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 midfidelity 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.

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

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

$$\dot{p} = \phi^T_{/x}\lambda + f_i(\dot{x},x,t) + f_e(\dot{x},x,t) \tag{1b}$$

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

where x are the kinematic unknowns, p the momentum unknowns, λ the algebraic Lagrangian multipliers, M is a configuration and time dependent inertia matrix, f_i,f_e are arbitrary internal and external forces, $\phi(x)$ are the nonlinear algebraic constraint equations (honolomic constraints) and $\phi^T_{/x}$ 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 f_i, possibly state-dependent external force fields 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 Morinolike 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.

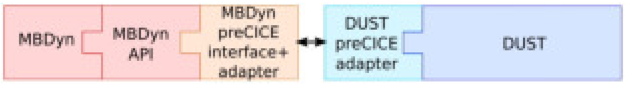

Figure 1: Communication scheme through the adapters

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.

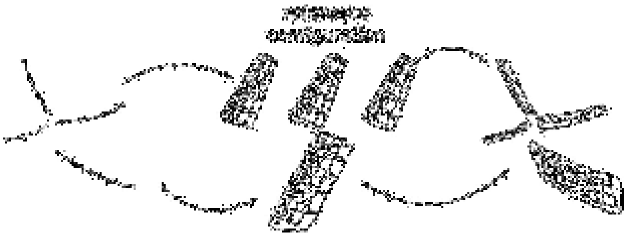

Figure 2: Intermediate reference configuration used for coupling procedure

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 helicopterlike 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 $\psi_{sp} = \mathrm{atan}\left(\frac{x_{sp}}{y_{sp}}\right)$ 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.

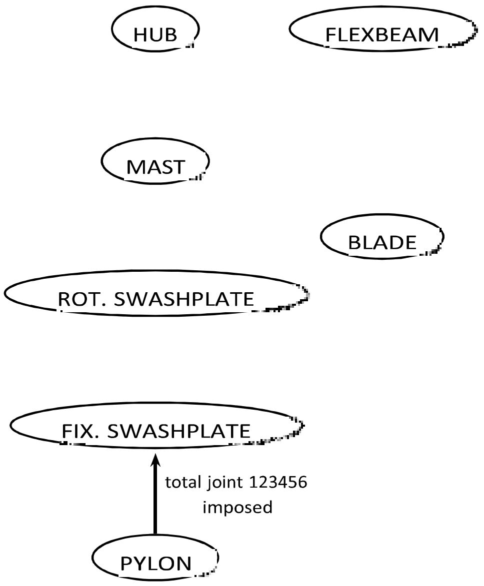

Figure 3: Flowchart indicating the individual blade pitch control system components and their connections

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