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SCUOLA DI INGEGNERIA INDUSTRIALE
E DELL'INFORMAZIONE

Executive Summary of the Thesis

Computational Fluid Dynamics Investigation over a Reconfigurable Blade Tip for Helicopter Rotors

Laurea Magistrale in Aeronautical Engineering - Ingegneria Aeronautica

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1. Introduction

Helicopters represent some of the most complex and efficient machines created by man. Nowadays, their hovering and vertical movement capabilities make them crucial assets in carrying out several operations.

The use of helicopters in densely populated areas has a great impact on the surrounding population because of the loud noise generated by the rotor, especially during the landing phases. Therefore, in recent years the study of blade geometry has focused on efficiency and reduction of the main cause of impulsive noise - the *blade-vortex interaction (BVI)*.

Along the history of rotary-wing applications, many different blade tip shapes have been considered. According to Brocklehurst and Barakos [2], there still is no common agreement on the best design for a helicopter blade tip. However, several studies showed that hover performances are generally increased with a downward tip deflection (so called *anhedral* angle). At the same time, the anhedral angle is not an optimal feature during forward flight as it increases the vortex-blade interaction effect and thus the rotor noise, besides generally reducing flight performances. Because of this, the idea of a reconfigurable blade tip is born.

The purpose of this thesis is to evaluate the feasibility of a passive helicopter blade tip reconfiguration. The tip should be able to reduce the anhedral angle autonomously thanks to the loads generated in specific flight conditions. The motion is made possible by the placement of a hinge at the start of the tip region, separating it from the inboard section of the blade, which remains undeformed. The reconfiguration mechanism could be released by the pilot depending on flight conditions.

This study is based on a preliminary examination of the problem made by J. Surra [3], consisting of a multi-body model analysis. This thesis dives further into the problem by implementing a Computational Fluid Dynamics model. Once the setup is validated and the simulations run, results will be analyzed and compared to better understand the aerodynamic behaviour of the blade tip and evaluate if and at what conditions the anhedral reduction is possible.

2. CFD model validation

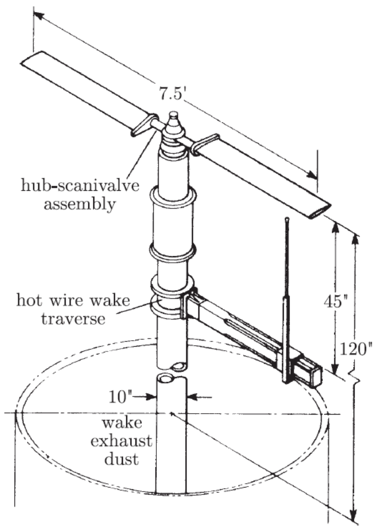


Figure 1: Caradonna-Tung experiment

In order to validate the CFD model, the Caradonna-Tung NASA experiment [1] was taken as a reference. Various simulations were performed on this setting and proven to be representative of true results. The experiment consists of two NACA 0012 blades rotating at a constant speed; for the validation, the case of 8° angle of attack was considered. Characteristic values are reported in table 1.

Blade Chord c	0.191 m
Blade Radius R	1.143 m
Aspect Ratio	1/6
Cut-out radius	0.191 m
Collective Pitch	8°
Rotational Speed Ω	1250 rpm
Experimental C_T	0.00459
Mach number at blade tip	0.439
Operative pressure P	103027 Pa

Table 1: Caradonna-Tung experiment setting values

2.1. Simulation domains

The validation consisted of two subsequent sets of CFD simulations based on the Euler equations. The first one with a large complete domain, and the second one with a much smaller, half-split periodic domain in order to reduce computational cost.

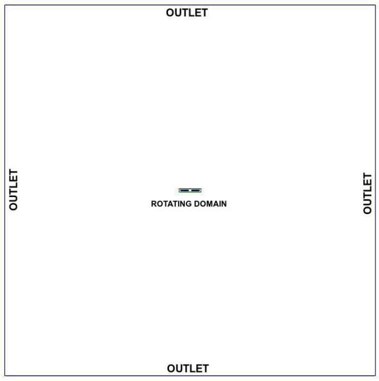


Figure 2: Full domain

The first simulation included a cylindrical domain of radius 30 R and same height. The whole boundary was set as a pressure outlet with standard values. A smaller cylinder of radius 1.5 R was placed around the blades as the rotating domain. The inner domain allowed for the application of the moving reference frame method, which delivers a stationary rotational flow around the rotor without the need of a moving mesh or time marching simulations.
The discretization methods chosen were a second order upwind for the momentum equation and a second order for the continuity equation. Considering the wing tip mach number, compressible conditions were met.

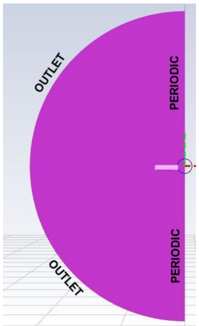


Figure 3: Half-split periodic domain top view

The second simulation consisted in a half-split domain with periodic boundaries in order to drastically reduce computational cost. Vertical dimensions were lowered to 4 R on the top and 6 R on the bottom, as these dimensions guarantee to avoid boundary proximity effects. In this new configuration, an inlet velocity boundary condition has to be placed on top in order to simulate the induced velocity that the rotor naturally generates in a wider domain.

The goal thrust of the rotor was evaluated through the experimental c_T. The inlet velocity was evaluated through the momentum theory, which gives the induced velocity of the rotor:

$$v_{iM} = \sqrt{\frac{T}{2\rho A}} \tag{1}$$

However, since the inlet of the domain is placed at a distance from the rotor to avoid boundary issues, the air further accelerates once close to the rotor and thus the thrust is excessively reduced compared to a true hovering case. Consequently, this primary formulation does not correctly represent the model. In order to solve this problem, an experimental coefficient was computed such that:

$$v_i = k \cdot v_{iM} \tag{2}$$

An evaluation study of k was conducted in order to find the best value that equals the thrust given from the Caradonna-Tung experiment. Eventually, the value of $k = 0.28$ was found as best.

2.2. Meshing and validation

The meshing of the full domain resulted in 4 million elements with a uniform refinement on the blade of 1 mm size. A finer region was created around the blades and the inner rotating domain, while keeping the outer cells larger. Poly-exacore elements were preferred over classic tetrahedrons as they allow for a strongly smaller mesh while maintaining and actually increasing quality and robustness. On the split domain, a better educated mesh refinement was applied on the blade, concentrating finer areas on the leading edge and trailing edge locations; this meshing was done using curvature and proximity algorithms.

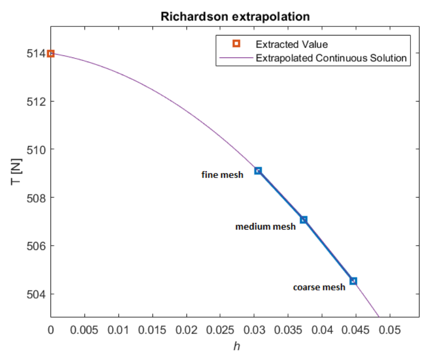


Figure 4: Grid convergence results

After assessing the quality of the setting, three differently sized meshes (*coarse*, *medium*, *fine*) were created to implement the Richardson extrapolation method. The extrapolated zero grid spacing value does not reach the experimental thrust of 516 N due to the inviscid nature of the simulation. However, all meshes deliver an error that is less than 2.2% on the expected value. Because of this and due to computational costs, the settings of the *medium* mesh were chosen as reference for all further simulations in the thesis.

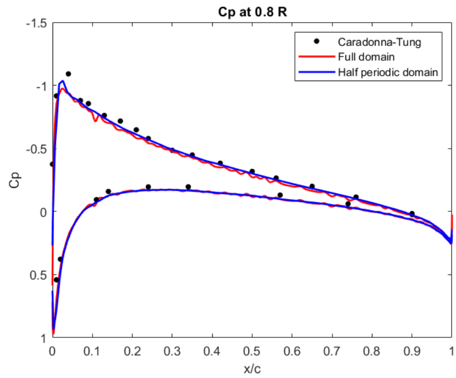
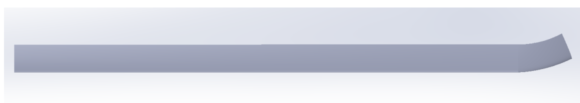


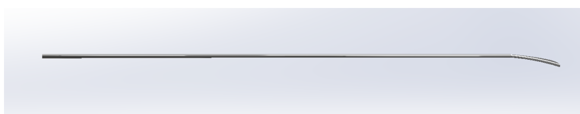
Figure 5: Pressure coefficient comparison at 80% radius section

The 80% R section C_P was considered as a reference validation. There is no significant difference in results between the full domain with a much finer mesh and the half-split domain with the *medium* mesh. The smaller domain-periodic boundaries simulation shows results that strongly relate both to the wide-domain simulation and the actual NACA experiment.

3. Geometry



(a) Top view



(b) Front view

Figure 6: Blade 3D model rendered in SolidWorks

The study is focused on a 7.3 m long rectangular helicopter blade. The tip was then modified in order to account for both a sweep and anhedral angle β_{tip}. The blade's section is a NACA 23012 airfoil with a linear varying twisting angle along the span. The blade tip starts at 91% R, where its hinge is located. The tip also presents a fixed sweep angle of 25° and a reference anhedral angle of 20°.

Blade Chord c	0.327 m
Blade Radius R	7.3 m
Cut-out radius	0.191 m
Blade linear twist	-0.0213 rad/m
Blade cut-out twist	0.101 rad
Collective at 75% R	0 rad
Feathering axis position	0.23 c

Table 2: Blade characteristics

The hinge is a line that runs from leading to trailing edge. A reference point is set at the feathering axis coordinate on the hinge line for moment evaluation; the rotation of the blade hinge around the reference point is defined by the angle ζ_{th}

3.1. Rotor Characteristics

The whole rotor consists of 5 rotating blades. In order to reduce computational effort, a periodic boundary condition is introduced and only one of the blades will be actually simulated in the CFD solver.

MTOW	8200 Kg
Collective pitch θ_{75}	14°
Blades number	5
Thrust T	80221 N
Torque Q	63061 Nm
Coning angle β_0	6.94°
Rotating speed Ω	27.9763 rad/s
Mach number at blade tip	0.6

Table 3: Rotor characteristics

The coning angle β_0 is the mean flapping angle that the blade reaches during hovering; it is the result of the dynamic equilibrium between inertia forces and aerodynamic loads. Given the fixed geometry nature of the CFD simulations, the values of coning angle for each configuration are taken from the previuos multi-body study.

The blade rotates around the flapping hinge, located at 7% radius.

3.2. Inertia definition

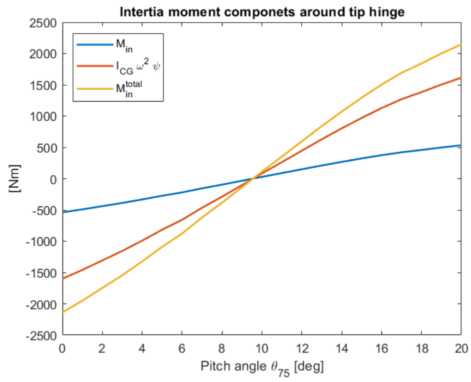


Figure 7: Inertia moment components

The inertia effects were considered to be crucial in the behaviour of the rotor and of the effects on the tip. Therefore, external computations were done by assuming the mass of the blade tip as concentrated in its center of gravity.
The inertia moment of the tip with respect to the hinge was calculated in various configurations by the use of geometrical values computed through rigid motions of the blade. The centrifugal force was multiplied by its arm with respect to the hinge to obtain the moment. However, as a purely point-wise approach dealt a great loss of information, the inertia component given by the tip moment of inertia was also included.

3.3. Blade CFD setup

The CFD domain is built by maintaining the same proportions as the Caradonna-Tung experiment. The same periodic conditions of the validation are applied; being this a 5 bladed rotor, the periodicity angle is of 72°.
The cell refinement on the blade is kept the same as the Caradonna-Tung one as the airfoils' chords dimensions are comparable.
Following the reasoning about the inlet velocity, the resulting value is $v_i = 3.92$ m/s.

4. Results

The reference blade was first analyzed and compared to the results of the multi-body study. Values matched greatly, with a goal hovering thrust error of 0.5%. All aerodynamic loads, including tip hinge moment, varied linearly according to the thin airfoil theory in which the blade operates. Required power presents a gap due to the smaller drag prediction given by an inviscid CFD simulation.

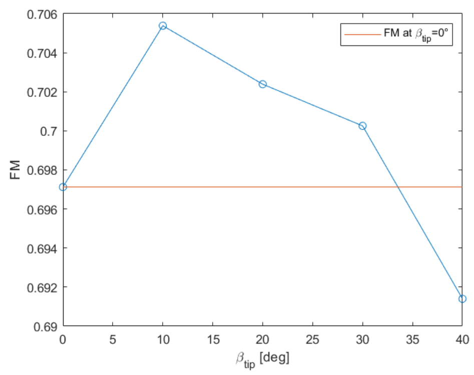


Figure 8: Figure of merit sensitivity to anhedral angle

The hover figure of merit was computed for various anhedral angle configurations. It is verified that a drooped tip increases hovering efficiency, with the exception of very large angles. This result was further investigated through the analysis of the lift distribution .

The tip vortex was studied by integrating the flow vorticity on a reference plane slightly behind the blade. A square numerical grid was created and the circulation was computed as the surface integral. Results show that vortexes become weaker with the increase of the anhedral angle; they are moved away from the rotor plane and also stretch further towards the center, as confirmed by literature.

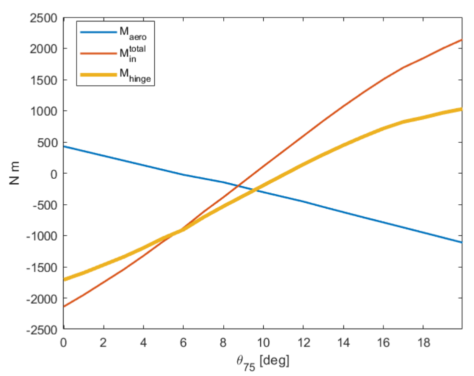


Figure 9: Total tip hinge moment pitch sensitivity

Eventually, the overall tip hinge moment was analyzed; aerodynamic loads were summed together with the previously computed inertia values. A polynomial fitting interpolation of the curve revealed the zero moment angle to be approximately $\theta_{75}^{0} = 11.15°$. A collective pitch lower than θ_{75}^{0} will result in an ahedral angle reduction if the reconfiguration mechanism is released. This value is lower than the 14° required for hovering.

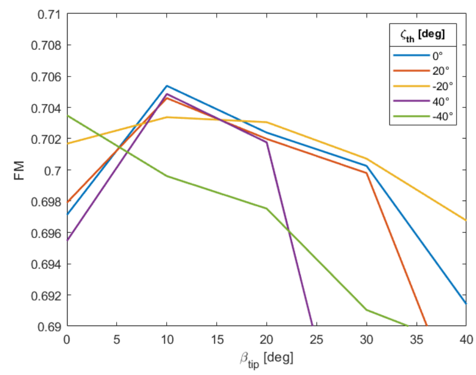


Figure 10: Hinge angle hover figure of merit

The variation of the hinge line skew angle ζ_{th} was investigated. The figure of merit reveals that, for the reference blade with 20° anhedral, a −20° hinge angle delivers the best hovering efficiency. Another option would be to lower the anhedral angle to 10° in order to achieve the overall best hover figure of merit.

The use of a negative hinge angle increases the tip moment slightly, elevating the zero moment angle and making it closer to the hovering pitch angle. On the other hand, lowering the anhedral generates more thrust and thus a lower collective pitch is required for hovering, consequently making the zero moment angle closer.

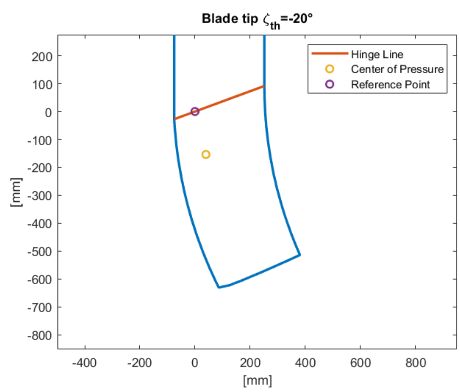


Figure 11: Tip center of pressure in $\zeta_{th} = -20°$ configuration

The tip moment variation was deeply studied thanks to the tip center of pressure analysis. With negative hinge line angles, the center of pressure moves away, therefore increasing the moment arm.

5. Conclusions

The results show that, in order for the tip to experiment an anhderal reduction moment, the collective pitch angle has to be smaller than a certain threshold, which is lower than the design collective pitch required for hovering. Therefore, the study concludes that it is not possible to directly achieve an anhderal reduction during hovering flight. However, according to the previous multi-body study, the pitch threshold is reached and passed during forward flight. This opens the possibility to operate the reconfiguration mechanism and thus gives a positive response to the idea of a passive actuation system.
The two best options for the blade configuration described in the results have to be further investigated, as the required power prediction given by inviscid CFD is lacking in preciseness.
Further developments of this study could focus on a viscid RANS model simulation and on the actual design of the reconfigurable mechanism for the tip.

References

[1] C. Tung F. X. Caradonna. *Experimental and Analytical Studies of a Model Helicopter Rotor in Hover*. NASA.

[2] A. Brocklehurst G. Barakos. A review of helicopter rotor blades tips shapes. *Progress in aerospace sciences*, 2013.

[3] J. Surra. Preliminary investigation over a reconfigurable blade tip for rotors. Master's thesis, Politecnico di Milano, 2019.