necessary, driven by a complex Flight Control System (FCS) able to mix the control action during the different flight conditions [1, 2]. The design of the control surfaces and the actuators selection require the correct evaluation of the aircraft loads during the maneuvers in order to improve the vehicle response, increase the efficiency and reduce the weight and the complexity of the control system. Tiltrotor maneuvers are often investigated through a multibody approach, which takes into account the nonlinear dynamics of the interconnected bodies representing the tiltrotor components during the transients [3, 4]. The multibody approach is also used to investigate aeroelastic phenomena, especially in airplane mode flight where whirl-flutter instabilities may occur [5, 6].

In the context of this work, the multibody software selected is MBDyn. Having to simulate transients, it is important to have an unsteady aerodynamic model that can be coupled to the dynamics of the system. The current aerodynamic tool implemented in MBDyn is able to predict tiltrotor aeroelastic stability phenomena [7, 8]; however, for the specific purpose of simulating tiltrotor maneuvers and for the estimation of aeroelastic loads, the aerodynamic solution obtained with the Blade Element/Momentum Theory (BE/MT) is not sufficiently accurate. No aerodynamic interference between the rotor and the wing is taken into account and this can lead to a significant underestimation of the aerodynamic loads and loss of information relating to periodic actions. In the past, coupling with computational fluid dynamics (CFD) solvers was implemented to cope with this limitation [9, 10, 11, 12, 13]. The downside of this approach relies in the computational cost of such detailed description of the aerodynamics. In order to overcome this obstacle a possible solution is the coupling of the multibody software with a mid–fidelity aerodynamic solver, in order to have a more efficient trade–off between efficiency and accuracy. With this aim, MBDyn has been combined with a mid-fidelity, fast and reliable aerodynamic solver, called DUST. The coupling of the two software relies on the partitioned multi-physics coupling library preCICE [14].

The present paper describes the methodology used for the coupling of the multibody software MBDyn with the mid-fidelity aerodynamic solver DUST. Then, a first validation of the coupled numerical tool is provided by analysing the performance of the elastic XV–15 three–bladed rotor. The work proposed represents an important benchmark for the validation of the coupled numerical tool aimed to the simulation of tiltrotor maneuvers. The research activity will be completed by the use of this novel coupled tool for the evaluation of the loads and of the vibratory levels of the XV-15 complete tiltrotor aircraft during some critical transient maneuvers.

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2 MULTIBODY-AERODYNAMIC TOOLS

2.1 MBDyn

In the last 20+ years Politecnico di Milano developed the free (released under GNU GPL 2.1 licence), general purpose multibody software MBDyn (`http://www.mbdyn.org/`), implementing efficient solutions for the multibody modeling of generic problems related to the dynamics of complex systems, including aeroservoelastic models of rotorcrafts and tiltrotor systems.

MBDyn automatically writes and solves the equations of motion of a system entities possessing degrees of freedom - nodes - connected through algebraic constraints, and subjected to internal and external loads. Constraint equations are explicitly taken into account, following a redundant coordinate set approach. Thus, the resulting system of Differential-Algebraic Equations (DAEs) is in the form

$$\mathbf{M}(\mathbf{x},\mathbf{t})\dot{\mathbf{x}} = \mathbf{p} \tag{1a}$$

$$\dot{\mathbf{p}} = \phi^T_{/\mathbf{x}}\lambda + \mathbf{f}_i(\dot{\mathbf{x}},\mathbf{x},t) + \mathbf{f}_e(\dot{\mathbf{x}},\mathbf{x},t) \tag{1b}$$

$$\phi(\mathbf{x}) = \mathbf{0} \tag{1c}$$

where $\mathbf{x}$ are the kinematic unknowns, $\mathbf{p}$ the momentum unknowns, λ the algebraic Lagrangian multipliers, $\mathbf{M}$ is a configuration and time dependent inertia matrix, $\mathbf{f}_i, \mathbf{f}_e$ are arbitrary internal and external forces, $\phi(\mathbf{x})$ are the nonlinear algebraic constraint equations (honolomic constraints) and $\phi^T_{/\mathbf{x}}$ is the Jacobian matrix of the holonomic constraints with respect to the kinematic unknowns. Each node instantiates the writing of balance equations (1b), while only nodes to which inertia properties are associated instantiate the writing of momenta definitions (1a). Additional states, associated with scalar fields (namely, hydraulic pressure, temperature, electric current) and thus the associated differential balance equations, can be taken into account through a specialized set of nodes.

Elements are responsible for the contributions to the balance equations through (visco)elastic internal forces $\mathbf{f}_i$, possibly state-dependent external force fields $\mathbf{f}_e$ (e.g. aerodynamic forces) and reaction forces, introduced by means of the Lagrange multipliers λ and the gradient of the nonlinear algebraic constraint equations 1c.

The DAE system can be integrated with several different A/L stable integration methods, among which an original multistep method with tunable algorithmic dissipation [15], specifically designed for the class of problems MBDyn is usually asked to tackle.

2.2 DUST

DUST is a mid-fidelity aerodynamic tool which has been developed at Politecnico di Milano since 2017 focused on the flexibility and robustness for the simulation of the interactional aerodynamics of rotorcraft and unconventional aircraft configurations [16]. The code is released as a free software, under the open source MIT license (`https://gitlab.com/dust_group/dust`). The code relies on an integral boundary element formulation of the aerodynamic problem and on a vortex particle model [17, 18] of the wakes. This choice naturally fits the Helmholtz decomposition of the velocity field from a mathematical point of view and avoids the numerical instabilities often occurring with structured wake models. In DUST an aircraft model can be composed of several components, connected to user-defined reference frames, whose position and motion can be defined in a hierarchical way. The presence of different aerodynamic elements allows for different levels of fidelity in the model, ranging from lifting line elements to zero-thickness lifting surfaces and surface panels for thick solid bodies. The simulation is evolved in time with a time-stepping algorithm, solving in sequence the Morino-like problem for the potential part of the velocity field, the nonlinear problem for the lifting lines and updating the rotational part of the velocity field, integrating the Lagrangian dynamical equations of the wake particles. To enhance the computational performance the code is extensively parallelized, while a fast multipole method is employed to accelerate the particles interactions.

3 MULTIBODY-AERODYNAMIC COUPLING

The coupled multibody-aerodynamic tool exploits the two codes, MBDyn and DUST, for the resolution of the structural and aerodynamic problem respectively. The communication between the two software takes place through PreCICE, which is an open-source software released under the LGPL3 license and available on GitHub (`https://github.com/precice/precice`) [14]. PreCICE (Precise Code Interaction Coupling Environment), is a coupling library for partitioned multi-physics simulations capable of simulating a subpart of the complete physics involved in a simulation.

The coupling procedure needs the implementation of the adapters for preCICE, available on GitLab (`https://gitlab.com/davideMontagnani/dust-mbdyn`). An adapter for MBDyn has been implemented to allow the communication of all the kinematic variables (position, orientation, velocity and angular velocity) and actions (forces and moments) acting on the nodes of a MBDyn model exposed through an external structural force. While MBDyn uses its own application programming interface (API) for communications with external softwares, no API was already available in DUST and few modifications to the source code were required before implementing the DUST adapter. Figure 1 shows the logic workflow between the two solvers through the relative adapters.

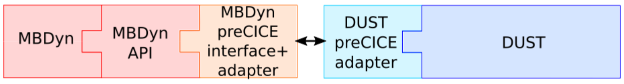

Figure 1: Communication scheme through the adapters

In order to obtain different levels of accuracy and discretization of the aerodynamic surface, three different coupling methods are designed.

- `rigid` coupling between a rigid component in DUST and a unique structural node in MBDyn. The resultant-force and torque of the aerodynamic actions are referred to the structural node, whose motion drives the motion of the rigid component;
- `ll` coupling between structural beam elements in MBDyn and aerodynamic lifting line elements in DUST, used instead of MBDyn aerodynamic beam elements;
- `rbf` coupling, the most general coupling between a set of structural nodes and the elements of an aerodynamic surface. The interface between the structural and the aerodynamic grids is obtained as a weighted average of the distance between the nodes of the two grids, and used for motion interpolation and the consistent force and moment reduction;

While `ll` coupling uses the *actual configuration*, both `rigid` and `rbf` couplings use an intermediate *reference configuration* as sketched in fig. 2 for the communication of kinematic variables, forces and moments through preCICE library.

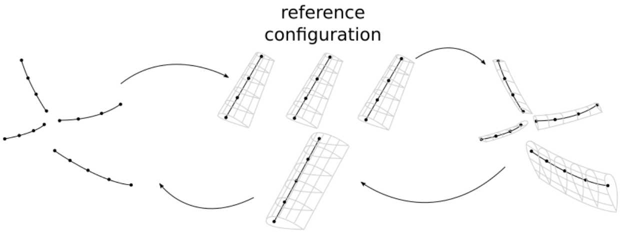

Figure 2: Intermediate reference configuration used for coupling procedure

The implemented communication allows to use different coupling methods in the same model at the same time. This detail is a fundamental characteristic for the analysis of complex configurations, in which different parts require different levels of modeling from both a structural and aerodynamic point of view.

4 ISOLATED ROTOR MODEL SET-UP

4.1 Multibody model

The XV–15 proprotor is a three bladed stiff-in-plane rotor with a gimballed hub. The MBDyn model is composed by three main sub-parts: the control chain, the flexbeams and the blades. The control chain has a traditional helicopter-like configuration: it is formed by five MBDyn static nodes:

- `Pylon`: this node represents the actual connection between the pylon extremity and the rotor; when the isolated rotor is analysed this node is clamped.
- `Fixed Swashplate`: this node is the one to which the commands (cyclics and collective) are imposed, in order to decouple the two cyclics the node is positioned on a reference system that is rotated by the angle $\psi_{sp} = atan\left(\frac{x_{sp}}{y_{sp}}\right)$ where x_{sp} and y_{sp} are the location of the pitch link attachment to the swashplate.
- `Rotating Swashplate`: this node is connected to the fixed swashplate by means of a revolute hinge; it is positioned on a rotating reference system.
- `Mast`: this node is the one that transmits the rotation to the hub and to the rotating swashplate. It is connected to the pylon node by means of a revolute hinge.
- `Hub`: This node is constrained to the mast node by means of a spherical hinge and a MBDyn gimbal rotation: the combination of these two joints allows the creation of an ideal constant velocity joint.

The flexbeams are rigidly connected to the hub node constraining all translations and all rotations of the flexbeam root node. The blade and the flexbeam are connected through a single load path constraint that allows only the pitch rotation of the blade. Finally the blade is connected to the swashplate by means of a flexible pitch link. A schematic representation of the control chain as modelled in MBDyn is presented in fig. 3 and fig. 4.

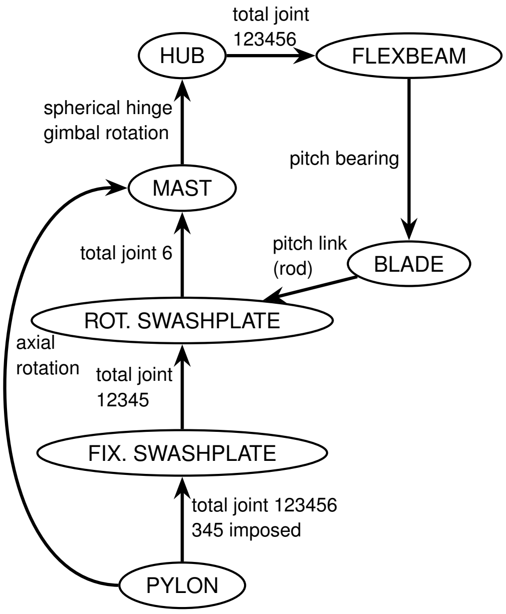

Figure 3: Flowchart indicating the individual blade pitch control system components and their connections

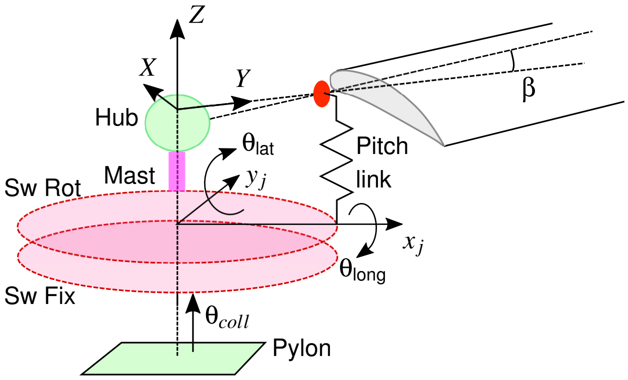

Figure 4: MBDyn rotor kinematic configuration

Each blade is modelled by 10 MBDyn three node finite volume beam elements [19] and each flexbeam by 4 three node beam elements, while the aerodynamic is introduced through the MBDyn aerobeam. All rotor data are taken from the original CAMRAD II model presented in [20]. Table 1 reports the principal rotor data, while table 2 synthesizes the airfoil distribution, taken from [21] along the blade span: on the MBDyn model there is a non-smooth transition between one airfoil and the following, while in DUST the properties of the airfoils are interpolated.

Table 1: Rotor main data

Rotor data		
Blade	3	
Solidity	0.0891	
Radius	12.5	ft
Precone β	2.5	deg
Chord	14	in
Twist	45	deg
Nominal speed	589	RPM

Table 2: MBDyn airfoil data

Airfoil data		
Profile	**start**	**end**
Naca 64-935	0.09	0.13
Naca 64-528	0.13	0.34
Naca 64-118	0.34	0.655
Naca 64-(1.5)12	0.655	0.9
Naca 64-208	0.9	1

4.2 Aerodynamic model

The aerodynamic model of each blade is provided by a DUST lifting line component. Lifting line aerodynamic elements are used for the rotor blades, because they naturally encompass both compressibility and viscous effects. This simple aerodynamic model gives accurate result on high aspect ratio bodies while being computationally very efficient [16, 22].

The coupling scheme adopted is the `ll` one. With this type of coupling, two consecutive nodes of a beam element delimit a lifting line aerodynamic element. Each spanwise section of the component is represented with two nodes of the aerodynamic mesh, one at the leading edge and one at the trailing edge, and with the related .c81 table collecting the aerodynamic coefficients of the aerodynamic section. The wing airfoils and their distribution in spanwise are taken from [21].

In DUST is possible to define smooth transition between one airfoil and the following. Therefore a slightly different airfoil distribution is used with respect to the one reported in table 2, which is considered more realistic with respect to the actual blade.

Table 3: DUST component airfoil data

Airfoil data	
Profile	**x/R**
Naca 64-935	0.09
Naca 64-528	0.181
Naca 64-528	0.272
Naca 64-118	0.363
Naca 64-118	0.636
Naca 64-(1.5)12	0.727
Naca 64-(1.5)12	0.818
Naca 64-208	0.909
Naca 64-208	1

Table 3 reports blade airfoil data at specific span stations, dimensionless with the rotor radius (x/R). A region between two sections with different airfoils has intermediate aerodynamic properties, interpolated as a function of the distance between them.

Any distance offset between the trailing vortex of the lifting line elements and the nodes used for the structural-aerodynamic coupling are defined, allowing to locate the lifting lines in the aerodynamic center. The motion of the i–th of these points drives the motion of points at the leading edge and the trailing edge of the same aerodynamic section, with a rigid motion.

A single panel is generated to represent the object surface, and implicitly the first wake panel. The panel is long 75% of the indicated chord, and it is angled according to the twist inherited from the orientations of the corresponding structural node.

The structural model of each blade is composed of ten three node finite volume beam elements, each of which is made up of three structural nodes. Therefore each blade has 21 exposed nodes to be used for the coupling procedure. Thus each blade is composed by 20 regions spanwise.

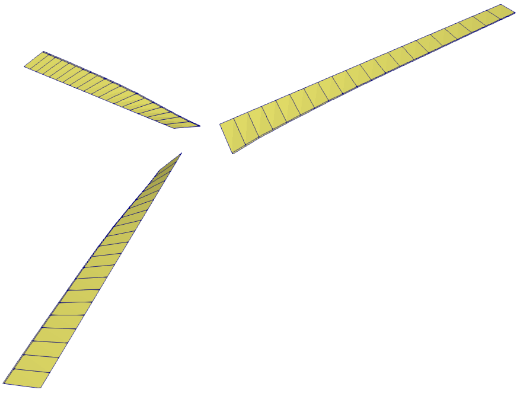

Figure 5: rotor lifting line DUST aerodynamic mesh

Figure 5 shows the aerodynamic mesh generated for the three-bladed rotor.

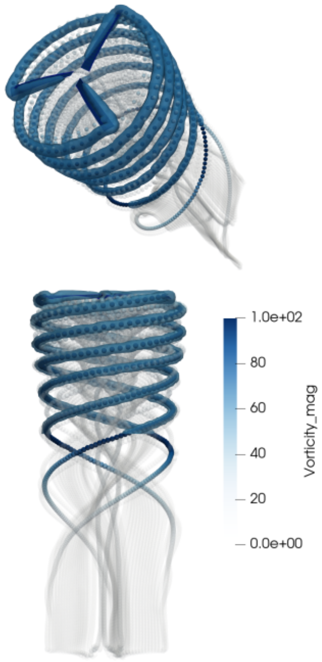

Figure 6: DUST wake particles wake for the coupled rotor model, both vortex particles and vorticity contours are depicted

In figure 6 the particles wake is depicted, in terms of vorticiy magnitude generated by DUST for the *coupled* XV–15 three–bladed elastic rotor model during a transient condition.

4.3 Results

The dynamic behaviour of the isolated rotor is validated by means of a fanplot at 0° collective: the MBDyn frequencies are compared against the CAMRAD II and RCAS results provided by [23]. The major differences between the three models are located on the first torsional mode and on the third flap mode. The first torsion and the third flap frequencies of MBDyn are the softest between the three models. Overall however, the frequency error between the three models can be considered sufficiently small.

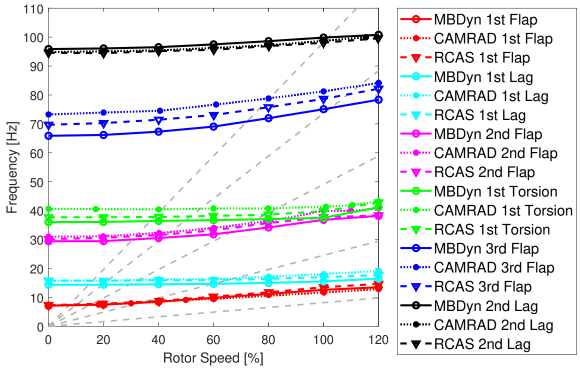

Figure 7: Rotor Fanplot in vacuum 0° – Collective Modes: comparison between MBDyn, CAMRAD II and RCAS model [23]

The coupling between MBDyn and DUST has been validated comparing different polar curves coming from the aerodynamic experimental data of [21], the simulation conducted with DUST and MBDyn alone and the coupled simulation. From fig. 8, it is clear that the polar curve obtained by coupling the two softwares is the one that better match the experimental results.

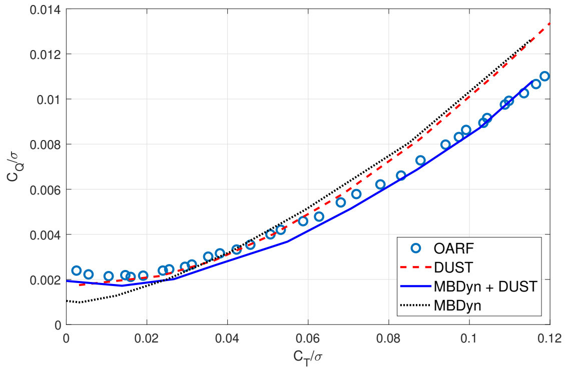

Figure 8: Rotor coefficient of torque over solidity C_Q/σ vs coefficient of thrust over solidity C_T/σ : comparison between experimental data and the presented models

The differences between the models are amplified by plotting the figure of merit (fig. 9) against the thrust coefficient over the solidity factor (C_T/σ). For lower values of thrust all the models and the experimental data show the same trend of the figure of merit, while for higher values of thrust the coupled results better represent the experimental data, while the results with each of the two separated software lead to lower values.

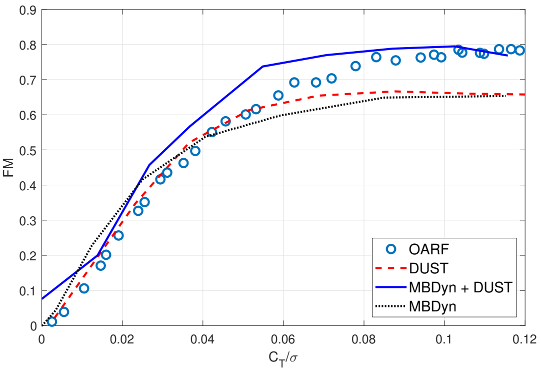

Figure 9: Rotor Figure of Merit vs coefficient of thrust over solidity C_T/σ: comparison between experimental data and the presented models

5 SIMULATIONS OF TILTROTOR MANEUVERS

The results obtained encourage to use the novel coupled tool for the analysis of the critical maneuvers of a complete Bell XV–15 semi–model tiltrotor. The three different coupling methods presented will be exploited in order to obtain a coupled multibody–aerodynamic model capable of simulating different flight conditions. The MBDyn multibody dynamic model setup of the tiltrotor will include:

- the wing, modeled using the non-linear, geometrically exact finite-volume beam elements implemented in MBDyn [19], including the flap and the flaperon control surfaces;

- the pylon/nacelle, attached to the wing-tip; its tilting with respect to the wing can be driven to model the tiltrotor in airplane mode (APMODE), in helicopter mode (HEMODE) or in any intermediate configuration;

- the rotor, modeled using an ideal gimbal joint [24] between the mast and the hub. The yoke and the three blades are modeled using beam elements.

Sensors of torsional and bending moments along the wing and blade span will be used to evaluate the loads during the simulation maneuvers. Figure 10 shows the semi-span multibody model of the XV-15.

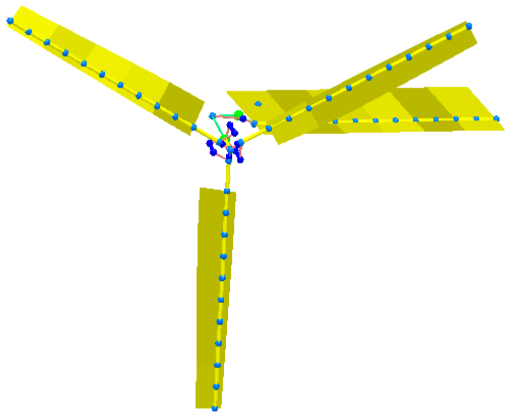

Figure 10: Tiltrotor multibody model.

DUST aerodynamic components to use for coupling procedure will consist of:

- the wing-nacelle assembly, whose geometry is imported from CAD and modelled with surface panel elements, including the control surfaces;
- the rotor blades, already modeled with nonlinear lifting line elements;
- a mixed panel-vortex particle model of free wakes in the domain, ensuring an accurate estimation of blade loads and a stable description of the aerodynamic interactions, accelerated by means of the fast multipole method presented in Ref. [25].

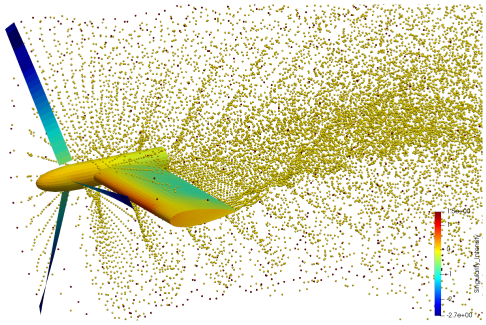

Figure 11: Tilrotor aerodynamic model in DUST.

Three maneuvers will be investigated:

- take-off/landing (in HEMODE), to evaluate the download force due to the rotor wake impacting on the wing;
- roll maneuver, to evaluate the roll authority and the roll-damping requirements in APMODE;
- conversion maneuver, by imposing the angular rate of the pylon/nacelle during the transition;

These maneuvers are critical for the movable surfaces sizing, for handling qualities predictions and for the aerodynamic performances of the flapped wing during low-speed flight regimes and thus they require to be correctly predicted during a preliminary design phase.

6 CONCLUSIONS

In the present work, the coupling between the multibody software MBDyn and the mid-fidelity aerodynamic tool DUST is described. Then, the novel coupled numerical tool was used to analyse the isolated rotor of the XV–15 tiltrotor equipped with metal blades from the dynamical and aerodynamical point of view.

The dynamic model of the rotor was developed by using MBDyn and validated by comparing the collective rotating modes against the CAMRAD II and RCAS model. All MBDyn modes showed a good correlation with the other two models apart for the third flap mode in which MBDyn is the more compliant, however all models showed the same trends even for the third flap mode.

The rotor performances were analysed by using three different approaches: an aeroelastic model employing the MBDyn strip theory model, a rigid aerodynamic model using the DUST lifting line model and finally an aeroelastic model in which the structural deformations are taken from MBDyn whereas the loads are produced by the DUST aerodynamic solver. The results were validated by comparison with experimental data showing a better agreement of the coupled solution with respect to the multi-body and aerodynamic models alone in terms of torque vs thrust coefficients and figure of merit. These results are encouraging for the use of this coupled tool for the simulation of critical maneuvers of the complete tiltrotor aircraft.

Acknowledgments

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Copyright Statement

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