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EXECUTIVE SUMMARY OF THE THESIS

Potential modelling of tubercled wings

LAUREA MAGISTRALE IN AERONAUTICAL ENGINEERING - INGEGNERIA AERONAUTICA

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1. Introduction

Tubercled wings are a field of interest in the development of urban mobility aircrafts and prevention of abrupt stall phenomena on rotor blades. Garrow *et al.* [4] assessed different geometries of UAM, with different rotor geometries and number of propellers. Smaller rotors provided the best compromise between performance, efficiency and safety, although leading to higher rotor loads. The tubercles provides a solution to this problem, ensuring rotor capability of working properly at high angles of incidence without encountering abrupt stall phenomena. Butt *et al.* ([2]) tested through CFD analysis, using RANS turbulence models, two, three and four blades geometries, with both clean leading edge and tubercled leading edge. For each geometry an increase in the propeller efficiency η_p is observed, with the increase in efficiency from the baseline solution becoming larger at higher advance ratios J. Colpitts *et al.* ([3]) analyzed the effect of tubercles introduction and its shape compared to baseline rotor blade. Different tubercles geometry are tested in comparison to the baseline geometry. An improvement of 9.5% in rotor Figure Of Merit is observed. Smaller and denser distribution of tubercles produces similar distribution of pressure of the wing compared to the baseline geometry, while having mayor benefit in drag reduction. Tubercles with sin shape performs better in improving FOM, reducing rotor CP (Coefficient of Power) while increasing its CT (Coefficient of Thrust). Tubercles following a power law improves the rotor CT while increasing at well the CP due to increased skin friction.

2. Thesis scope

The scope of this work will be the evaluation of a modified potential method to better estimate the effect of the aforementioned vortex structures. The dependency of the studies geometry on viscous phenomena should discourage from usage of panel methods, due to the inviscid nature of such numerical solution. CFD solutions are better suited for this work, being more capable of capturing the complexity of these flow structures. Panel methods, however, are far more used and suited for the initial design and evaluation of a wing geometry, due to their implementation easiness and fast computational times. The motivation of this work is to modify a classical virtual singularities panel method to predict the influence of leading edge tubercles not only from a geometrical point of view, but from a viscous one as well. The advantage of a potential method compared to F.V. (Finite Volume) methods can be summed up in:

- Reduced programming effort
- Reduced computational cost
- Accurate flow description for applications at high Reynolds numbers
- Good prediction of viscous flows with minor tweaks

3. Numerical modeling

The problem is modelled taking advantage of linearization of the Navier-Stokes equations. Introducing the hypothesis of inviscid, irrotational and incompressible flow the equations can be rewritten as follows:

$$\nabla^2 \vec{u} = \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} = 0 \tag{1}$$

The wing is modelled using a distribution of constant doublets and sources. The Green function, which describes the problem as a linear system where the doublets intensities are the unknown.

$$\begin{aligned}\Phi(x,y,z) = \\ &- \frac{1}{4\pi} \int_{body} \sigma \left(\frac{1}{r}\right) dS \\ &+ \frac{1}{4\pi} \int_{body+wake} \mu \boldsymbol{n} \cdot \nabla \left(\frac{1}{r}\right) dS \\ &+ \Phi_\infty \end{aligned} \tag{2}$$

where Φ is the potential in the point of interest, σ is the source intensity, μ is the doublet intensity and Φ_∞ is the free-stream potential. The potential of each panel can be computed from the geometrical dimensions of each panel. The influence coefficient of each panel is computed, and the matrices describing the influence coefficients of doublets and sources between each panel are computed. Being the sources intensities known from the free-flow conditions, the only unknowns are the doublets intensities of wake and body panels. The former are defined as function of the latter, and hence the problem can be solved, being only the body doublets the unknowns. To evaluate the influence of the tubercles on the overall wing performances, the vortices originating from the leading edge are implemented. Those are modelled as a free vortex line originating from the wing surface, which circulation is equal to the corresponding panel of origin.

$$\Gamma_{VORTEX} = \mu_{PANEL} \tag{3}$$

To avoid singularities a vortex core model is developed. The Vasistas vortex core model is used:

$$\bar{V}_\theta = \frac{\bar{r}}{(\bar{r}^{2n} + 1)^{1/n}} \tag{4}$$

Where $\bar{V}_\theta$ is the induced radial velocity, $\bar{r}$ is the vortex core radius, r is the distance from the vortex axis and n is a tuning parameter set at 2 from experimental evidence. To assess the frequency response of the wing in harmonic motion, the Theodorsen model is implemented to describe small oscillations of pitch and plunge motions. A thorough description can be found in the work of Brunton *et al.* ([1]).

4. Code validation

To validate the code a comparison with the 2D solution is made. The reference solution is computed through XFOIL.

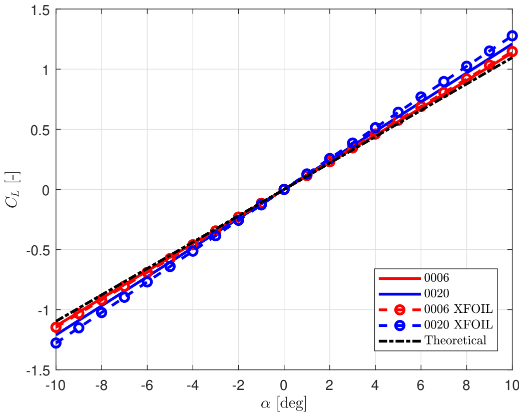

Figure 1: $C_L - \alpha$, $\lambda = 1000$ wings

For a semi-infinite wing, the solution is close to the 2D one as expected, with minor reduction due a residual wingtip influence. All the computed lift values are larger compared to the thin airfoil theory result, which does not take into account the influence of the airfoil thickness. In Figure 2 the frequency response to an harmonic pitching motion is represented. The developed numerical solution produces an increased lift generation as the reduced frequency increases, while the phase lag is unchanged through the frequency sweep. For lower reduced frequencies, the amplitude is decreased compared to the Theodorsen solution, and the phase is subjected to a minor lag.

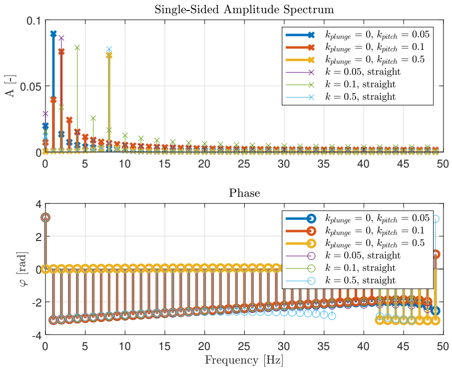

Figure 2: Frequency response at different reduced frequencies

5. Tubercles assessment

The reference case of study is taken from the experimental activity of Hansen *et al.* [5], which applied different tubercles geometry to a baseline NACA-0021 wing in order to assess the influence of tubercles number and amplitude.

$A/c[-]$	$\lambda/c[-]$	Label
0.06	0.21	A4λ15
0.06	0.43	A4λ30
0.06	0.86	A4λ60

Table 1: Geometries evaluated

The results are reported in Figures 3 and 4. Curves represented by circles are referring to the experimental data, while curves represented with crosses are referred to numerical data. As expected, when the experimental wings experience a reduction in produced lift due to the insurgence of stall, the developed model is not capable of replicating this effect. However, in the region $0 - 10°$, the model is fitting the experimental data. Compared to the test results the numerical model presents a more robust behaviour, with the curves having a more linear behaviour, albeit over predicting the actual lift coefficient. It's interesting to notice the abrupt stall of the $A4\lambda60$ configuration, which can be explained by the small amplitude variation between peaks and troughs. This makes the tubercle effect negligible, or even detrimental.

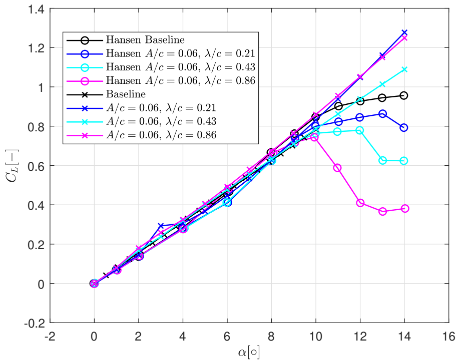

Figure 3: Caption

Looking at the curves at $\alpha = 5°$, the baseline and $A4\lambda60$ are more represented by the numerical model. The other geometries lift capabilities are over-predicted by the numerical model. It's interesting to notice that for the experimental results the difference in the generated lift is negligible between $A4\lambda15$ and $A4\lambda30$. For the $A4\lambda15$ the numerical model is closer to the experimental data.

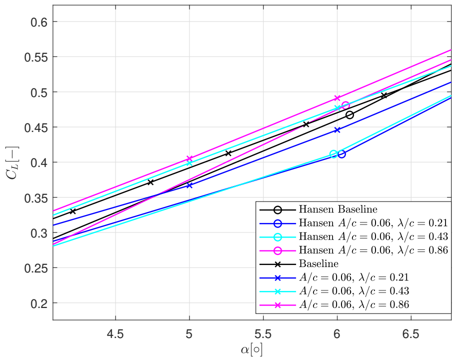

Figure 4: Caption

When considering the polar at $\alpha = 10°$, the solution delta between the considered geometries is reduced, with all C_L values fitting in the range of $0.7 - 0.8$, as happening with the experimental data. The over-prediction of the numerical model is reduced with reference to the experimental solution. This could be explained by confirming the hypothesis of a separation bubble, which produces a non-linearity in the lift production. The overall comparison is deemed satisfactory, being the lift values consistent with the experimental results. The minor differences can be attributed to the viscous phenomenology happening in the experimental case. This is particularly evident when the wing is working at high angles of incidence, where important separations start to occur. However, when considering small amplitudes, the results can be described as coherent with the experimental evidence, hence the modelling base can be considered as a good estimation method for the potential modelling of tubercled wings.

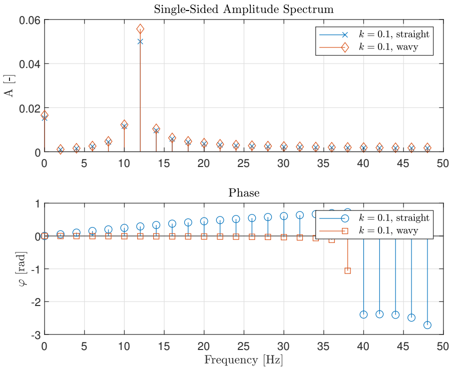

Figure 5: Caption

The maximum lift production is increased. The phase lag between the baseline geometry and the tubercled geometry is negligible, both for the C_L and the C_M. When looking at Figure 5, the amplitude increase becomes more evident, with the maximum C_L increase occurring at $f = 12\ Hz$. The phase lag is increasing with the frequency for the base case, only to see a sudden drop at higher frequencies. For the tubercled geometry, the phase lag is constant for a wide frequency spectrum, and has a decrease when reaching frequencies above 30 Hz.

	k	$A_{wavy}/A_{straight}$ [-]	$\Delta\varphi[\circ]$
C_L	0.1	1.1146	1.5857
C_M	0.1	1.1516	1.4490

Table 2: Waves amplitude and phase Δs, pitch, $\alpha = 5°$

6. Conclusions

The introduction of tubercles and leading edge vortices provided the expected results. A decrease in C_L at low angles of incidence was observed, in accordance with literature. This can be attributed to the nonuniform shape of the leading edge, which resulted in cross flow phenomena across the wing surface, decreasing the overall suction and as such reducing the overall lift.

The modelling of the free vortices enabled the induction of surface spanwise and normal velocities, that coupled with the pressure distribution granted by the presence of peaks and troughs produces the increases in peak pressure.

The wing performance followed what was observed in precedent studies. A reduction in the tubercle amplitude and wavelength results in a pressure distribution and produced lift converging with the unmodified geometry. The results obtained shown the effect of the modelled tubercles and leading edge vortices, being the number of vortices a direct influence on the lift production. When the wing is subjected to a pitching harmonic motion, the maximum lift produced is increased, due to the effect of the induced velocity on the wing surface. The increase of 11% in lift production is accompanied by a slight phase lag.

References

[1] Steven L. Brunton and Clarence W. Rowley. Empirical state-space representations for theodorsen's lift model, Apr 2013.

[2] Fahad Rafi Butt and Tariq Talha. Numerical investigation of the effect of leading-edge tubercles on propeller performance. *Journal of Aircraft*, 56(3):1014–1028, May 2019.

[3] Robert R. Colpitts, Ruben E. Perez, and Peter W. Jansen. Effect of leading-edge tubercles on rotor blades. In *AIAA AVIATION 2020 FORUM*. American Institute of Aeronautics and Astronautics, June 2020.

[4] Laurie A. Garrow, Brian J. German, and Caroline E. Leonard. Urban air mobility: A comprehensive review and comparative analysis with autonomous and electric ground transportation for informing future research. *Transportation Research Part C: Emerging Technologies*, 132:103377, November 2021.

[5] Kristy Hansen, Richard Kelso, and Bassam Dally. An investigation of three-dimensional effects on the performance of tubercles at low reynolds numbers. 12 2010.