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AEROELASTIC MODELING OF THE HUB AND BLADE ROTOR SYSTEM OF THE NICETRIP TILT-ROTOR AIRCRAFT USING MECANO FEM MULTIBODY SOLVER

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ABSTRACT

Nowadays the European rotorcraft community aims to develop a civil tilt-rotor aircraft with the key target of having a flying demonstrator in the 2010 decade. The NICETRIP project summarized in Ref. [1], which is part of the 6th Research Framework Program of the European Union, fits in this roadmap. Its main objectives are to acquire new knowledge and validate critical technologies, systems and concepts relevant for tilt-rotor architecture. The work presented in this paper highlight some modeling activities performed to support full scale testing activities of the rotor. Those tests will be performed on the Eurocopter whirl tower test facility at Marignane, France, with the rotor shaft in the vertical position, at nominal rotor speed and maximum power representative of hover flight conditions.

INTRODUCTION

Modern rotors and especially the Nicetrip one, integrate many flexible components, such as elastomeric bearings, and also structural flapping and lead-lag hinges, that influence strongly the kinematical and dynamic behaviors of the rotor. Blades used for tilt-rotor are also quite specific in order to match helicopter and fix wing modes requirements. Those have significant curvature and twists that induce a coupling between axial and torsional behavior that should be accounted by advanced beam models. Those reasons, among others yield to select the SAMCEF Mecano Multibody simulation software presented in Ref. [2] to model this system. This tool using the Finite Element approach is based on the work of Géradin and Cardona described in Ref. [3].

An advanced tilt-rotor hub was developed in the frame of DART, one of the Critical Technology Project (CTP) partially funded by the European Commission in the 5th framework program. In the frame of DART CTP, DART rotor hub, designed under ERICA concept specification, was manufactured and then tested in static conditions at scale 1. The NICETRIP project, partially funded by the European Commission in the 6th framework program, is the continuation of previous CTP’s. As far as rotor hub is concerned, NICETRIP project aims at improving DART rotor hub (weight, compactness, loads) and testing the rotor on a whirl tower bench. For that purpose, Multibody simulation, as presented here, is of great interest in order, to first predict what will be the behavior, and then help to understand the origins of discrepancies between expectation and actual measurement.

ROTOR TECHNOLOGY

The detailed presentation of DART/NICETRIP rotor hub technology and the reason of design choices are far beyond the scope of this paper. Nevertheless, it has to be reminded that the challenge of an appropriate dynamic layout for a tilt rotor hub is far from obvious and in order to fulfill the related requirements, DART/NICETRIP design activity started with the following guidelines:

- Stiff in-plane rotor design
- Gimbal type rotor system
- Homokinetic gimbal joint
- Low negative pitch-gimbal coupling
- Hub virtual coning hinge

The Design activities lead to the following features, having a direct impact on the rotor behavior:

- An inner constant velocity joint, featuring a symmetry of order 4, generating vibration of the same frequency as the dominant one (4/Rev), since constant velocity joint designed to transmitting very high torque cannot be perfectly homokinetic, and with the simplest connection between mast and hub through drive links.
- A pitch control system coping with the installation of constant velocity joint inside the hub, and thus proposing quasi-horizontal rods whose inclination provide the required low negative pitch-gimbal coupling and vertical rods linked to a classical swashplate assembly. Between the two sets of rods, combiner, hinged on a combiner plate, transform the vertical motion of the vertical rods into horizontal motion of the horizontal control rod. That system offers also low positive pitch-cone coupling, high precision pitch control, high pitch control stiffness and a compact layout.
- The hub-spring, made of two members, connects the yoke to the mast in order to provide a gimbal degree of freedom while transmitting torque and reacting thrust and in-plane loads.
- The yoke, large and thin with flap-wise flexible zones to accommodate static deflections induced by thrust while providing stiff-in-plane properties, its central area providing room for constant velocity joint installation. The yoke transmits in-plan and thrust loads to the mast through hub-spring members.
- Elastomeric pitch bearings, installed on the yoke, transmit centrifugal and shear forces.

In the frame of the present paper, the accurate modeling of those features, and of blade mass and stiffness properties, is of prior importance to capture the global behavior of the complete rotor hub.

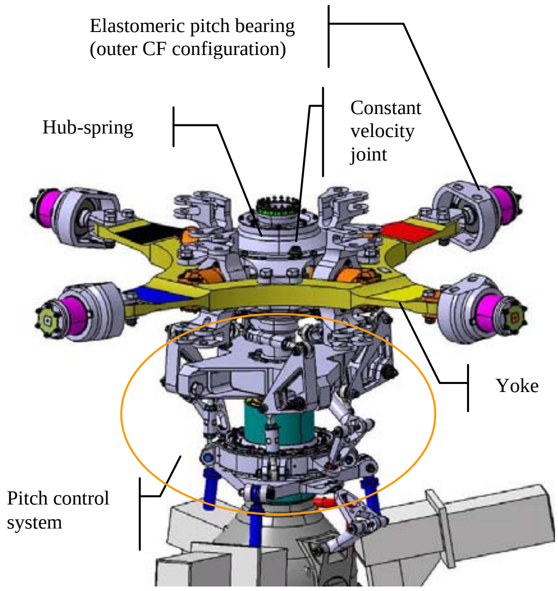

Figure 1: Rotor architecture

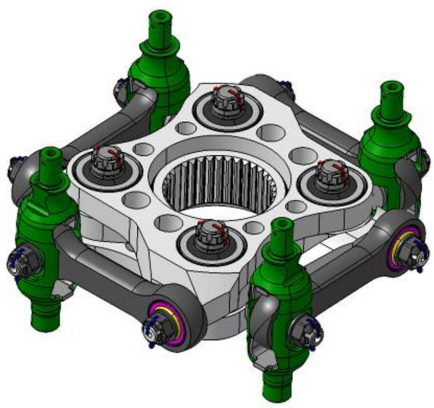

Figure 2 : Constant velocity joint

ROTOR MODEL

Usually, many rotorcraft analyses and design problems are addressed by comprehensive rotorcraft codes. Those specific tools allow estimating performances, aeroelastic stability, vibrations and loads. Modern comprehensive codes combine two complementary techniques that are finite element method and multibody dynamics. Those tools are usually in-house tools (DYMORE, RCAS, HOST) or very specific commercial tools as CAMRAD. In this paper, we will show that such analyses can also be conducted using SAMCEF Mecano, a general finite element solver. This opens new modeling perspectives, by including in those comprehensive models advanced 3D models of sensitive components having highly non-linear behaviors that influence the dynamics of the rotor.

Structural blade model

One of the main components of those comprehensive tools is the beam model that is used to describe the structural behavior of the blades. According to Ref. [4], a suitable beam theory for rotorcraft application must at least include geometric nonlinearities, initial twist, and the ability to model composite blades. The first requirement is met if the element uses geometrically-exact equations in their complete form, including extension, torsion and bi-axial shear and bending. When beams are twisted and submitted to large centrifugal forces, the extension-torsion coupling should be considered. All those requirements are met by the Mecano's beam. Also in order to represent composite beams, the element should allow accounting for different neutral, shear, gravity and inertia centers and axes systems. A beam model based on the section by section CARPAL definition used by Eurocopter as been generated to model the specific blade (large curvature and twist) used for this tilt-rotor, which is shown on Fig. (3).

Figure 3: Blade Layout

This beam model was validated performing modal analyses in free-free conditions; obtained results were compared to FEM 3D models and experimental results. Table 1 demonstrates the good accuracy of the beam model, which is in the dispersion range of the 3D and experimental results.

Mode	Beam model	References
Flap 1	60.7 Hz	58 – 61 Hz
Flap 2	131.5 Hz	125 – 143 Hz
Pitch 1	157.5 Hz	157 - 210 Hz
Flap 3	247 Hz	222 - 268 Hz
Lag 1	312.5 Hz	308 – 355 Hz
Flap 4	420 Hz	338 – 426 Hz

Table 1: Modal validation of the beam model

Aerodynamic loads

In this work, modeling of blade is a crucial task, as those are the main contributors to rotor loads that are targeted by this model. In addition to the structural model previously described, it is important to evaluate accurate aerodynamic loads. In the proposed approach, those loads are implicitly generated by using the blade element momentum method as described in Ref [5]. This method assumes that the blade can be divided in elements that operate aerodynamically as 2D independent airfoils whose aerodynamic forces are computed based on the local flow condition. The velocity field computed from structural dynamics and wind condition is corrected by induced velocities computed from the momentum theory. For this work, we used an induced velocity model for rotor in hover mode that was inspired from Ref. [6]. This blade model provides an accurate representation of the rotor loads.

Practically, the blade geometry is discretized by surface contributions A_I, which correspond to the airfoil span multiplied by the chord length of section I; accordingly, the discretization of aerodynamic loads corresponds to the structural discretization in terms of nodes of the structural model of the blade.

In order to account for the three-dimensional shape of the blades, a local "*blade section coordinate system*" is introduced; it follows naturally any deformation or rotation of the blades. The wind loads are computed with respect to a "*convective wind coordinate system*", with an orientation a priori unknown, because it is rotated with respect to the associated local *blade section coordinate systems* by the unknown *angles of attack* α^I. The angles of attack α^I depend implicitly on the unknown induced wind velocities and structural velocities at each blade section and thus on the solution of the global coupled field problem.

The aerodynamic force components can be stated in the a-priori unknown "*convective wind coordinate system*" by the classical expression*:*

$$F^I_{Lift} = \frac{1}{2} C^I_{Lift}\left(\alpha^I, M\right)\rho V^2_{rel\,I} A_I \tag{1}$$

$$F^I_{Drag} = \frac{1}{2} C^I_{Drag}\left(\alpha^I, M\right)\rho V^2_{rel\,I} A_I \tag{2}$$

$$M^I_{Pitch} = \frac{1}{2} C^I_{M}\left(\alpha^I, M\right)\rho V^2_{rel\,I} A_I C_I \tag{3}$$

Where the lift force F^I_{Lift} acts normally to the relative wind velocity vector and analogously the drag force, F^I_{Drag} acts in the direction of the relative wind velocity. The momentum generated with respect to the blade pitch axis is denoted M^I_{Pitch}. Aerodynamic coefficients are obtained from lookup table, depending on the angle of attack and the Mach number. It is noted that the relative velocities V_{rel} account for the induction corrections due to the global flow interaction with the blades and have to satisfy the constraint build by identifying the contribution of the current blade section to the thrust with the same variable computed from the momentum theory. The normal induced velocity in hover v_h is therefore

$$v_h = \sqrt{T / 2\rho A} \tag{4}$$

Where T is the rotor thrust corresponding to the annular area (A) described by the considered blade element. It is emphasized that the applied methodology allows a "strong coupling", because all equations associated either to aerodynamics, structures and mechanisms, are solved simultaneously. A major benefit of a "strong coupling" is that blade vibrations induced by aerodynamic forces affect implicitly the latter.

Hub mechanism

Starting from the CATIA model shown on Fig. (4), this geometry could be imported in SAMCEF, and the model completed using the capability of the tool to build hierarchical models from sub-components called parts that can be easily duplicated, positioned and assembled.

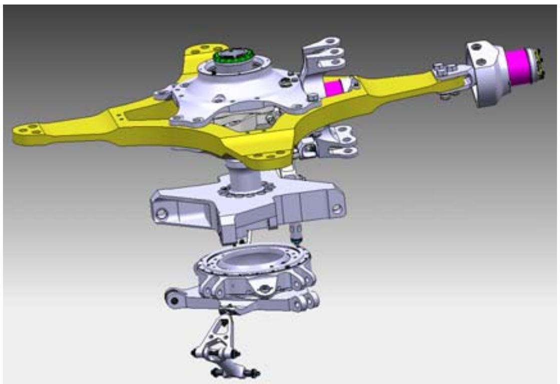

Figure 4: CAD model of the hub

When all the parts are built, the kinematical joints are introduced to define the complete kinematical chain. The final Multibody model is shown on Fig. (5). Rods connecting the plates of the pitching mechanism are considered as rigid. The shaft is considered as flexible and modelled with beam elements. All elastomeric bearings shown in red are modelled with bushing elements. The composite yoke should also be considered as flexible; a super-element is defined from the green mesh. This type of modelling is also used for both cuffs (yellow mesh). Flexibility can optionally be considered for the combiners and for combiner plate; all other components are assumed rigid.

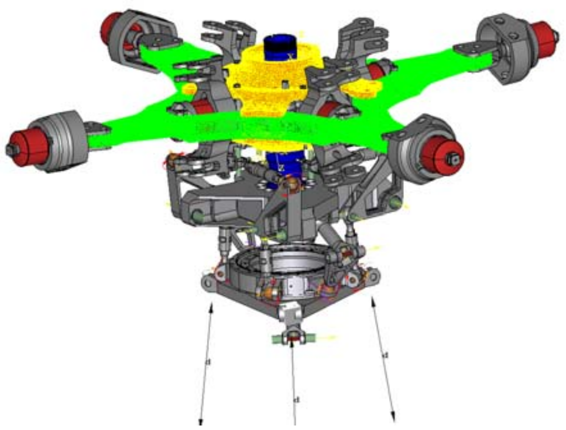

Figure 5: Flexible Multibody model of the hub

Aeroelastic model of the rotor

The complete model of the rotor is obtained by connecting the beam models of the blade to the hub. This connection is done thanks to an additional beam model representing the cuff, which is attached to the blade extremity and to a pair of supports (internal and external) fixed to the yoke. It has to be noted here that DART design included a double capacity for CF load restraint: either at the outer end of the yoke arm, or inside the yoke hollow shape. Both above mentioned supports (internal and external) withstand shear forces (lead-lag and flapping loads) but only one will bear the CF loads. Two distinct behaviors can thus be studied.
Fig. (6) shows the complete system, with graphical representation of the beams. Nodes of the quarter chord, where aerodynamic loads are applied are identified by yellow crosses. Those are connected to the beam nodes by a set of rigid bodies.

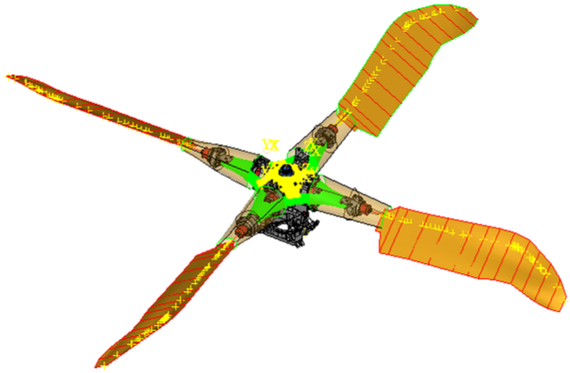

Figure 6: Rotor model

VALIDATION

Kinematical coupling

The first validation of our model consists in checking the correct kinematics and the ability of the hub mechanism to control the pitching motion of the blade while the shaft is rotating the complete system. This is done by driving the shaft and the 3 actuators during static simulations verifying the kinematics of the blade.

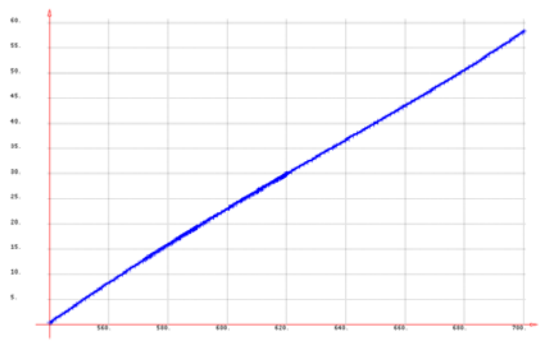

Figure 7: Pitch-actuation law

The Pitch actuation law post-process from the model matches perfectly the measurements. Other validations consist in applying cyclic prescribed displacements on the yoke extremities and observing adequate pitch-flap and pitch-lag coupling. An example of such coupling is shown on Fig. (8), where the pitch variation is plotted as function of the imposed flap angle for three different initial pitch settings.

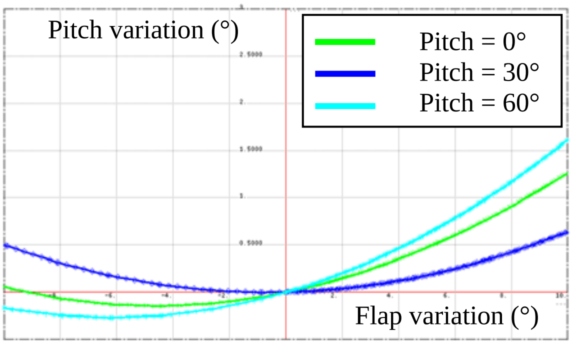

Figure 8: Pitch-flap coupling

Load prediction

Finally this rotor model is used for load prediction. An imposed shaft velocity of 500 rpm is applied, while several cyclic pitching levels are imposed. Transient analyses are performed and stationary results plotted. The measured thrust and power are successfully compared to the Eurocopter in-house comprehensive rotorcraft code.

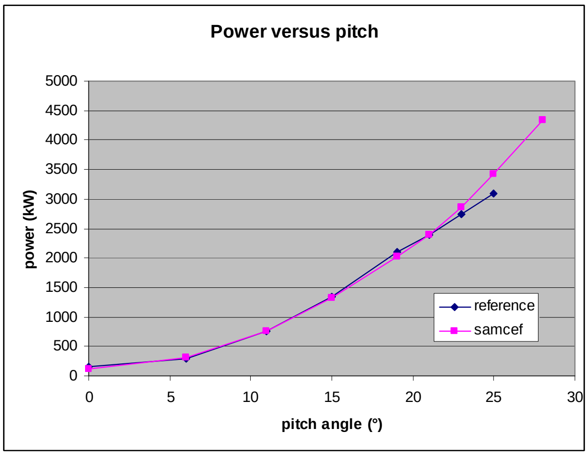

Figure 9: Rotor power

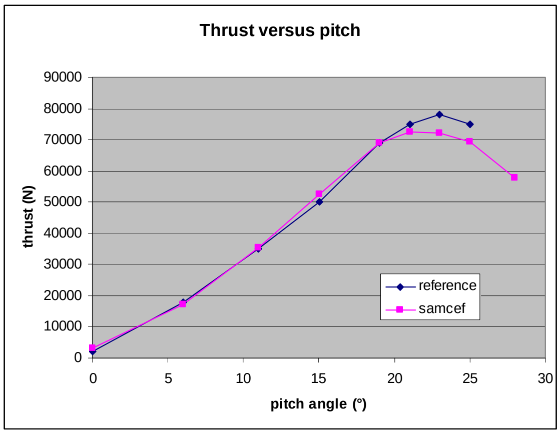

Figure 10: Rotor thrust

Discrepancies are observed when the pitch angle goes over 20°. In this case, for such a curved and twist blade, we are out of the hypothesis of the blade element theory used to evaluate the induced velocity field and both Eurocopter and Samtech codes are inaccurate for the tip part of the blade were instabilities are observed. More complex induce velocity models could also be considered. However, those pitch levels are not reached for this velocity (the engine torque limit of 40000 Nm is reached at a pitch of 20°).

CONCLUSIONS

The validation steps proposed in the previous chapter shows that kinematics and global aerodynamic behavior have been well modeled. That model has now to be used for dynamic behavior study considering all the flexible elements in the model (yoke, elastomeric bearings, metallic parts whose stiffness has to be considered) as well as aerodynamic loads. It will offer the opportunity to predict dynamics and loads that will occur during the NICETRIP whirl tower test.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude and esteem to the partners involved in the NICETRIP program for their very fruitful contribution and co-operative and open-minded attitude.
Gratitude is also expressed to the European Commission who has sponsored this program and encouraged this co-operation among European helicopter manufacturers, suppliers, design and research centers as well as university.

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