Numerical analysis issues in the evaluation of the helicopter’s main rotor stability

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Abstract. The paper presents selected aspects of numerical analyses on the assessment of the helicopter’s main rotor operational stability, presents key issues for stability assessment, and discusses the application of the co-simulation methodology for helicopter’s main rotor examined by a prototype unmanned aerial vehicle rotor. The presented approach enables the analysis and mapping of the rotor’s operation taking into account the effects of the aeroelasticity of the blade itself. The impact of wind on the tested structure is presented for two cases and thrust force for the cases of starting the rotor for front and crosswind was evaluated. The transition of the rotor between the idle and working revolutions at a small collective angle does not generate unstable states independently in the wind direction.

1. Introduction
Aircraft stability is an important issue in terms of operation and safety [1]. It refers to the ability of an object to recover its balance. Stability can be lost even by a strong blow of wind [2]. The possibility of improving the safety of aircraft [3-6] has been frequently investigated and every single accident is analysed in detail by relevant committees. Due to the growing popularity of unmanned aerial vehicles, which are not usually subject to certification [7], concepts and solutions after numerical analyses are tested on unmanned platforms [8-11]. Their operation seems to be not as risky as that of manned aircraft, but numerous accidents with falling drones are already known [12]. The analysis of the helicopter’s main rotor stability will allow us to assess how much the developed design is sensitive to stability loss. Three main aspects influence the rotor’s operational stability: the path along which the blade tip moves, vibrations, and pulsation of the thrust force or bending moment on the propulsion shaft. The main rotor is equipped with prototype blades allowing for active control of the geometric twisting angle. This concept has been presented in several studies [13-16]. Many researchers [17-20] systematically investigate the issue of changing the twist angle of a rotor blade. This analysis is based on the co-simulation methodology which in the Matlab environment combines solutions used in Multi Body Dynamics (MBD), Finite Element Method (FEM), and Computational Fluid Dynamics (CFD) [21-24].

The alternative solutions are non-classical methods such as fluid-structure interaction (FSI). The presented analysis is based on a simplified methodology to obtain correct results and includes complete input data. This approach enables a reliable analysis. The basic parameter influencing rotor performance is the shape of main rotor blades, namely the radius, chord, and type of aerodynamic
One of the most important factors behind the rotor performance that can also define the rotor in terms of utility applications is the value of the geometric angle of the blade twist. The geometric twisting value, referred to as $\theta$, is defined at the technological stage by the appropriate formation of the blade structure. The analysis carried out in this paper aims to assess the sensitivity of the structure and thus the operational stability of the helicopter rotor and the safety of aircraft operation.

2. Methodology

The research main rotor is dedicated to light unmanned aircraft, special category MTOM (for units with a mass over 25 kg yet under 150 kg. The classification is in accordance with the ministerial regulation [26]. The calculation methodology is based on a discrete model of MBD rigid elements using co-simulation between FEM analyses and dependencies resulting from the aerodynamics of generating the lifting force based on the active disc method. The computational model presented here is a simplified model of the main rotor in which the blade is represented by 10 computational segments with their individual mass, geometric, stiffness, and aerodynamic properties.

2.1. Description of the calculation model

Figure 1 shows the blade’s sections. According to the assumed calculation scheme, a bushing element is a component connecting rigid solids.

Aeroelastic issues require a precise mapping of rotor design features by defining:
- the type of rotor (e.g. articulated or flexible),
- the position of horizontal, vertical, and torsional hinges,
- the position of the lever of the blade rotation concerning the blade’s attack edge,
- the value of the fluctuation compensator,
- the values of the longitudinal and transverse feedback factor.

A visualisation of the hinge arrangement interpretation is shown in Figure 2.

![Figure 1. Distribution of calculation sections.](image1)

![Figure 2. Visualisation of the classic hub system.](image2)

The parametric approach allows for the assessment of the rotor design and thus the sensitivity of the object to change. The range of 5% corresponds to the possible production spreads resulting from the adopted technological process of blade production based on materials provided for pre-preg technologies. The physical interpretation of the presented values reflects possible production deviations in mass measurement and moments of inertia estimated from our own experience.

| Table 1. Definition of parameterisation of mass geometric characteristics. | Section | Change | Mass | IXX $\text{kgmm}^2$ | IYY $\text{kgmm}^2$ | IZZ $\text{kgmm}^2$ |
|-----------------------------|---------|--------|------|-------------------|-------------------|-------------------|
| 0 | +/-5 | 0.012 | 9.25 | 5.79 | 3.83 |
| 1 | +/-5 | 0.012 | 9.24 | 5.80 | 3.81 |
| 2 | +/-5 | 0.015 | 11.55 | 7.24 | 4.75 |
| 3 | +/-5 | 0.015 | 11.54 | 7.18 | 4.73 |
| 4 | +/-5 | 0.015 | 11.52 | 7.16 | 4.68 |
| 5 | +/-5 | 0.03 | 19.48 | 11.88 | 7.96 |
| 6 | +/-5 | 0.05 | 39.29 | 23.61 | 16.22 |
| 7 | +/-5 | 0.08 | 59.72 | 35.46 | 24.85 |
| 8 | +/-5 | 0.09 | 105.5 | 75.79 | 30.27 |
| 9 | 0 | 0.14 | 91.17 | 66.82 | 28.35 |
The bushing element between sections (computational cross-sections) shows real stiffness in individual directions, determined by FEM analysis and composite material data. The strategy of selecting the section length is closely related to the mass-stiffness properties.

Table 2 shows the stiffness values in the respective directions (Figure 3) described by parametric variables:
- `blade.DV_XPMS` – blade stiffness in the plane of lower stiffness,
- `blade.DV_XPWS` – blade stiffness in the plane of higher rigidity,
- `blade.DV_XTQ` – blade torsional stiffness,
- the X symbol – calculation section number.

![Figure 3. Visualisation of the load definition system](image)

**Table 2.** Parameterisation of equivalent stiffnesses for individual calculational cross-sections.

| Variable  | Stiffness EI/GJ₀ | Change % | Variable  | Stiffness EI/GJ₀ | Change % |
|-----------|------------------|----------|-----------|------------------|----------|
| `blade.DV_1PMS` | 217,014          | 0        | `blade.DV_4PMS` | 4,340            | +/-10    |
| `blade.DV_1PWS` | 498,883          | 0        | `blade.DV_4PWS` | 8,347            | +/-10    |
| `blade.DV_1TQ`  | 8,881            | 0        | `blade.DV_4TQ`  | 4,640            | +/-10    |
| `blade.DV_2PMS` | 16,693           | 0        | `blade.DV_5PMS` | 4,134            | +/-10    |
| `blade.DV_2PWS` | 78,914           | +/-5     | `blade.DV_5PWS` | 7,483            | 0        |
| `blade.DV_2TQ`  | 5,413            | +/-5     | `blade.DV_5TQ`  | 4,060            | 0        |
| `blade.DV_3PMS` | 4,569            | +/-5     | `blade.DV_6PMS` | 2,411            | 0        |
| `blade.DV_3PWS` | 12,401           | +/-5     | `blade.DV_6PWS` | 7,750            | 0        |
| `blade.DV_3TQ`  | 3,846            | +/-5     | `blade.DV_6TQ`  | 1,367            | 0        |

The basic values of torsional and bending stiffness are shown in Table 2. The EI, GI₀ parameters have been determined from FEM analyses that enable the use of feedback between the composite ANSYS APC and ANSYS Mechanical modules taking into account the full nonlinearity of materials and ensuring continuous communication between the modules using the FSI methodology. The main purpose of the above analyses is to determine the stiffness of the individual sections as well as to preliminarily assess the structural resistance. Figure 4 shows the MES model of the blade’s base section.

![Figure 4. MES model of the blade section.](image)
According to the approved convention of analysis, each section corresponds to a given property set defining mass stiffness and aerodynamic characteristics. The calculation model of the main rotor blade uses typical aerodynamic aerofoils from the NACA 230XX family, distributed linearly and described by a straight line with an initial twisting of 12°. Each section has different geometric properties for aerofoil thickness in line with the scheme: R=0 m – NACA 23018; R=1 m – NACA 23009.

Full integration of the numerical model requires the introduction of loads related to the mechanics of lifting force generation, i.e. each section of the model is impacted by forces and moments originating from aerodynamic phenomena. The accuracy of calculations depends on the quality of values of drag coefficient $C_d$, lift force $C_l$, and moments $C_m$, determined for both steady and unsteady states oscillating with the frequency corresponding to the first harmonic of rotations [27].

### 2.2. Integration of the calculation model

The computational methodology assumes an application of a model based on the multi-module rigid MBD method that uses susceptible elements with strictly defined stiffness properties. The strategy of discrediting the computational model is to separate analyses between individual computational modules and integrate the results with external software based on Matlab/Simulink. This means that for each calculation section the loads resulting from both motion dynamics and rotor aerodynamics are specified. This approach enables the analysis and mapping of the rotor’s performance taking into account the effects of the aero-elasticity of the blade itself. The induced velocity diagram acting on the blade is presented in Figure 5 and in [15].

![Induced Velocity Diagram](image)

**Figure 5.** Visualisation of induced velocity in hover (Out of Ground Effect).

The analysis is carried out in real-time with a time step strictly dependent on the rotor speed and so the azimuth of the blade position (average analysis time $t=0.01s$). The model of aerodynamic loads and performance generation is based on the Blade Element Theory method and takes into account the uniform induced velocity model. Table 3 presents the boundary conditions and parameters of CFD analysis.

### Table 3. The configuration of CFD analysis.

| Boundary conditions   | Analysis Parameter                                      |
|-----------------------|--------------------------------------------------------|
| Pressure              | Ansys Fluent + VBM UDF code                            |
| Ambient temperature   | SST K-ω                                                |
| Wind velocity         | Transient, time increment 0.01s                        |
| Mesh size             | $10^6$ elements                                        |
Estimated induced velocity value will be used for calculation aerodynamic forces for a particular section presented in figure 1 and contains inputs value in the co-simulation process.

3. Results
The rotor dynamics analysis is aimed at a qualitative and quantitative evaluation of the rotor in terms of its performance, an evaluation of the rotor blade behaviour in the area of acting mass and aerodynamic forces, and an evaluation of the stability of the rotor relevant for assembly dynamics. The operating stability of the rotor can be determined from the dynamic twisting angle. Regarding aircraft operation, the selected case has the operation spectrum as 35% of the total time the object is in the air, i.e. for cruising speed v=150 km/h. This state is defined in Table 4.

| Parameter                  | Value | Unit |
|----------------------------|-------|------|
| Flight speed               | 150   | km/h |
| Rotor speed                | 1520  | rpm  |
| Collective pitch angle     | 9     | °    |
| Temperature               | 15    | °C   |
| Flight height              | 500   | m    |

Table 4. Definition of flight parameters.

The evaluation of the dynamic twist angle value is determined by measuring the absolute change in value against the initial value according to the relationship:

$$\delta = \theta_{coll} - \theta_{dyn}$$

$\delta$ – angle change due to dynamic deformation
$\theta_{coll}$ – value of the overall stroke setting angle
$\theta_{dyn}$ – value of twist angle including the dynamic change

Figure 6 presents the averaged changes of twisting taking into account the dynamic change $\theta_{dyn}$, determined for the whole area of material and stiffness spreads. The results in Figures 7 and 8 show that the maximum dynamic twisting deformation evaluated for the blade end section is less than 0.5°, which means that the rotor is operationally stable and the material damping depends on the material property have hardly impact on the rotor operation. Following this concept, the distribution of the static thrust force and thrust force amplitude estimated for the individual computational sections was determined. The averaged values for the horizontal flight test are given in Figure 7.

Figure 6. The dynamic twisting average static angle value.

Figure 7. The distribution of static thrust values in particular sections of one blade is estimated for a 9° collective pitch.
There is an additional, related to start-up issues criterion for confirming the stability of the rotor. This means that the rotor should show stable operation with no significant pulsations of the thrust force when speed increases from idle to cruising. Our analysis assumes an evaluation of the thrust force value measured in the axis of the rotor shaft during the run-up of the rotor between idle speed, corresponding to 60% of the nominal rotor speed and the nominal speed of \( n = 1520 \text{ rpm} \). The start-up time foreseen in the simulation is 4 s. One of the important assumptions of the boundary conditions is that the position of the overall pitch lever and thus the value of the setting angle is constant. An important aspect of the analysis is the value and direction of the wind during the start-up. The considered cases assume a maximum wind speed of 5 m/s and two wind directions: front and side. The thrust values are shown in Figures 9 and 10.

As seen, the wind direction and the spread of mass and stiffness properties do not affect the stability of the system, i.e. there is no pulsation of the thrust force in the steady-state of operation (3-4s).

4. Conclusions
The findings are that the co-simulation method allows us to assess the stability of the helicopter’s rotor system in the critical state of the rotor start-up. The strategy adopted in the first stage of the analysis assumes that safety will be confirmed. It was found that the adopted design is safe from phenomena such as ground resonance. The kinematic system of the rotor guarantees that the rotor is insensitive to external conditions (inflow to the rotor). The transition of the rotor between the idle and working revolutions at a small collective angle does not generate unstable states independently on wind direction.
The next stage of the research will expand the states for which the rotor stability such as overhanging, flight at a speed corresponding to the design speed $V_{dr}=1.11V_{ne}$ with the assumed speed $V_{ne}=150$ km/h will be analysed. The calculation model will be extended by a modal part to determine non-harmonic frequencies to avoid the danger of self-excited vibrations. The results reached so far allow the conclusion to be drawn that the proposed structure is stable, and the proposed kinematic rotor system is capable of stabilising the rotor by reducing pulsation of forces and keeping the moving blades in a single path.

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