REPÜLÉSTUDOMÁNYI KÖZLEMÉNYEK
31. évfolyam (2019) 2. szám 115–126. • DOI: 10.32560/rk.2019.2.8

Balázs Gáti, Tamás Gausz

Using Tools Developed for Wind Turbines for Investigating the Aeroelastic Behaviour of the Rotors of Rotary-Wing Airplanes

Rotor blades of an autorotating helicopter or a gyrocopter work very similarly to the rotor blades of a wind turbine in skew wind. In this publication we present the results of a multiple analysis of a rotor blade of a rotary-wing airplane, but the analyses were performed with a software package developed for investigation of wind turbine blades. The results of several analyses seem to be valid for rotary-wing airplanes in some special, but very important cases, and can be useful for more detailed investigation. It was stated, that the fact leads to uninterpretable numerical solutions, that the angle between the undisturbed airflow and the Tip Path Plane is much lower in case of helicopters and gyrocopters than by wind turbines in most operational conditions.

Keywords: *rotor, rotor blade, wind turbine, gyroplane, autogiro, autorotation, aeroelasticity*

Introduction

One of the important subsets of rotary-wing airplanes are gyrocopters. They have a main rotor, which is driven by the oncoming airflow. From this point of view, the main rotor of the gyrocopter is similar to the wind turbine rotor, which is also driven by the wind. In both cases, the direction of this airflow can be arbitrary. Considering this, the aeroelastic calculation methods developed for wind turbines can also be adopted to the investigations of gyrocopter rotors.

Rotors of Rotary-Wing Airplanes

There are many different types of rotorheads used by rotary-wing airplanes, but many of the gyrocopters have a teetering rotor – this kind of a rotor is used by wind turbines, too. Thus the teetering rotor was chosen for the investigation.

The teetering rotor has two blades, where these two blades are rigidly attached to each other, except for the feathering bearings. The change in the collective and cyclic pitch angle of the rotor blades can be realised by the movement of the swashplate.

The rotor blades of a rotary-wing perform different motions: they can move together with the fuselage of the airplane, can rotate around the rotorhead, can change the pitch angle around their own length axis, can flap up and down and can have elastic twisting, elastic feathering and elastic bending along their own length axis.

Generally, the construction of the rotors of the wind turbines is similar to the rotor of the rotary-wings (as seen in Figure 1) – except that they have no possibility for cyclic pitch changing and they only rarely have flapping hinges.

In Figure 1, the scheme and the main working properties of a teetering type main rotor can be seen. The direction of the rotation is positive, and the cyclic control of the blades have a 90° delay. In this article the notation system of [1] and [2] is used.

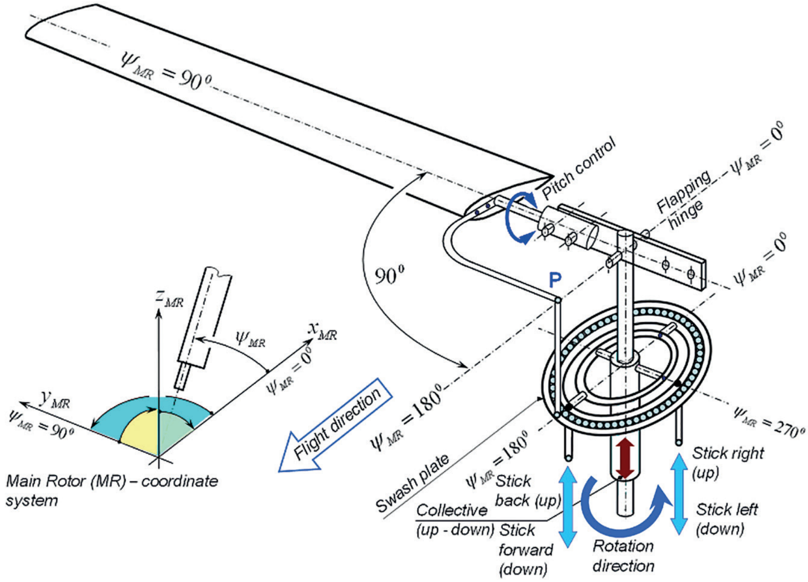

Figure 1.
Sketch of a teetering (zero offset) rotor [Drawn by the authors.]

Blade Element Momentum Theory

Momentum Theory

The rotor of the rotating wing airplane influenced the path of the airflow around itself. The main properties of the flying gyrocopter (or autorotative flying of a helicopter) can be seen in Figure 2.

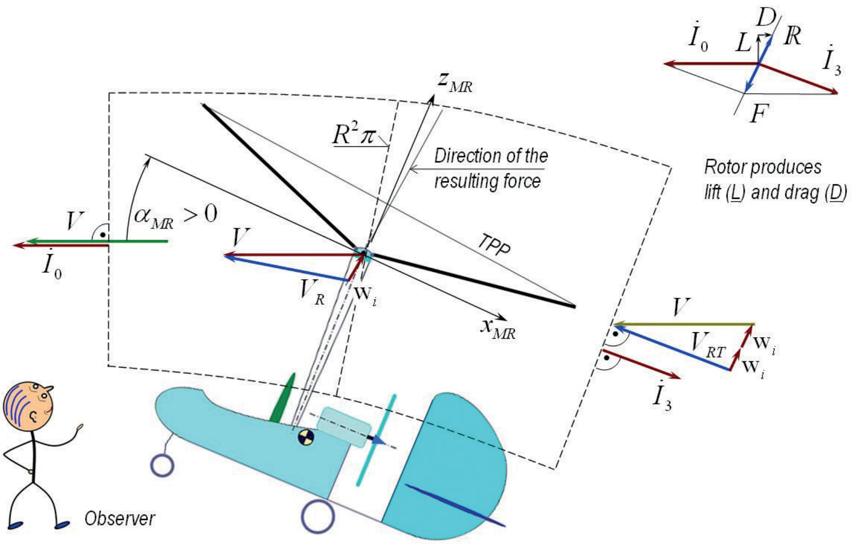

Figure 2.
Flying gyrocopter – momentum theory [Drawn by the authors.]

In Figure 2, a stream tube is shown – the boundaries of this are plotted with a dotted line. The stream tube has a down curving and shows velocity decreasing. This down camber means a downwind, and the reaction force of this downstream is the aerodynamic lift ($\underline{L}$). The drag ($\underline{D}$) of the main rotor originates from the decreasing velocity. The sum of the lift and drag is the resultant force ($\underline{R}$). As written in [2], the resultant force can be calculated by using the momentum theory:

$$\underline{R} = -\left(\underline{I_0} + \underline{I_3}\right) \tag{1}$$

The elaborated formulas of the momentum theory can be read in [2]. By using the momentum theory, the induced velocity distribution over the rotor surface can be determined – induced velocities are needed for the blade element theory.

Blade Element Theory

In the blade element theory – knowing the rotor blade section velocities – the aerodynamic force and moment of all blade sections is calculated. The general working properties – coordinates, angles and velocities – are seen in Figure 3.

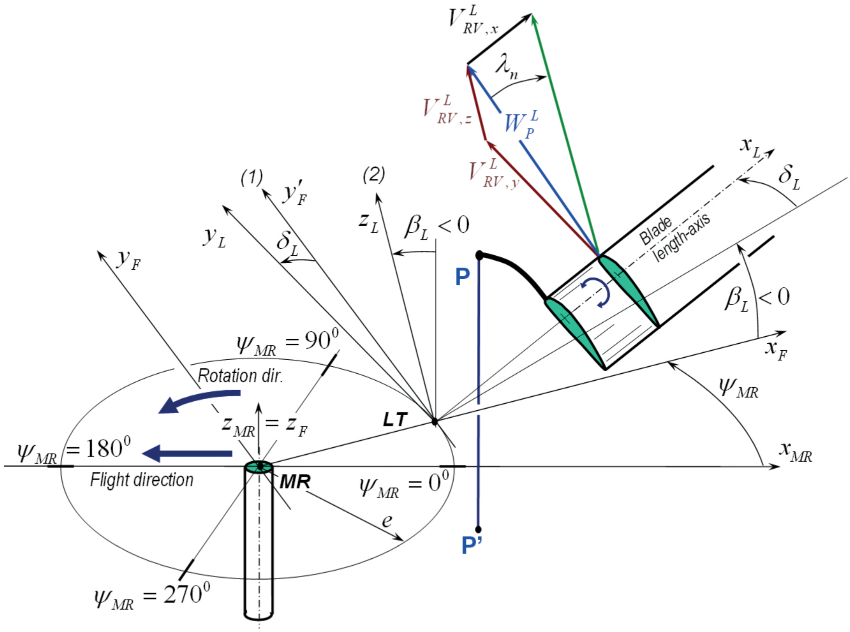

Figure 3.
Working relations – blade element theory [Drawn by the authors.]

This figure shows a general rotor head – the flapping, the lagging and the feathering motions of the rigid rotor blade can be seen in the figure. The flapping motion can be characterised by the flapping angle (β_L), the lagging motion by the lagging angle (δ_L) and the feathering by the motion of the point "P". In our case the "*LT*" point is identical with the "*MR*" point (zero offset rotor head) and there is no lagging motion ($\delta_L \equiv 0$). Due to the teetering rotor head, the flapping motion of the two blades are strictly connected.

At general flow conditions, the rotor blade sections have three velocity components: ${V^L}_{RV,x}$, ${V^L}_{RV,y}$ and ${V^L}_{RV,z}$. These velocity components change along the rotor blade length axis (x_L) and change by the azimuth angle (Ψ_{MR}) too. Because of this, the sweep angle and the angle of attack of the blade sections are variables. The induced velocity – calculated by the momentum theory – is a part of the ${V^L}_{RV,y}$ velocity component. Because of this connection, the momentum theory and the blade element theory, together with further theoretical fields, are to be solved together.

Solution Method

The equation system based on the blade element and momentum theory (BEMT) can be solved by numerical methods, because the unknowns are implicit in the equation system. Most of the numerical methods are looking for the proper value of the characteristic angle of the velocity triangle *(φ)* that fulfils all of the equations. This is an iterative process, that starts with an assumed value of the φ*,* then calculates the Angle of Attack, the aerodynamic forces, the blade flapping, the RPM of the rotor, the axial and angular induced speed and then a new value for the φ. If the convergence criteria of the iterative process are met, the solution for the next step can be started.

From Rotary-Wing to the Wind Turbine

In most cases, a rotary-wing is used to be investigated without the effect of the fuselage. If a vertical descending, autorotating, single rotor scenario is rotated by 90 degrees, it becomes very similar to a wind turbine scenario. (Figure 4.)

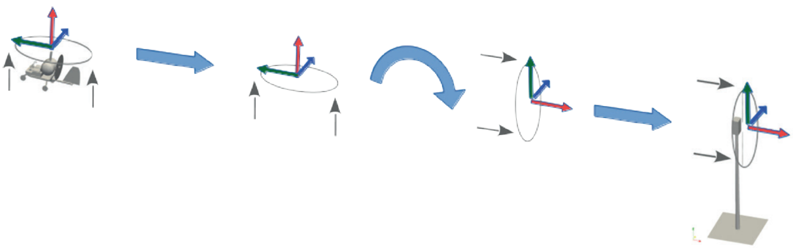

Figure 4.
From autorotation to wind turbine [Drawn by the authors.]

Based on this idea, we started to investigate if algorithms developed for the more and more popular wind turbines are applicable for rotary-wings and what are their limitations.

We choose the NREL FAST v8, as a typical wind turbine simulation tool, which is referenced by a high number of publications, even it is not a user friendly tool.

In order to perform proper simulations with NREL FAST, we had to modify or disable several of its modules. The most important change was to apply a constant wind profile instead of the default one which takes into consideration the boundary layer effect of the earth surface. (Figure 5.)

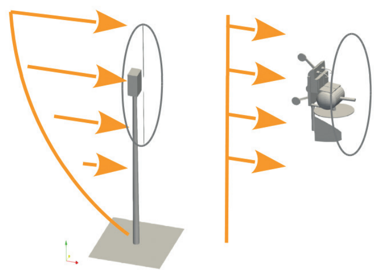

Figure 5.
Wind profile applied by wind turbines and gyrocopters [Drawn by the authors.]

Additionally, we disabled the effect of gravity and the wind shadow caused by the tower, while assumed an ideal, but non-producing generator to avoid improper losses. We also had to decrease the time step of the solver in order to make it suitable for higher RPM of a rotary-wing.

The simulation tool could be configured to include several additional effects that are useful for rotary-wing airplanes, too. The Viterna extrapolation augments the wind tunnel data of an airfoil to the –180° – +180° domain; the Beddoes-Leishman approximation calculates the effect of unsteady flow on the airfoil. The implementation of the Prandtl Tip and Mach correction also improve the precision of the simulation. The Pitt-Peters method considers the effect of airflow not parallel to the rotation axis of the rotor.

We implemented the rotor blade in the simulation based on the geometry of the rotor blade of the McDonnell Douglas MD-500 helicopter. The NREL FAST is limited to rigid and teetering rotorheads. We choose the latter because it is popular by gyrocopters.

Steady state Simulations

Gyrocopters in Cruise

Although we discovered a significant limitation, we were able to obtain several positive results. We were able to investigate the behaviour of a rotor of a gyrocopter in forward flight. This investigation was similar to a wind tunnel test: we did not consider the dynamics of the rotary-wing airplane itself. It means, that the forces on the rotor blades did not influence the acceleration and flight path of the airframe, thus the direction of the inflow was constant in fuselage and earth based coordinate systems.

The angle between the nominal rotor plane and the airflow was set to $\alpha_{MR} = 25°$ and the airspeed was changed between $10\ m/s < V_{TAS} < 30\ m/s$ in several steps. The Pitt-Peters method normally improves the precision of the results if the direction of the wind is not parallel to the rotation axis of the wind turbine rotor (skew wind), but, unfortunately, at this angle (an unusual high angle for wind turbines) seemed to result an incorrect numerical solution. This is also the case during a forward flight of a gyrocopter or an autorotating helicopter; the difference between the direction of the airflow and the rotor axis seemed to be too high for this implementation of the Pitt-Peters model, thus this module had to be deactivated.

Figure 6 presents the value of several parameters at $V_{TAS} = 20\ m/s$. The simulation does not contain a trim calculation that can be realised looking on the value of the RPM. But the simulation can be considered a quasi-steady state as the mean value of the force components can be considered constant. The periodic oscillations in the values are the results of the rotational motion of the rotor.

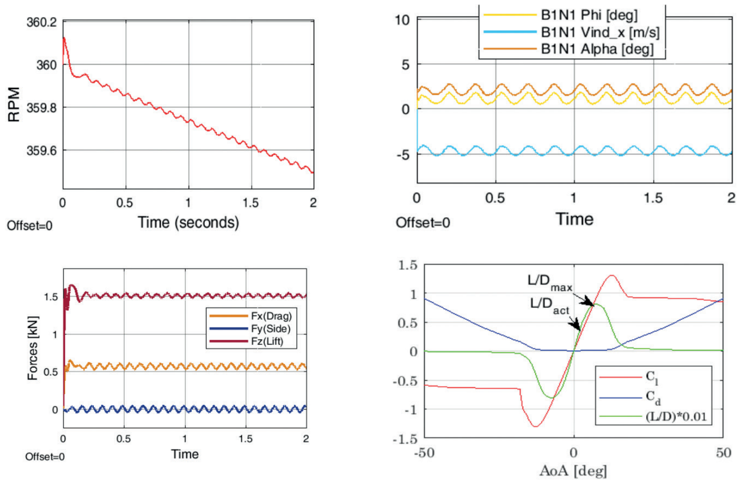

Figure 6.
Gyrocopter rotor blade in horizontal flight with V_{TAS} = 20 m/s [Drawn by the authors.]

Multiple simulations in the given airspeed domain can be seen in Figure 7. The RPM of the rotor seems to be approximately a linear function of airspeed, while the lift generated by the rotor seems to be a quadratic function of the airspeed which is similar to the case of a fixed wing airplane. The Angle of Teeter is relatively small in this airspeed domain because the high RPM does not provide enough time for large flapping angles. The deflection of the rotor blade tip is remarkable but not too significant. It seems decreasing by higher airspeed and lift, because the higher centripetal acceleration at higher RPM causes a bending moment counteracting the bending moment of the lift. The qualitative analysis of results is in conjunction with the expectations. Unfortunately, we could not perform a quantitative analysis yet.

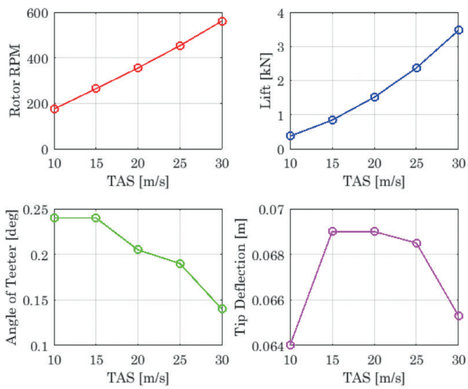

Figure 7.
Gyrocopter rotor blade in horizontal flight with V_{TAS} = 20 m/s [Drawn by the authors.]

Limitations

We also investigated the behaviour of the rotor by different main rotor angles. Unfortunately, the results by $\alpha_{MR} < 25°$ are disappointing, because we could not find a proper set of parameters to achieve a valid numerical solution. As it was already mentioned, after disabling the Pitt-Peters skewed wake model, the simulation was able to provide interpretable results, but only until an angle of 20.5° between the nominal rotor plane and airflow.

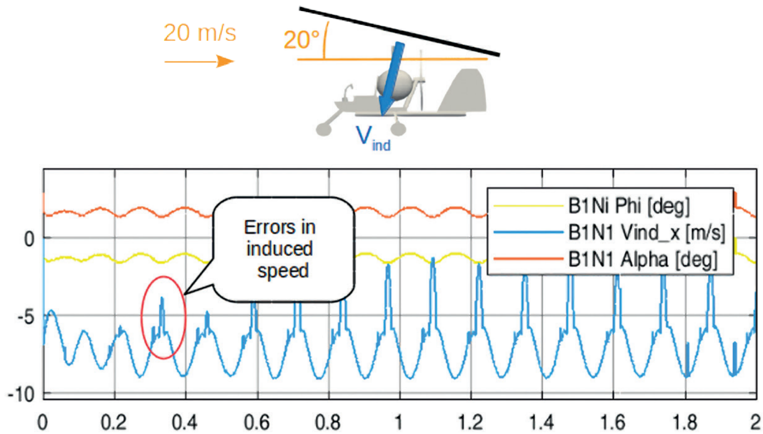

Figure 8.
Numerical error in forward flight of a gyrocopter [Drawn by the authors.]

Below this angle of the nominal rotor plane, an error in induced speed has been developed (Figure 8), that interestingly could not be observed in the two most important angles of the blade element theory, namely in the angle of attack α and in the characteristic angle of the velocity triangle φ. The situation stabilised after disabling the momentum theory and using only the blade element theory for the calculation, but we refused this opportunity.

We tried to simulate the forward flight of a helicopter, too. (Figure 9.) The simulation tool can be configured for simulating a constant speed rotor by disabling the rotational degree of the freedom of the rotor. This way an engine driven helicopter rotor seemed to be simulated. Unfortunately, the opposite direction of the induced speed (V_{ind}) component parallel to air inflow (compared to the case of the gyrocopter, Figure 8) seemed to confuse the solver, and resulted invalid induced speed.

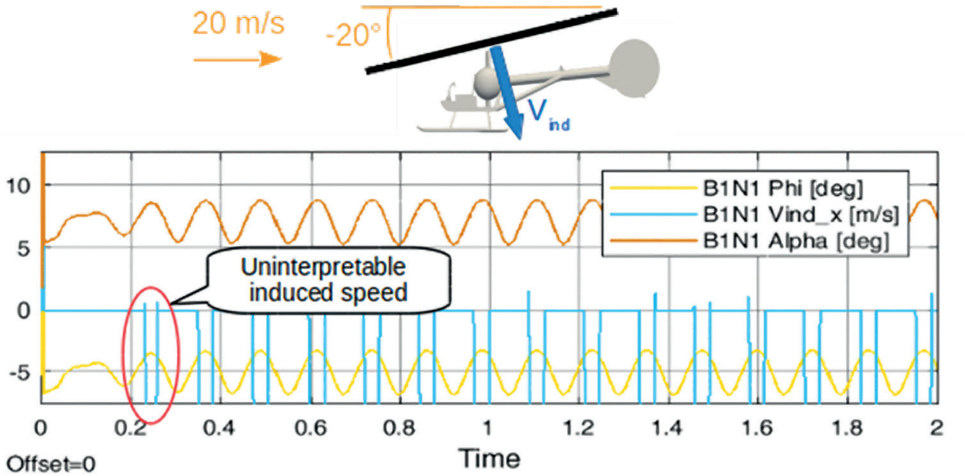

Figure 9.
Numerical error in forward flight of a helicopter [Drawn by the authors.]

Based on these results, the wake correction model and the solver seems to be the weakest points if one would like to simulate rotary-wings with wind turbine simulation tools.

Transient Simulation

As we concluded, the simulation tool developed for wind turbines is not suitable to predict the behaviour of the engine driven rotor blades of a helicopter at all, but the simulation of a gyrocopter blade in cruise flight also causes numerical errors in the results. However, the simulation of a vertical autorotation seemed to be affordable. In this case, the helicopter or the gyrocopter descends vertically, thus the airflow is parallel to the rotational axis of the rotor. This flight mode is not optimal even in case of an engine failure, because some forward speed during autorotation results in better flight performances. However, the conditions in the last phase of an emergency landing looks very similar in case of helicopters. During emergency landing, the pilot increases the rotor RPM and in the flare manoeuver he/she quickly increases the collective pitch angle, resulting in a temporarily high lift for stopping vertical speed of the helicopter just above the ground. The high lift results in a high bending moment and high tip deflection, while the increased drag causes rapid loss of RPM.

The simulation of the emergency landing was started at an RPM of 200 and collective blade pitch angle of $\theta = 0°$. (Figure 10.) An airspeed of 10 m/s was set constant during the simulation.

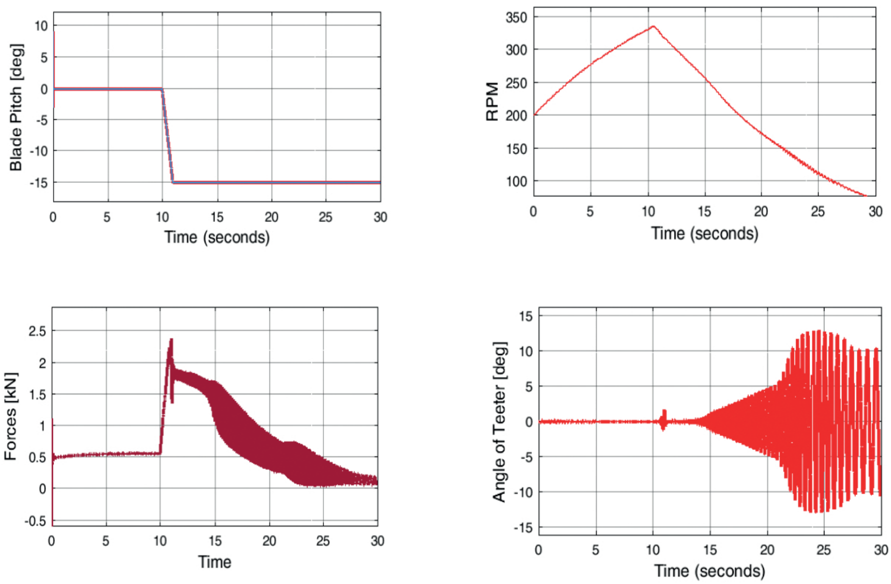

Figure 10.
Rotor parameters in flare manoeuver [Drawn by the authors.]

This pitch angle at this airspeed caused a continuous increase in RPM, but after 10s the pitch angle was changed to $\theta = -15°$. The negative sign comes from the conventions applied by wind turbines, and in this case it increased the Angle of Attack. The lift increased rapidly by more than four times while the RPM started to decrease. The loss in RPM caused loss in lift. Interestingly, we could observe an increasing Angle of Teeter after approximately $t = 14$ *s.* This could be the result of some instability in the transient manoeuver, because teeter occurs normally by forward flight.

Blade tip deflection is a function of lift and RPM. Lift increases the bending moment in the blade while RPM (via centripetal acceleration) causes an opposite bending moment, which decreases the tip deflection. The calculated time function of the tip deflection during flare and the shape of the blade at maximum deflection is shown in Figure 11.

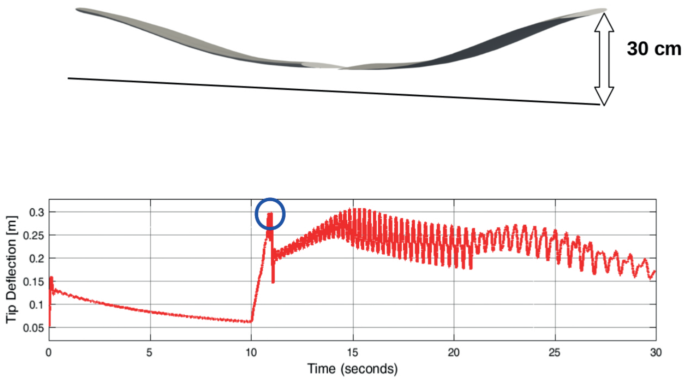

Figure 11.
Blade shape and tip deflection during flare [Drawn by the authors.]

Conclusion

The Blade Element Momentum Theory is often used to describe the behaviour of both wind turbines and rotary-wing rotors. We investigated if a simulation tool developed for wind turbine rotor simulation can be used to simulate helicopter and gyrocopter rotors. We found that the opposite axial induced speed in case of an engine driven helicopter rotor can cause failure to a numerical solver optimised for wind turbines. Additionally, we found that the implementation of the Pitt-Peters skew wake model applied by wind turbines is not suitable for simulating rotary-wings in forward flight. However, in cases where the airflow is approximately parallel to the rotor main axis and the rotor is driven by the airflow, such is the flare manoeuver in emergency landing, that the tool can be used for even a detailed transient aeroelastic analysis.

References

[1] T. Gausz, „Autogírók és helikopterek," Budapest, 2015, ***doksi.hu,*** [Online]. Available: https: //doksi.hu/get.php?lid=21529
[2] T. Gausz, „Autogíró és helikopter rotorok előzetes aerodinamikai és dinamikai számítása," Budapest, 2017, ***doksi.hu,*** [Online]. Available: https: //doksi.hu/get.php?lid=22826

Further Reading

R. L. Bisplinghoff, H. Ashley, and R. L. Halfman, *Aeroelasticity,* Cambridge: Addison-Wesley Publishing Company, 1955. DOI: https://doi.org/10.1002/zamm.19560360764
A. R. S. Bramwell, G. Done, and D. Balmford, *Helicopter Dynamics,* Oxford: Butterworth-Heinemann, 2001. DOI: https://doi.org/10.1017/S0001924000017978
T. Gausz, „Aeroelasztikus jelenségek és dinamikai terhelés," Budapest, 2015, *doksi. hu,* [Online]. Available: https: //doksi.hu/get.php?lid=20964

B. Gáti, T. Gausz, and I. Jankovics, "Repülésmechanikai modellezés," Repüléstudományi Napok, 2015.

E. Hau, *Windkraftanlagen,* Berlin, Heidelberg: Springer Verlag, 2003. DOI: https: //doi.org/10.1007/978-3-662-10948-9

J. G. Leishmann, *Principles of Helicopter Aerodynamics,* Cambridge: Cambridge University Press, 2008.

J. M. Jonkman, G. J. Hayman, B. J. Jonkman, and R. R. Damiani, AeroDyn v15 User's Gide and Theory Manual, Technical Report, NREL, 2016.

FORGÓSZÁRNYAS REPÜLŐGÉPROTOROK AEROELASZTIKUS VISELKEDÉSÉNEK VIZSGÁLATA SZÉLTURBINALAPÁTOK SZÁMÁRA KIFEJLESZTETT ESZKÖZÖKKEL

Az autorotáló helikopterek és az autogírók rotorjának működése nagyon hasonló lehet a ferdén megfújt szélkerekek működéséhez. Ebben a munkában forgószárnyas repülőgépek rotorlapátjainak olyan szimulációit mutatjuk be, amelyeket egy szélturbinák lapátjainak vizsgálatára kifejlesztett alkalmazáscsomag segítségével végeztünk el. Néhány speciális, de nagyon fontos esetben elfogadható, bár a gyakorlatban még ellenőrizendő eredményre jutottunk, amely további, részletesebb vizsgálatok kiinduló pontja lehet. Megállapítottuk, hogy több esetben értelmezhetetlen eredményekhez vezethet az a tény, hogy helikopterek és autogírók esetében a zavartalan áramlás iránya és a lapátvégsík közötti szög jelentősen kisebb, mint a szélturbinák esetében.

Kulcsszavak: *rotor, rotorlapát, szélturbina, autogíró, autorotáció, aeroelasztikus jelenségek*

Gáti Balázs (PhD)
Egyetemi docens
Budapesti Műszaki és Gazdaságtudományi Egyetem
Közlekedésmérnöki és Járműmérnöki Kar
Járműelemek és Járműszerkezetanalízis Tanszék
gati.balazs@kge.bme.hu
https://orcid.org/00000-0002-1202-9949

Balázs Gáti (PhD)
Associate Professor
Budapest University of Technology and Economics
Faculty of Transportation Engineering and Vehicle Engineering
Department of Vehicle Elements and Vehicle-Structure Analysis
gati.balazs@kge.bme.hu
https://orcid.org/0000-0002-1202-9949

Gausz Tamás (PhD)
Nyugalmazott egyetemi docens
gausz.tamas@gmail.hu
https://orcid.org/0000-0001-7026-0666

Tamás Gausz (PhD)
Retired Associate Professor
gausz.tamas@gmail.hu
https://orcid.org/0000-0001-7026-0666

http://journals.uni-nke.hu/index.php/reptudkoz/article/view/257/169