Numerical analysis of the rotor in the co-simulation methodology

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Abstract. The co-simulation method in the composite analysis of the rotor enables connection between Multi Body Dynamics (MBD), Finite Element Method (FEM) and Computational Fluid Dynamics (CFD) by using MATLAB code control algorithms. The idea of unidirectional analysis assumes the use of a rigid rotor model with implemented flexible elements of specific mass-rigidity properties, a special Modal Natural Frequency matrix. In this paper, the MBD model complemented with flexible elements was loaded with inertial forces and additional aerodynamic forces. These aerodynamic forces were determined from CFD analyses considering the aeroelasticity of the rotor blade (static and dynamic characteristics appropriate for a given aerodynamic airfoil). The validation of the computational model was performed on the basis of Virtual Blade Model analyses of the rotor, completed with additional algorithms based on the Blade Element Theory method.

1. Introduction

Co-simulation is a methodology for integrating various algorithms and numerical environments to create continuous data coupling transmission in the computational loop (for bidirectional analyses) and to enable data transmission without feedback (for unidirectional analyses). The co-simulation methodology is capable of analysing physical phenomena based on different discretisation methodologies using a different mathematical description, e.g. Lagrange, Euler. The co-simulation-based approach has the following objectives: reducing numerical computing time, which has a direct impact on product implementation costs; reducing expensive stand tests, mainly fatigue and endurance tests; improving computational convergence compared to conventional numerical computational combinations; analysing multiple physical phenomena in a single step (computational loop).

However, this approach shows many disadvantages such as: advanced hardware, complicated integration of boundary conditions between numerical environments, complicated schemes of element discretisation, difficult selection of the time step size for transient analyses and a long-term process of preparing a computational model.

In the world aviation industry, there is a lot of research connected with the development of rotorcraft [1, 2, 3, 4] and application of innovative technologies improving their performance [5, 6, 7]. In the paper [8] numerical investigations of aircraft components were made. In work [9] numerical research with Ansys Fluent was examined in order to check the static longitudinal stability for the given ranges of horizontal stabiliser angles and angles of attack. Due to the necessity to meet numerous safety requirements resulting from aviation regulations, R&D on passenger aircraft is very
expensive. Unmanned aircraft [10, 11, 12] have recently intensively developed so technologies used in manned aircraft naturally migrate to unmanned aircraft. The Brandenburg Institute for Society and Security report [13] on unmanned aerial systems used in civil aviation claims that the number of unmanned aircraft vehicles (UAV) projects and manufacturers more than doubled only between 2005 and 2011. The strongest growth was observed in civil and commercial applications. The leading manufacturers of UAV are the USA (30.33%), France (6.42%), Great Britain, Israel and Russia. The costs of innovative research conducted in unmanned aircraft are much lower, which also affects the development of technologies used in passenger aircraft and the need to integrate unmanned airborne UAV systems with passenger aviation [14, 15].

This publication focuses on performing integrated numerical simulations of a prototype test articulated main rotor, dedicated to rotorcraft with a maximum starting mass of MTOW=150 kg. The main rotor is an object on which both, mass (inertial) loads and complex states of load resulting from aerodynamics and dynamics of rotational motion of a system with many degrees of freedom, act. For this purpose, a series of numerical analyses based on the co-simulation methodology has been used to achieve a unidirectional coupling of issues covering:

- aerodynamics of the main rotor: loads resulting from the generated thrust force and resistance on a particular blade, phasicity (variability) of the thrust force resulting from the cyclic change of the blade setting angle, variable loads resulting from the generated control torque (acting along the blade axis of geometric rotation);
- inertia of the main rotor: centrifugal force loads, phasicity (variability) of the thrust force resulting from the cyclic change of the blade setting angle, loads resulting from the interaction of gravitational forces (static blade deflection, gap over the beam);
- dynamics of the main rotor: issues of loads resulting from structural dynamics and body dynamics in rotational motion (resonance, frequency of natural vibrations of the rotor blades), loads of assemblies located in a heterogeneous field of both tangential and axial accelerations, loads resulting from kinematic couplings of the control system, loads resulting from the dynamics of the control system, loads resulting from fluctuations of the blade in the plane of thrust and rotation of the main rotor.

2. Methodology

The main method of scientific research used in this paper was computer simulation which has not been widely used at the beginning of the 20th century [16]. Currently, the method of computer simulation is considered to be one of the most important methods dedicated to the study of phenomena for which the real process would be too expensive or dangerous or the object of research does not exist yet.

![Figure 1. Global load system a) on the rotor, b) on the blade, where: Mt – twist moment, Mb – beam wise moment, Mc – chordwise moment, PCA – pitch control axis, FC – centrifugal force, FD – drag force, FL – lift force, CF – control force, MCA – control moment, MSH – shaft moment.](image-url)
The use of coupled analyses enables integration of calculation algorithms with different definitions of boundary conditions, as well as a continuous data exchange between individual calculation blocks. The figure 1 shows a typical simplified load diagram working on the rotor.

As can be seen from the above diagram, loads in the rotor are associated with both aerodynamic loads (FL, FD, Mc, Mt) and dynamic loads (MSH, Mb, Mc, FC). It should be noted that the Fc, Mb and Mc loads are both aerodynamically and structurally related.

An application of Co-Simulation methodology to combined analyses allows to integrate CFD and MBD computational issues. As indicated in the paper [17], currently, there is no simulation tool to simulate the whole system with a necessary complexity, level of details and a sufficient performance. For this reason, a combination of many simulation environments is applied using the so-called cooperative simulation (co-simulation, cooperative simulation, coupled simulation) [18, 19, 20]. The methodology of co-simulation and its application have been described in detail, among others, in the publications [17] and [21].

Co-simulation is a methodology to integrate different algorithms, numerical environments to create continuous data transmission coupling over the time of the computational loop (for bidirectional analyses) and to enable data transmission without feedback (for one-way analyses). A characteristic feature of the co-simulation methodology is the ability to analyse physical phenomena based on different discretisation methodologies, characterised by a different mathematical description, e.g. Lagrange, Euler. The above assumptions serve as a foundation for basic blocks of Co-Simulation couplings used within the framework of numerical analyses of the carrier rotor:

a) a numerical analysis of the MBD model considering the susceptibility to the component element of the rotor by means of linear discretisation of the element (figure 2). Such a numerical analysis is performed in the time domain, which means that the loads are transferred on an ongoing basis under constant boundary conditions of the restraint (figure 3).
b) a numerical analysis of the MBD model including external aerodynamic forces (figure 4). External loads can be discretely adapted based on the aerodynamic characteristics obtained from CFD analyses. Inside the ADAMS environment, the resultant force is determined on the basis of the current setting angle and the current rotational speed of the supporting rotor shaft (figure 5).

![Figure 4. Aerodynamic characteristics drag force (on the left) and lift force coefficient (on the right) for NACA 23012 clean airfoil [22].](image)

In order to supplement the numerical MBD model of the supporting rotor, a MATLAB Simulink or MSC EASY5 integrator is used, which allows to determine the value of aerodynamic loads acting on a particular blade section. The integrated value of the partial forces determines the total aerodynamic force of thrust and resistance according to the diagram below (figure 6).

\[
\begin{align*}
    dD &= \frac{1}{2} \rho U^2 c \ast dr \ast cd & \text{-- aerodynamic drag force} \\
    dL &= \frac{1}{2} \rho U^2 c \ast dr \ast cl & \text{-- lift force of the blade element section} \\
    dT &= dL \cos \phi - dD \sin \phi & \text{-- total thrust force of the rotor}
\end{align*}
\]

![Figure 5. Current rotor speed value for co-simulation methodology for unidirectional coupling.](image)

![Figure 6. Schematic diagram for determining aerodynamic loads.](image)

The visualisation of the coupling in the MATLAB is shown in this diagram below (figure 7). The diagram below allows for coupling between the mechanical part responsible for the rotational speed and the aerodynamic part considering the aerodynamic characteristics and atmospheric parameters in accordance with the current ISA standards.
3. Research object
The research object is an articulated load-bearing rotor in which the horizontal and vertical pivot joints are mounted on a common axis. The angle is changed by means of an axial joint to which the rotor blades are attached. The diagram below shows the schematic diagram of the supporting rotor and its numerical interpretation in the MSC ADAMS environment (figure 8).

Figure 8. Visualisation of the numerical model schematic diagram of the CAD model (on the left) and MBD numerical model (on the right).

The MSC ADAMS numeric model is based on a geometric CAD model imported into the MSC ADAMS environment as a Parasolid including mass parameters and a linear definition of the material. The ADAMS environment represents MBD issues within which to every geometric figure are assigned appropriate mass geometrical properties and kinematic pairs that unambiguously define degrees of freedom of an object in computational space. Additionally, the computational model enables a simulation of elastic damping elements simulating the hydraulic damper with variable compartment characteristics. Figure 9 shows the geometric interpretation with the typical characteristics of the viscous silencer used in the calculations.
The following schemes are adopted for the blade modelling:

a) an indirect method consisting in segmenting the blade (figure 10). The numerical MES analyses enabled us to specify different types of stiffness in each direction, i.e. flexural stiffness in the plane of higher stiffness, flexural stiffness in the plane of lower stiffness and torsional stiffness. In the environment of the MBD model, the synthesis of individual sections takes place by means of a bushing type intermediate element or an element of stiffness matrix M [6x6].

The mass and inertia values for the individual sections are determined according to the analysis of the CAD model parameterised by the material properties (figure 11).
b) a direct method by replacing a rigid model with an FEM model and a complete database with information on the form-related deformations relevant to individual forms of natural vibration (Modal Natural Frequency database).

The coupled numerical MBD model includes a geometric interpretation of the geometric model of the rotor hub with the basic assemblies of the supporting rotor. The following figure shows the interpretation of the calculation model (figure 12).

![Figure 12. Visualisation of MBD interpretation of the calculation model.](image)

The MBD model, supplemented with the susceptible elements, was loaded with inertial forces and additional aerodynamic forces determined from the CFD analyses considering the aeroelasticity of the carrier rotor blade (static and dynamic characteristics appropriate for a given aerodynamic airfoil). The calculation model will be validated in line with the Virtual Blade Model analyses of the carrier rotor, supplemented with additional algorithms based on the Blade Element Theory method.

![Figure 13. Visualisation of the MBD model together with the system of ties determining the degrees of freedom](image)
The application of the co-simulation method in the combined analysis of the carrier rotor enables the connection between the MBD, FEM and CFD environments via control algorithms using the MATLAB code. The idea of one-way connection assumes the use of a rigid rotor model to which susceptible elements with specific mass-rigidity properties and the individual matrix of Modal Natural Frequency are entered. The idea behind the MBD model is to use appropriate kinematic pairs reflecting the physics of the motion of the articulated supporting rotor (figure 13).

The following connections are important for the model of the supporting rotor:

- a sliding kinematic pair with a single degree of freedom to provide an unambiguous linear transformation of the system corresponding to the action of the general stroke;
- a kinematic pair of rotation with a single degree of freedom corresponding to the rotation of the rotor within the set speed range;
- a kinematic pair of rotation with a single degree of freedom to provide rotation corresponding to the fluctuations of the blade in the plane of thrust;
- a kinematic pair of rotation with a single degree of freedom to provide rotation corresponding to the fluctuations of the blade in the plane of rotation;
- a kinematic pair of rotation with a single degree of freedom to provide rotation corresponding to the rotation of the axial joint;
- a three-degree freedom spherical kinematic pair corresponding to the operation of a control disc correlated with the cyclic control action of the rotor.

4. Simulation results

Numerical analyses cover complex issues of correlation between particular groups of analyses. One of the basic goals is to provide necessary information on the mechanics and dynamics of rotor operation. The diagrams below show the results of the dynamic analysis of the rotor based on the Co-simulation methodology including the coupling between the rigid MBD model and susceptible elements, as well as aerodynamic forces and moments (figure 14 and figure 15). Combined analyses allow to evaluate only kinematics of motion to determine possible collisions and, above all, dynamic loads, including stability of work. The following figure shows the visualisation of the change in the cyclic angle at the comb joint caused by transverse restraint. A large area of instability due to system vibration is clearly visible.

**Figure 14.** Rotor control in the transverse direction.
Figure 15. Visualisation of the load flow, with a clear area of high instability.

An additional advantage of the Co-simulation approach is using feedback on the borderline between MBD and the rigid body and implementation of susceptible elements by the possibility of integration with algorithms of structural dynamics. The analyses of frequencies and forms of vibrations of a system with many degrees of freedom (such as the load-bearing rotor) enable easy validation of the model using the results of numerical analyses based on the Galerkin method, etc. The diagram below shows the visualisation of the Campbell diagram of the model rotor. Comparing the results presented in figure 11 with numerical results, a correlation in the nominal speed range (RPM relative value = 1) and the form of single-node vibration in $h_1$ in the plane of rotation with the area of unstable operation is visible (figure 16).

Figure 16. Campbell diagram corresponding to the common form of the vibration of the main rotor.

5. Conclusions
This co-simulation approach aims to: reduce the time required for numerical computing, which has a direct impact on product implementation costs; reduce the impact of costly, mainly fatigue and endurance, bench tests; improve computational convergence compared to conventional numerical computational combinations; and analyse multiple physical phenomena in a single step (computational loop). However, it also shows many drawbacks such as high hardware requirements, a complex integration of boundary conditions between numerical environments, complex component discretisation schemes, a problematic selection of time step sizes for transient analysis, and a long process of building the computational model.
This paper discusses the research using the method of computer simulation so the goal of creating a virtual laboratory to perform static and dynamic tests was achieved. Summing up, the Co-simulation analyses easily and transparently allow for an evaluation and optimisation of the rotor at the level of the computational model, which has a significant impact on the reduction of product implementation costs. The ultimate plan is to conduct a laboratory experiment to verify the adopted design assumptions.

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6. References
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