Aeroelastic analysis of a helicopter rotor in hover

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Abstract. The paper deals with the numerical analysis of a helicopter rotor in hover conditions, including aeroelastic effects. In existing literature the effects of an aircraft structural deformation on airloads distribution and performance are fairly well described but mainly for airplanes. The purpose of the presented work is to indicate the possible influence of blades elasticity on helicopter rotor loads and performance in hover. Additionally, it aims to validate a new computational method based on a set of experimental results for a UH-60A helicopter rotor. The method used combines a high fidelity Navier-Stokes aerodynamic model coupled with a low-order beam structural model. This approach made it possible to take into consideration blade deformations in simulations and revealed the high influence of aeroelastic effects on rotor loads and performance at hover conditions. To authenticate the results, the presented method was validated with experimental data from two different flight test programs, three small-scale wind tunnel tests and one full-scale wind tunnel test. They were conducted for the UH-60A helicopter rotor by different organizations. The comparison of results revealed that the created computational method has high accuracy.

1. Introduction
Determining the loads and performance of a helicopter rotor is a very complex research problem. This is the result of a large variety of phenomena connected with the rotating rotor and the highly multidisciplinary nature of the issue. In existing literature the effects of an aircraft structural deformation on airloads distribution are fairly well described but mainly for airplanes. It is difficult to find information about the possible impact of blades deformability on rotor performance. Some conclusions can be drawn from the articles presenting the results of a rigid blade simulation compared with experimental data. The example is the simulation of W-3A Sokół helicopter rotor presented in [1]. In this article the analysis is carried out with a very accurate - from the rotor aerodynamics point of view - computational method, but is omitting blade deformability and rotor trimming. As a result, an error of 20% was obtained for global rotor performance parameters. However, in the aforementioned work the rotor was simulated in a forward flight, not hover. The purpose of this article is to indicate the possible influence of blade elasticity on helicopter rotor loads and performance in hover (on the example of UH-60A helicopter), and to validate created computational method based on a set of experimental data.

2. Computational method
In the presented work, a simplified structural model is used, based on the Euler-Bernoulli beam theory (also known as engineer's beam theory or classical beam theory). [2] It assumes that there are no shearing effects (cross-section perpendicular to the neutral axis of the beam remains perpendicular after deflection) and can be used for analysis of beams with high elongation. Due to the fact that the
elongation of helicopter blades is relatively large, it is possible to use the classical theory of Euler-
Bernoulli beams for the analysis of this type of construction. Its advantage in comparison to the e.g.
Timoshenko theory is simplicity, and thus the ease of numerical implementation. Then, the blade
deformations were obtained from the following relationships:

\[ \frac{\partial^2 z}{\partial r^2} = \frac{M_g}{E I_x} \]  

(1)

\[ \frac{\partial \theta}{\partial r} = \frac{M_s}{G I_s} \]  

(2)

where \( r \) is the radius, \( z \) is the deflection, \( M_g \) is the bending moment, \( E I_x \) is the bending stiffness, \( \theta \) is the torsional deformation angle, \( M_s \) is the twisting moment, and \( G I_s \) is the torsional stiffness.

The described beam theory was used to formulate partial differential equations for blade bending/flapping and blade torsion/pitch steering. Both equations were coupled together. The lead-lag motion of a blade and bending in the plane of the highest stiffness was neglected in the presented model. The derived system of equations was similar to that described in [3, section 9-4.3]. The beam model equations were numerically implemented using a finite difference method to create Blade Deformation Solver (BDS). In BDS, the unknown values of the individual quantities are obtained in the consecutive time steps using an explicit time stepping method.

The high fidelity aerodynamic model is based on the Navier-Stokes equations solver and the method of Moving Deforming Mesh (MDM), that determines the type of analysis as transient. This is one of the most accurate and time-consuming rotor aerodynamics models available. A similar approach is presented in [4][5]. This method uses the sliding mesh interface separating the part of the domain rotating with the rotor and the remaining stationary part. Additionally, the changes of the blade pitch angle and the articulated motion and deformations of the blades require the use of algorithms that deform and rebuild the computational grid. In order to get the final convergent solution, it is necessary to perform calculations for at least a few rotations of the rotor to get the required periodicity or constant values of monitored parameters. The MDM method is able to capture high variety of aerodynamic phenomena (interference, flow separations, shock waves, etc.).

The tight coupling between structural and aerodynamic model was implemented in the User Defined Functions (UDF) environment of the well-known CFD commercial code - ANSYS Fluent. This type of coupling makes it possible to get a time accurate solution. At each time step, this requires gathering information about the blade loads, mapping the loads to the beam model, and determining the beam deformations and corresponding nodal displacements in the CFD mesh. The obtained blade aerodynamic loads were applied gradually to the BDS beam model to avoid rapid blade response and undesirable vibrations. All of these processes and algorithms were implemented in the developed UDF.

In some cases concerning rigid blades, which were analyzed for comparison purposes, Moving Reference Frame (MRF) method and the steady state solution type were used. This approach was also utilized to get the initial solution for other calculations in a reasonably short time. It is worth mentioning that aeroelastic analysis of a helicopter rotor in hover could be performed with similar accuracy using the coupling between BDS and MRF model to get final steady state solution. However, it was decided to use the unsteady MDM model just to allow the developed method to be used later in a forward flight cases, which cannot be treated as steady state problems.

3. Test case and computational process

Simulations were performed for the full-scale, isolated UH-60A helicopter rotor in hover conditions. Three different cases regarding blade elasticity and articulation (relative motions) were analyzed: the no-relative-motion rigid blade (MRF simulation), the rigid blade with the possibility of flapping motion and the elastic blade with the possibility of flapping motion. The calculations included a number of collective pitch angle (\( \Theta \)) values and were compared with a set of experimental results [6-13] to validate developed computational method.
In order to speed up the calculations, the MRF model was initially used with the intention of generating approximate flow field around the rotor, which would require a lot of time in the case of transient analysis. MRF simulations were performed for collective pitch angles equal to 8, 10 and 12 degrees. Unsteady analysis using the MDM-BDS module was additionally performed for 14 degrees and 16 degrees (as start-up cases the results of MDM-BDS simulations for 12 and 14 degrees were used respectively). The convergence of the thrust and torque acting on the blade and the entire rotor obtained with the MDM-BDS module is shown in figure 1. The initial values visible in the graph correspond to the results of the MRF analysis (no-relative-motion rigid blades). Through the first rotation of the rotor, the forces determined in CFD were gradually applied to the blade beam model, which resulted in its deformation and the largest change in the monitored forces and moments. Their values converged after about 4 revolutions of the rotor - without using the MRF initial solution it would take about 15 revolutions.

4. Simulation results discussion

The obtained values of thrust ($C_T$) and power ($C_P$) coefficients divided by rotor solidity ($\sigma$) are shown in figure 2. They were calculated based on the following relationships:

$$C_T = \frac{T}{(\rho A (\Omega R)^2)}$$  \hspace{1cm} (3)

$$C_P = \frac{P}{(\rho A (\Omega R)^3)}$$  \hspace{1cm} (4)

where $T$ is the thrust, $P$ is the power, $\rho$ is the fluid density, $A$ is the area of the rotor, $\Omega$ is the angular speed and $R$ is the radius of the rotor.

The results showed that in the presented case, the elasticity has significant impact on global performance characteristics of the rotor and blades airloads distribution. For example, at collective pitch angle of 12°, the values of $C_T/\sigma$ and $C_P/\sigma$ were reduced respectively by 37% and 51% (figure 2). It can be easily seen that when the flexibility of the blades is taken into account, the required collective pitch angle should be increased by about 4-5 degree to ensure a similar level of thrust. This is the angle close to the average torsional deformation angle at the blade tip, obtained as a result of the simulations and shown in figure 3. Neglecting of the blade deformability causes excessive load occurring at the tip of the blade. The level of aerodynamic loads in this region, obtained for a collective pitch angle of 10° and rigid blades, is comparable to that obtained for a pitch angle of 16° with flexible blades. One of the factors conducive to such differences can be the swept blade geometry at the tip, which increases the torsional moment and deformation angle of the blade.
Figure 2. Comparison of thrust and power coefficients for elastic blade (MDM-BDS) and no-relative-motion blade (MRF).

Figure 3. The comparison of the torsional deformation angle (theta_\text{elastic}) and blade normal load (FNb) for \( \theta = 10^\circ \) and \( \theta = 16^\circ \).

Figure 4. Graphic representation of the flap angles with pressure coefficient distributions for a no-relative-motion blade, a rigid blade and an elastic blade.

Figure 5. Comparison of pressure distributions around the blade in the section of 97.8% radius for a rigid and elastic blade.

The changes in the blade pitch angles are of key importance when analyzing the performance of a helicopter rotor, especially if the helicopter is equipped with modern blades with an advanced tip geometry. The impact of blade deformation on blade surface pressure distribution and pressure distribution in the plane perpendicular to the blade axis (in the region of the tip), is shown in figures 4 and 5 respectively. When comparing the variants presented, it can be noticed that the rigid blades have very similar pressure distributions. This is in line with expectations, because in the case of hover, the flapping angle of the isolated rotor does not depend on the blade's azimuth (it is constant). Therefore, the effective angle of attack in a given blade section is similar to that obtained for a blade that does not have the ability to make a flapping motion. However, the pressure distribution looks different in the case of the elastic flapping blade. Also the much smaller aerodynamic forces acting in the plane normal to the rotor disk cause the blade to have a smaller deflection angle than the rigid blade, as shown in figure 4. For the presented case (\( \theta = 10^\circ \)), the value of deflection at the tip of rigid flapping
blade is 0.66 m, compared to 0.42 m for the elastic blade. The maximum torsional deformation angle of the blade is -4.26°, which significantly affects the flow around the tip. A decreased angle of attack results in a significantly lower loading in the region of the airfoil nose (figure 5).

5. Simulation results validation

The obtained results of calculations were compared with the following experimental data for the UH-60A helicopter rotor in hover (two flight test programs, three small-scale and one full-scale wind tunnel program - more information about them could be found at given references):

- First set of flight test programs was conducted by U.S. Army Aviation Engineering Flight Activity (AEFA) and consisted of a series of flight test on different UH-60A aircraft. The data presented in this paper is the hover data from the 1st Year [6] and 12th Year [7] production aircraft - the primary difference between them is the installation of Extended Stores Support System on the second aircraft.

- The second flight test program was the UH-60A Airloads Program conducted by Army/NASA. [8] The noticeable scatter of data is due in part to variable wind conditions during testing. [9]

- The first two small-scale programs were hover tests conducted at the Sikorsky Model Hover Test Facility. The first test (Balch [10]) used a 1/5.97-scale model of the UH-60 helicopter, the second (Lorber [11]) used a 1/5.73-scale model. The hover performance data presented in this paper is concerned with the isolated rotor measurements. The third small-scale program was conducted at the Duits-Nederlandse Windtunnel (DNW) and used the same model as the second test. [12]

- The full-scale wind tunnel program was conducted by Army/NASA at the NASA Ames 80-by 120-Foot Wind Tunnel. The presented results were obtained at low to medium thrust conditions, with different values of the shaft angle \( \alpha_s \) to indicate the effect of wind tunnel walls on the hover performance measurements. The test model included NASA's Large Rotor Test Apparatus (LRTA) - it was not the isolated rotor. [13]

The values of \( C_p/\sigma \) as a function of \( C_T/\sigma \) are shown in figure 6. Very good agreement of the results was achieved. In order to more accurately present the differences between individual experimental tests and the results of numerical simulations, the Figure of Merit \( (F_M) \) parameter was determined according to the following formula:

\[
F_M = C_T^{3/2} / (C_p \sqrt{2})
\]  

The \( F_M \) parameter is the equivalent of the aerodynamic energy function determined for fixed wing aircraft and is characterized by greater sensitivity to any changes than thrust and power coefficients. A comparison of the obtained \( F_M \) values with experimental data is shown in figure 7. It reveals the advantage of the aeroelastic analysis (MDM-BDS) over the simplified simulation (MRF). The advantage is especially visible for a large values of thrust, where an incorrect distribution of angles of attack (and therefore loads) for the rigid blade causes an underestimation of the \( F_M \) value. It should also be noted that the visible difference would be much larger if the \( F_M \) values were presented not as a function of thrust coefficient but collective pitch angle of the blade.

The discrepancies in rotor performance calculated by MRF (rigid blades) and MDM-BDS (elastic blades) models are caused by, among others, the flow separation at the blade tip that appears in the case of rigid blade computations. It is visualized by the chordwise wall shear contours in figure 8. Negative values of the wall shear correspond to the reversed flow over the blade surface and indicate flow separation. The flow separation also begins to appear at high collective pitch values for elastic blade cases (figure 9). This effect cannot be fully captured with Reynolds-averaged Navier-Stokes (RANS) simulation, so the flow separation could also be an explanation of the differences between experiment and simulation results, especially at high thrust conditions.
Figure 6. Rotor power comparison - results of MDM-BDS and MRF cases compared with one full-scale and three model-scale experiments. [13]

Figure 7. Comparison of $F_M$ values - results of MDM-BDS and MRF cases compared with all available experimental data. [13]

Figure 8. Wall shear (X-direction) contours on the surface of a no-relative-motion and elastic blade for $\Theta=12^\circ$ (max $\Theta$ for MRF simulation). Negative values mean reversed flow (separation).

Figure 9. Wall shear (X-direction) contours on the surface of an elastic blade for $\Theta=16^\circ$ (max $\Theta$ for MDM-BDS simulation). Negative values mean reversed flow (separation).

It can be noticed that the MDM-BDS model also underestimates the value of the $F_M$ parameter in relation to the average value from experiments. It is approximately a constant error, independent of the $C_l/\sigma$ value. Known factors that may have contributed to this error are as follows:

- Spalart-Allmaras turbulence model used in simulations (it is expected that using finer mesh and one of transitional models should increase the $F_M$ values slightly, due to possible decrease of aerodynamic drag and power reduction caused by laminar flow regions),
- inaccurately reproduced tip geometry of the blade which could happen due to some uncertainties in geometry definition (based on report [14], no access to CAD file).
Nevertheless, the consistency of the $F_M$ results should be considered good, because, as already mentioned, the $F_M$ parameter could be very sensitive to geometric changes and many other factors. It is also worth noting the discrepancies between different experimental data themselves.

6. Conclusions
Aeroelastic effects can have significant influence on helicopter rotor loads and performance in hover conditions. Changes in the angle of attack due to elastic blade twisting are the main cause of airloads reduction. Deformability of the blades influences in particular the flow conditions around the blade tip and at given collective pitch angle could reduce the rotor thrust by up to 37% and the rotor power by up to 51%. These values were obtained for the UH-60A helicopter rotor at high thrust hover conditions. The comparison of simulation results with a set of experimental data for the UH-60A helicopter revealed good accuracy of the developed computational method in terms of global performance parameters prediction.

Simulation of a helicopter rotor is a multidisciplinary problem. Of which, a strong fluid structure interaction should not be omitted. Otherwise, this can result in the outcomes that differ considerably from the actual performance of the helicopter.

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