Dynamic effects on different rotor profiles for eVTOL applications

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Abstract.

Electric Vertical Take-Off and Landing (eVTOL) aircraft, commonly known as eVTOLs, represent a recent and promising concept for enhancing urban mobility, particularly in densely populated areas. However, the development of eVTOLs has been accompanied by various technical and technological challenges, primarily due to the rapid introduction of new concepts. Among these challenges, this study focuses on investigating the dynamic effects on rotor blades designed for such aircraft. Rotor blades, being subject to rotational dynamic effects, exhibit behavior distinct from components lacking angular velocity. Therefore, they are of particular interest for dynamic analysis. The study begins by defining a simplified geometry representative of a rotor blade, which serves as the basis for applying finite element methods using Ansys software. This approach enables the observation of the system's response to rotation. Following, more detailed geometries representing rotors are modelled, respectively in NACA 0012, VR 08 and VR 12 airfoils, which are then subject to the rotational effects numerical calculations. The results obtained for the different aerodynamic profiles are then compared, presenting the differences caused by the different geometries and mass distributions implied. The results obtained from the analysis highlight the significant impact of angular velocity on the fundamental frequencies and modes of the dynamic system. These findings suggest the presence of effects such as spin softening and strain stiffening, along with identifying important frequency coupling points.

Keywords: eVTOL, Rotor, Dynamics, Urban Air Mobility

1 Introduction

Population growth and its tendency to concentrate in major urban centers, leading to the phenomenon of megacities such as Tokyo and New York, for example, has brought significant engineering challenges across various fields of technology, including urban mobility. Traditional land-based transportation methods have shown their limitations regarding implementation due to the scarcity of physical space, traffic congestion, and consequently long travel times. This brings forth the idea of utilizing vertical space over urban centers as a potential solution for transportation through the concept of urban air mobility as in Jha et al. [1].

Urban Air Mobility (UAM) is a concept that aims to expedite point-to-point travel in high-density population areas using aerial vehicles adapted for this purpose, navigating through established corridors and potentially, in the future, autonomously. One of the primary vehicle models stemming from this concept is the eVTOL, or electrical Vertical Takeoff and Landing, as is described in Radotich [2] a new category of short-range aircraft designed with the principles of urban air mobility in mind.

However, the development of a new type of aerial vehicle brings numerous technical and technological challenges. In the case of eVTOLs, the shift from traditional engine power matrices to electric power is one of the main technological bottlenecks, as well as the modeling of flight dynamics, which depending on the model, can even couple fixed-wing and rotary-wing models depending on the phase of flight. For the purposes of this work, the dynamic behavior of a key component of these aircraft's propulsion systems, the rotors, will be observed.

Rotors, as defined in Genta [3], are components that exhibit significant angular rotation velocity around an axis. It is precisely this rotation that makes them an object of interest for dynamic analysis, as effects not present in rotationally static structures will emerge when there is a significant angular velocity, such as Coriolis and gyroscopic dynamic effects. The presence of these effects, along with the abandonment of the small deformation hypothesis commonly used in simpler dynamic analyses, tends to push the dynamic analysis of rotors into the non-linear field as presented in Rafiee et al. [4].

These effects have significant impacts on the dynamic behavior of a system, as they alter the behavior of the stiffness matrix, which by definition models the behavior of modes and natural frequencies of a dynamic system. Therefore, analyzing a rotor without considering the phenomena arising from rotation risks inaccurately depicting the true behavior of the body.

This work will, therefore, numerically analyze the dynamic behavior of rotary wings with three different aerodynamic profiles: NACA 0012, VR08, and VR12, as well as a flat plate for reference. Additionally, a brief analysis will be conducted regarding rotor configurations and the number of blades.

2 Methodology

Due to the still experimental nature of eVTOL-type aircraft and the fact that various companies are independently working on their development, it is possible to find several different fuselage designs and engine arrangements with a brief search. The aircraft developed by Airmobility [5], Lilium [6], Airbus [7] and Volocopter [8], for example, present very diverse configurations. However, to be able to compare the results obtained through the analysis to be conducted here, there must be a standard among the proposed rotary wings.

Therefore, the blade length and chord dimensions found in Wright [9] are adopted, as well as the structural damping according to the specifications in Tab. 1.

Table 1. Wing geometry properties

Propriety	Value [unity]
Lenght	2,1153 [m]
Chord	0,2658 [m]
Structural damping	0,5 [%]

It should be noted that, regarding the profile thickness, it is defined for the reference plate as 0.02167 meters in order to distribute the average volume of the other profiles along the blade's chord, while the other cases are determined according to the distribution of the applied aerodynamic profile itself. To illustrate the geometry, the 3D model generated for the NACA 0012 profile can be seen as displayed in Fig. 1

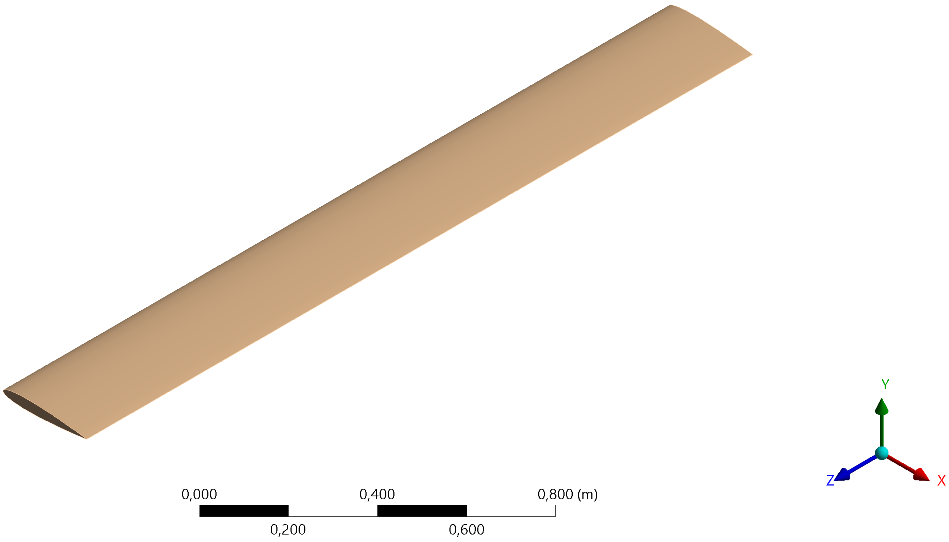

Figure 1. NACA 0012 geometry

The geometry is considered as a single, fully solid piece made of the same material for all four cases. For the purposes of this simulation, the material is defined as one of the models available in the finite element software for carbon fiber. Since carbon fiber is an orthotropic material, its mechanical properties depend on the material direction, as shown in Tab. 2.

Table 2. Simulated material elastic properties

Propriety	Value [Pa]
Young's Modulus X direction	5,916eˆ10
Young's Modulus Y direction	5,916eˆ10
Young's Modulus Z direction	7,5eˆ9
Shear Modulus XY	3,3eˆ9
Shear Modulus YZ	2,7eˆ9
Shear Modulus XZ	2,7eˆ9
Poisson's Ratio XY	0,04
Poisson's Ratio YZ	0,3
Poisson's Ratio XZ	0,3

Thus, having defined the objects of analysis, each profile is inserted into a numerical simulation environment, where the proximal end of the geometry is considered fixed as if attached to the rotor shaft, with the other end free in all degrees of freedom. A range of angular velocities is then applied, with the points taken according to Tab. 3 to analyze the frequency behavior for the first ten modes of the geometries. This allows for the construction of the Campbell diagram for each of the profiles analyzed.

Table 3. Angular velocities taken at simulation

Point Nº	1	2	3	4	5	6	7	8	9	10
Rads/s	0	15	30	45	60	75	90	105	120	135

The results obtained for each of the profiles are then compared to observe the dynamic behavior of each geometry in relation to the others, as will be presented in the results section.

A brief aerodynamic analysis is also conducted for each of the three suggested aerodynamic profiles, excluding the flat reference plate. This is performed using the QBlade software, where the geometries are defined according to each profile as shown in Fig. 2.

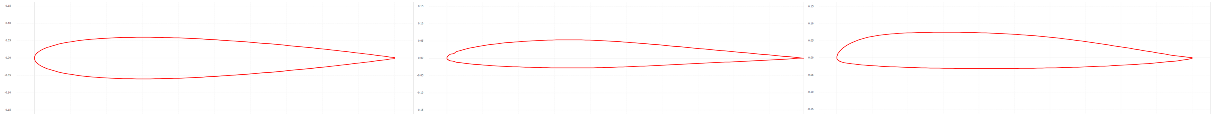

Figure 2. Aerodynamic profiles as defined in Qblade being them, from left to right: NACA 0012, VR 08 and VR 12 respectively

For comparison purposes, three cases are then tested for each of the profiles discussed. The base case is a rotor composed of two blades, with the same dimensions as the previously described simulation, each 2.12 meters in length. The following two scenarios involve a redistribution of the total blade area from the first case, resulting in an analysis for a rotor with three blades, each approximately 1.41 meters long, and a rotor with four blades, each 1.06 meters long. Examples of these configurations for the VR 12 profile can be seen in Fig. 3.

The purpose of this aerodynamic analysis is, first and foremost, to identify which of the three studied profiles can generate the most lift under the same flight conditions. This data will later be compared with the results obtained during the dynamic analysis stage.

Furthermore, the study of different rotor blade number configurations aims to demonstrate the relative behavior between blade length and the lift each of the three rotor models can generate.

Figure 3. Illustrative image of the proposed rotor configurations

3 Results

3.1 Dynamics

After performing the numerical simulation for the four presented cases, the frequencies obtained for each point of the angular velocities for each profile are used to generate a graphical representation known as the Campbell diagram. This diagram allows for the observation of frequency behavior over the range of applied angular speeds. For illustrative purposes, see Fig. 4, which shows the Campbell diagram generated for the simplest case, the plate.

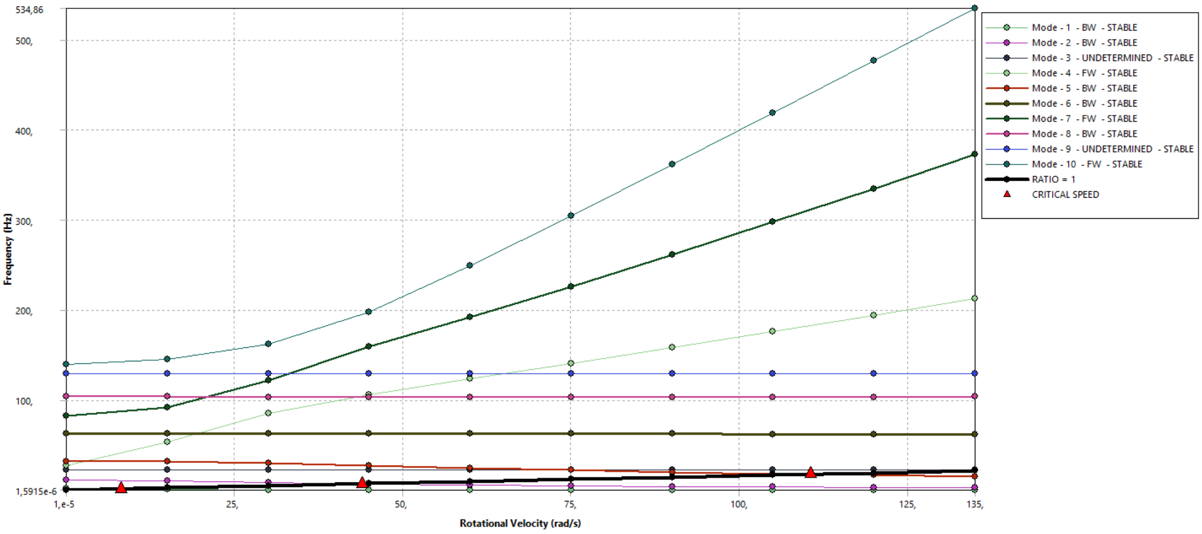

Figure 4. Campbell diagram for the plate

The points from the Campbell diagram for each profile are then taken and, for each mode, graphically compared for the four studied profiles simultaneously. Due to the large number of modes, only the first two bending modes and the first two torsional modes are presented in this study, as is presented in Fig. 5 and Fig. 6 respectively. This selection is based on the fact that modes with lower initial frequencies are the most likely to be excited in practical terms.

It can be noted from the results in Fig. 5 that for the bending modes, both the NACA 0012 and VR 12 profiles exhibit higher frequencies compared to the reference plate, with NACA having the highest among them. However, the VR 08 profile shows lower bending modal frequencies than the reference values.

For the torsional modes, as shown in Fig. 6, it is observed that all three aerodynamic profiles generally present higher frequency values than the reference, especially as the angular velocity applied to the blade increases.

It is interesting to observe the opposite behavior between bending and torsional modes as the rotational speed progresses. Visually, it is clear that the frequencies for the bending modes tend to decrease as the angular velocity increases. On the other hand, for the torsional modes, it is evident that the frequencies of the blades increase in the same way as the rotational rate. This trend is noticeable for all the analyzed profiles, so, with the differences in values and scales considered, the overall behavior of the curves is similar among the hypothetical airfoils.

This behavior is due to the occurrence of dynamic phenomena known as spin softening and stress stiffening, respectively. These opposing behaviors result from the divergence or alignment of the dynamic forces as shown in Wang et al. [10], originating from the rotational effects, relative to the longitudinal axis of the body. When these forces are not aligned with the longitudinal axis, they act as destabilizing factors, increasing the precession of the blade tip movements. Conversely, when they are oriented in the same direction as the blade's length, they tend to

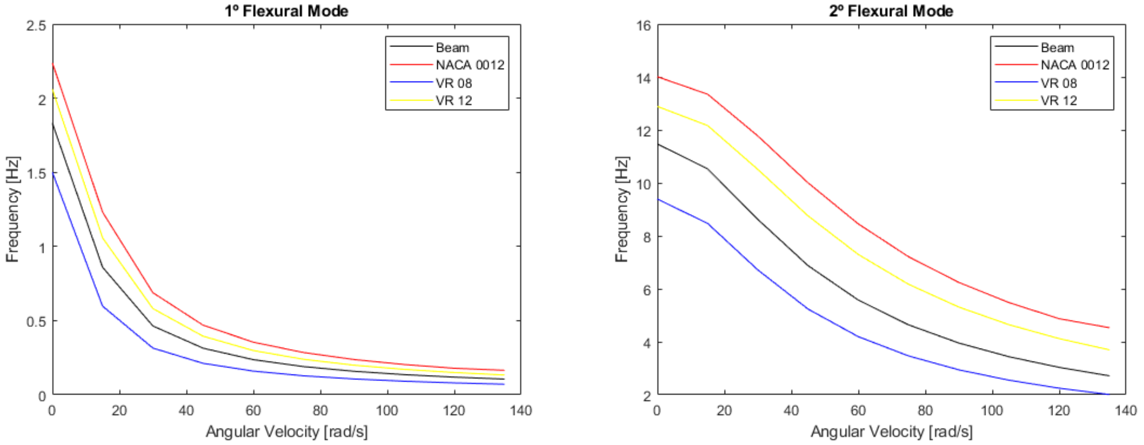

Figure 5. First and second flexural modes comparison between the studied profiles

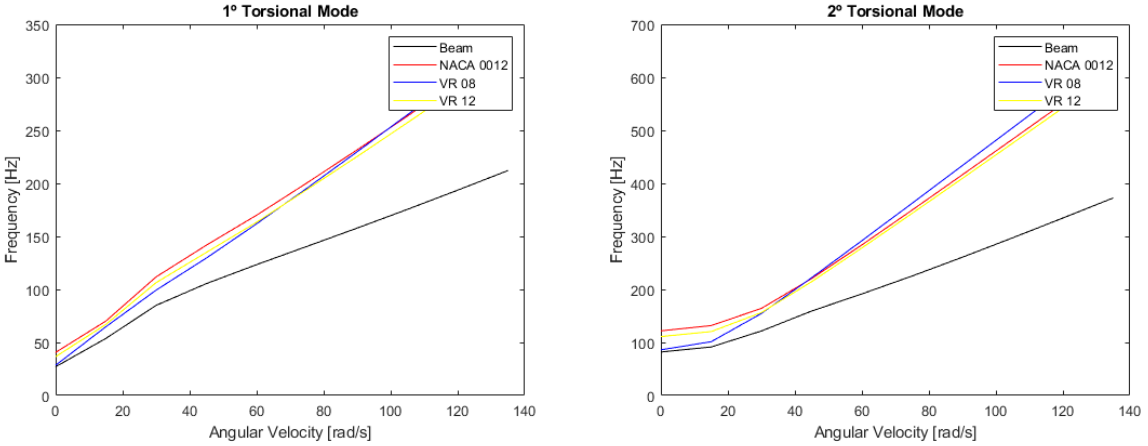

Figure 6. First and second torsional modes comparison between the studied profiles

increase the system's stiffness, thereby also enhancing its stability.

Another noteworthy phenomenon observed from the obtained results is the frequency coupling points. As seen in Fig. 4, there are instances where the lines representing the frequencies of different modes intersect. At these points, frequency coupling is considered to occur, where, simply put, it is possible to harmonically excite two or more modes at the same structural frequency, potentially resulting in resonance. Therefore, it is crucial to consider and avoid these points during the design of a structural component.

3.2 Aerodynamics

The aerodynamic analysis carried out here, as previously mentioned, has two objectives: to compare the thrust provided by blades shaped with each of the three proposed aerodynamic profiles, and to compare the thrust provided by three different rotor configurations with two, three, or four blades, while maintaining the total blade area constant.

To obtain data for the first of the two proposed analyses, simple simulations are performed using QBlade software for rotors containing two blades, each measuring 2.12 meters in length, as per the parameters of the previously executed dynamic simulation, for each of the aerodynamic profiles addressed. The results presented in Fig. 7 consider a rotational speed of 135 radians per second, with the blades having a fixed angle of attack of 10º relative to the free flow.

It is observed from this comparison that under these conditions, the VR 12 profile demonstrates the best performance in terms of aerodynamic lift among the three profiles studied. Therefore, the VR 12 profile is selected for the next stage of the aerodynamic analysis, which involves comparing the different rotor configurations in terms of the number of blades.

Three models are then constructed for simulating the different configurations, where the total blade length

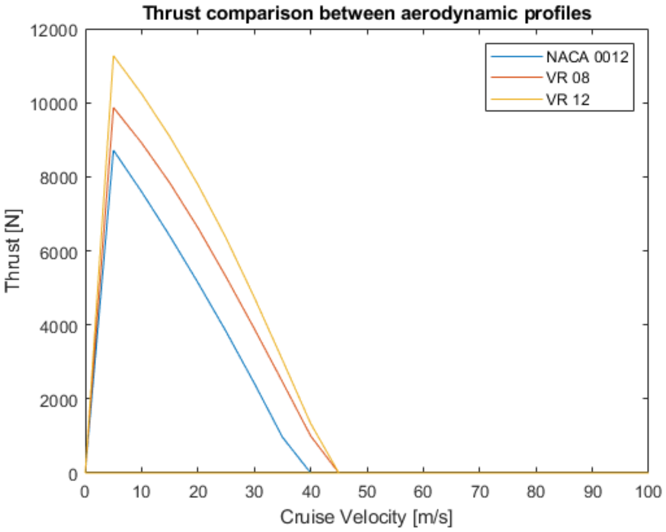

Figure 7. Thrust comparison between aerodynamic profiles

of the base rotor with two 2.12-meter blades is evenly distributed into three and four blades for the subsequent models. All other parameters, such as chord length, angle of attack, and rotational speed, are kept constant as previously specified to ensure a standard basis for comparison.

The results are then obtained and presented as shown in Fig. 8 for ease of visualization.

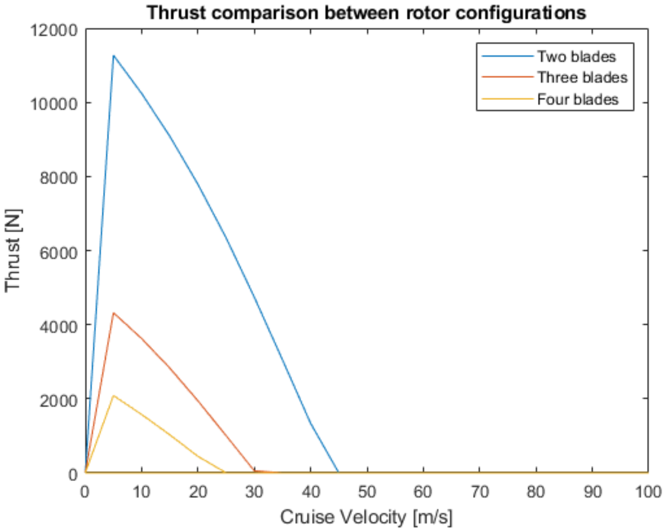

Figure 8. Thrust comparison between rotor configurations

It is notable that the thrust produced by the rotor model with two blades is significantly higher than the other cases. Additionally, it is observed that generally, the greater the number of blades in the configuration and consequently the shorter their length, the lower the lift provided by the rotor.

This result aligns with physical expectations, as the linear velocity of the flow relative to the blade in the case of rotating wings depends directly on its radius. Therefore, the shorter the blades of a rotor, the lower the thrust produced. Thus, based solely on this result, the two-blade rotor model can be considered the most efficient arrangement among those proposed here.

4 Conclusions

Not only important for the case studied here of a rotor aimed at electric vertical takeoff and landing (eVTOL) aircraft, the dynamic effects arising from the presence of angular velocity acting on a system directly affect its behavior and stability, as demonstrated. These impacts must be considered when designing components of rotating mechanisms. Significant effects such as spin softening, stress stiffening, and frequency coupling points can be observed for the cases discussed as previously stated.

Of the profiles analyzed during this work, higher frequencies are observed across the entire spectrum of speeds for the NACA 0012 model in the flexural modes addressed. For the torsional modes, the behavior of the profiles is similar, except for the reference flat plate, which does not match the intensity of the others. Being more robust profiles, both the NACA 0012 and VR 12 exhibit higher frequencies than the reference, indicating greater rigidity, while the VR 08, being a more slender profile, shows lower frequencies, indicating a greater vulnerability to dynamic instability effects.

From the aerodynamic analysis, it is concluded that according to the thrust simulation results, among the three aerodynamic profiles considered, the VR 12 appears to be the most efficient and effective for future studies. Additionally, the results for different rotor configurations indicate that models with longer blades tend to deliver better lift performance compared to models with more but shorter blades.

Therefore, the results suggest that the more elongated the blade attached to the rotor, the better its aerodynamic performance. However, from the dynamic analysis, it is understood that very elongated structural elements tend to exhibit lower dynamic stiffness and higher vulnerability to destabilizing effects. In other words, the design of a blade intended for application in eVTOL rotors strikes a delicate balance between aerodynamic efficiency and the control of structural dynamic effects. Nonetheless, studying this balance independently in terms of structural dynamics and aerodynamics can only take us so far.

Therefore, future work will focus on the aeroelastic analysis of these components to better integrate the dynamic and aerodynamic effects present in the system.

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6 Authorship statement

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