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Evaluation of Potential Flow Capabilities for Ground Effect Predictions of a Single Propeller

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***Abstract*—The present work aims to investigate the capabilities of a potential flow approach to predict the ground effect of a single double-blade propeller. Proper models of propeller working close to solid surfaces, e.g. multi-rotor drones or helicopter tail rotors, can be useful for control end manoeuvrability studies. A low-fidelity approach can be suitable for preliminary design stages where the responsiveness is more important than very accurate estimations. The panel code VSPAERO is developed by NASA and implemented in the desktop application OpenVSP where it is possible to model several geometries. Firstly, using the propeller outside the ground effect, a mesh sensitivity is documented comparing results with respect to wind tunnel tests. Secondly, the ground is modelled in OpenVSP using geometries available in the software. The numerical results are compared to theoretical ones in order to highlight the prediction capability of the proposed approach when the propeller works in ground effect. Moreover, a flow analysis is performed in order to highlight the limitations of the proposed approach to simulate a propeller in ground effect.**

***Index Terms*—component, formatting, style, styling, insert**

I. INTRODUCTION

Interaction between the propeller wake and solid surfaces is crucial to evaluate the propeller performance in ground effect or to evaluate the aerodynamic forces and moments generated by the aircraft parts.

For drone applications, the ground effect affects take off and landing but also when flying close to the ground. Modelling the ground effect can be useful for performance evaluation and handling qualities close to ground [1]. The efficiency of controller design can be adapted to the ground model [2]. Although some theoretical and semi-empirical models exist, the ground effect is highly affected by several factors that would require dedicated experiments to be modelled on the selected aircraft. In fact, with multi copters, several propeller wakes interact with each other in addition to the interaction with the ground and other drone parts. Modelling with adequate accuracy such a phenomena can be challenging and flight test campaigns are often required [3]–[5].

Another example is given by the helicopter tail rotor that is usually installed on the vertical tail. The vertical tail has an important role in helicopter stability, whereas the tail rotor is crucial to guarantee the equilibrium and controllability [6]. On the other side, the vertical tail, interacting with the tail propeller's wake, produces a drag force in the opposite direction of the thrust delivered by the tail propeller. At the same time, a propeller close to a surface works in ground effect (IGE) and the propeller efficiency will be increased: it would deliver a larger thrust (e.g. $+25\,\%$ in hovering) with same power [6]. Working in ground effect is beneficial for the work load on the pilot's pedals especially when flying across the hovering conditions when the dynamic pressure is negligible to produce significant aerodynamic forces on the vertical fin. Trade-off between the vertical fin surface (that has impacts on the helicopter stability) and the thrust produced by the tail rotor (that has impacts on the pilot's work load) can be tricky. Interactions between the main rotor wake and the helicopter fuselage and tail boom is also investigated in [7].

Moreover, another important aspect to be considered is that the most of ground effect problems involves propellers that work around the hovering conditions. From a numerical standpoint, computational aerodynamic simulations can be challenging dealing with a fluid at rest.

The use of mid-fidelity codes can help the optimisation problems of propeller working close to aircraft parts or in the presence of other propellers. The trade-off between the computational costs and the achievable accuracy is fundamental to adopt a mid-fidelity code within the design process.

In fact, the present work aims to investigate the capability of a panel method developed by the NASA and implemented in VSPAERO [8] to predict the in ground performance of the propeller. The propeller is modelled using rotating blades.

The free propeller predictions, out of ground effect (OGE), are compared with experimental data. The same propeller is simulated in ground effect (IGE) with VSPAERO and results are compared with a theoretical trend [9].

The geometry for each configuration was created with OpenVSP [10]. All surfaces are modelled with the panel method in order to simulate the presence of a bluff body.

II. PROPELLER IN GROUND EFFECT

According to the momentum theory [6], the power required, Π, by a free propeller that delivers a given thrust, T_∞, can written as

$$\Pi = \frac{T_\infty V_\infty}{2} \left(\sqrt{1 + \frac{2T}{\rho_\infty A V_\infty^2}} + 1 \right) \tag{1}$$

where, V_∞ is the freestream airspeed, ρ_∞ is the freestream air density and A is the area of the propeller disk. In the case of quasi-hovering regime where the $V_\infty \simeq 0$, the formula can be written as

$$\Pi = \frac{T^{3/2}}{\sqrt{2\rho_\infty A}} \tag{2}$$

The matter of propeller in ground effect was firstly studied in 1937 [11] for helicopters. Performance of propeller IGE are usually presented in terms of normalised power, P_{IGE}/P_{OGE}, or in terms of normalised thrust, T_{IGE}/T_{OGE}. As the present work deals with inviscid predictions in hovering conditions, the normalised thrust is considered. Some experimental results are available in [12].

The theory proposed in [11] is based on the method of images. The rotor is replaced by a sink and the ground by an image sink of equal strength placed below the rotor at a distance equal to twice the height of the rotor. The theory was split for small distance ($z/D < 0.25$) and large distance ($z/D > 0.25$) compared to the propeller diameter.

In [9], theory proposed in [11] was proven to be in direct opposition to experimental evidence for $z/D > 0.25$ and, hence, the rotor image was replaced with a source rather than a sink. The theoretical model proposed by [9] leads to the following IGE to OGE thrust ratio in hovering

$$\frac{T}{T_\infty} = \frac{1}{1 - \left(\frac{D}{8z}\right)^2} \tag{3}$$

where, z is the vertical distance of the propeller from the ground. It can be noted that when $z = D$, $T \simeq 1.02 T_\infty$ and the ground effect can be neglected, and the propoller essentially works OGE.

Flight tests were conducted in [13]–[15] for helicopters and semi-empirical formulas were proposed in [16] with the following regression:

$$\frac{T_{IGE}}{T_{OGE}} = \frac{\frac{z}{D}}{a\frac{z}{D} + b} \tag{4}$$

where, a and b are two semi-empirical constants based on the propeller solidity [6] and tabulated according to the blade pitch (or power setting).

From [13] (Sikorsky S-60, $22\,\mathrm{m}$ rotor, four blades) and [16] (Bell-47 J-2, $11.3\,\mathrm{m}$ rotor, two blades), high and low solidity IGE to OGE thrust ratio are measured experimentally. Considering Eq. (4), the regression are performed with the fitting tool of Matlab [17] and plotted in Fig. 3.

The effect of the pitch on the ground effect is investigated in [14]. On the other side, it is shown experimentally that the RPM can affect the ground effect [18] only if $z/D > 0.5$.

According to the state-of-the-art, the ground effect is at least influenced by the propeller pitch and solidity and RPM.

The ground effect study on propeller performance can be challenging also considering that in ground-effect the effective angle of attack would increase [6], anticipating the tendency towards the stall. However in extreme ground effect, detailed flow visualization are helpful to clarify the matter [19], [20], such as the particle image velocimetry [21], [22]. An analysis of propeller wake in ground effect and a massive review of experimental results are presented in [23]. In [24] a ground model was proposed based on the following expression

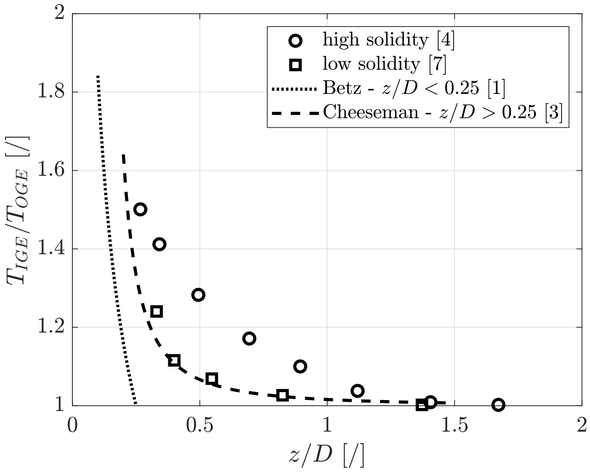


Fig. 1: Experimental data on IGE to OGE thrust ratio as function of z/D

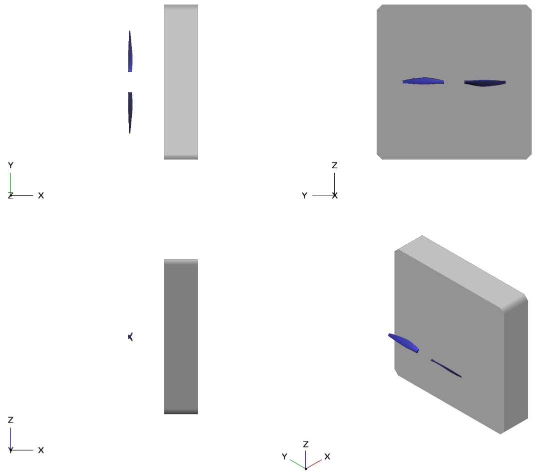


Fig. 2: View of the OGE propeller's model in OpenVSP. The view is referred to a ground area of $1.5D.5D$ and a vertical distance of $x = 1\,\mathrm{m}$ ($x/D = 0.333$)

$$\frac{T_{IGE}}{T_{OGE}} = 1 - \rho_G \left(\frac{D}{8x}\right)^2 \tag{5}$$

where ρ_G is a parameter estimated from experimental data. For the identification of ρ_G hovering test at different altitudes were performed.

For the scope of the present work a low solidity propeller is chosen as in [25], [26]. OGE mesh setup results are compared with [25] and IGE results are compared with the theory from [9].

III. VSPAERO

OpenVSP [10] is an open source tool developed by NASA based on the parametric solver OpenVSP [8]. VSPAERO version 3.31.1 is used for the present work. VSPAERO analyses are performed using the geometries modelled with OpenVSP using the panel method. A vortex lattice method (VLM) is also available but it is not suitable to simulate the ground effect.

The panel method is a numerical scheme for solving linear, inviscid, irrotational flow around single or multiple bodies in subsonic or supersonic regime. Source, doublet, and vorticity singularities are some of the fundamental analytic solutions to the numerical scheme. The panel method is based on the principle of placing the latter singularities on the body surface discretised using small portions (panels) [27]. Therefore, around the bodies, there is no mesh volume as for CFD analysis.

IV. OGE MESH SENSITIVITY

As far as the panel method is concerned, where n_W specifies the number of nodes in chordwise direction, and hence, the number of panels in chordwise direction is $n_{p,c} = n_W - 1$ distributed on the top and bottom side of the airfoil. The parameter n_U specifies the number of nodes in radial direction, the number of panels in radial direction is $n_{p,r} = n_U - 1$. The total number of panels for a single propeller is $n_p = (n_W - 1)(n_U - 1)$. A medium aspect ratio parameter χ can be introduced to highlight the mean shape of the propeller panels. Considering a mean chord of the blade, e.g. the $\bar{(}c)/R = c(0.75R)/R = 0.12R$. The top side of the propeller's airfoil is discretised with $n_{p,c}/2$ panels. Therefore, the reference panel of the blade has a mean chordwise length equals to $l_c = \bar{(}c)/(n_{p,c}/2)$, a mean radial length $l_r = R/n_{p,r}$. The parameter mean aspect ratio is $\chi = l_r/l_c$. It is clear that the χ parameter should be around the unity. All mesh sensitivity analysis are performed considering a single advance ratio $J = 0.787$ and results are compared in terms of the thrust coefficient.

The mesh configurations that are used to simulate the OGE propeller are collected TABLE I where a single discretisation parameter is fixed and the other is changed. The objective of the mesh sensitivity is to find a surface discretisation to predict the C_T coefficient within minimum uncertainty with respect to the wind tunnel data. Results of TABLE I are plotted in Fig. 1 and referred to the advance ratio $J = 0.787$.

It can be seen from Fig. 1 that the OGE C_T is not influenced by the aspect ratio χ for U variations (panel length in the radial direction), whereas the it is affected significantly by the aspect ratio χ for W variations (panel length in chordwise direction). It can be concluded that for the radial direction, the discretisation parameter U does not play an important role even though mesh convergence is achieved in the range $\chi = [4, 7]$. On the other side, the discretisation parameter W plays an important role and mesh convergence is only achieved for $\chi \geq 8$.

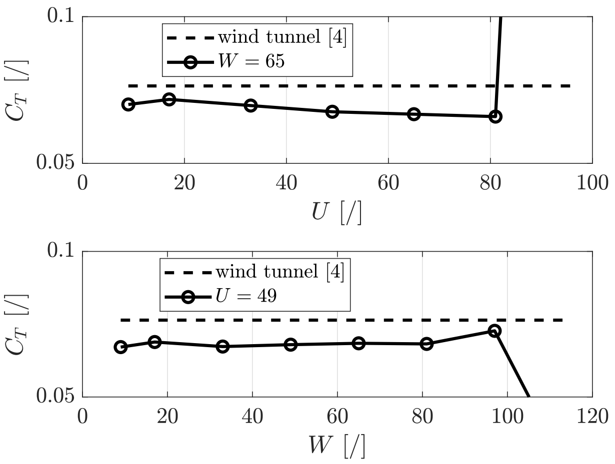


Fig. 3: Mesh sensitivity for the OGE propeller

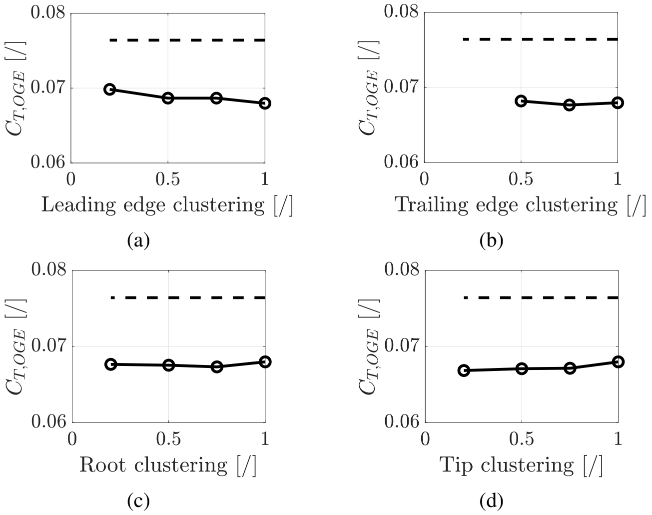
TABLE I: OGE thrust coefficient calculated adopting several discretisations for a given advance ratio $J = 0.787$. The expected value from wind tunnel tests is $C_{T,WT} = 0.0764$

n_U	n_W	C_T	χ
49	9	0.06714	0.694
49	17	0.06888	1.39
49	33	0.06732	2.78
49	49	0.06797	4.17
49	65	0.06844	5.56
49	81	0.06823	6.94
49	97	0.07272	8.33
49	113	0.0278	9.72
9	65	0.07008	33.3
17	65	0.07181	16.7
33	65	0.06971	8.33
49	65	0.0676	5.56
65	65	0.06677	4.17
81	65	0.06595	3.33
97	65	0.600	2.78

Increasing the n_U parameter would reduce the thrust coefficient estimation. Moreover, for $n_U > 81$ (i.e., $\chi > 6.94$) some numerical issues arise and the estimated $C_{T,OGE} = 0.6$ is not physical. On the other side, increasing the n_W parameter can be beneficial even though between 33 and 81 a plateau can be observed , whereas beyond $n_W = 81$ some numerical issues arise and the values becomes very small ($C_{T,OGE} = 0.0278$). For the latter considerations (from analysis of data of TABLE I) the n_W converges to 49 as well as the n_U converges to 49. The discretisation $n_U \times n_W = 49 \times 49$ is, therefore, used in the present work.

A. *Clustering effect*

Other parameters affecting the surface mesh, is the clustering, both in chordwise - CC and radialwise directions - RC. In OpenVSP, the clustering is the parameter to control the surface mesh refinement: the lower is the clustering, the finer is the surface mesh in that area. The effect of mesh refinement is analysed considering to change the clustering from 1 to 0.2 for



(a) (b) (c) (d)

Fig. 4: Effect of clustering the propeller's leading edge trailing edge, root or tip.

the propeller's leading edge, trailing edge, root and tip. Results are presented in Fig. 4. The thrust coefficient estimation is not significantly affected by increasing the mesh ratio for the propeller's root and the tip as can be seen from Fig. 4c-4d. The same conclusion can be derived for the trailing edge clustering and noticing that below 0.5 some numerical issues arise that do not allow to obtain physical values. Improving the mesh ratio around the leading edge is beneficial even though below 0.2 some numerical issues arise. Considering the clustering effect on the OGE thrust estimation, the uniform surface discretisation is maintained.

V. IGE MESH SENSITIVITY OF THE GROUND MODEL

The IGE thrust calculations are carried out considering a null freestream velocity in order to simulate a perfect hovering condition (neither horizontal nor climb velocity).

The IGE propeller is modelled using the "box" element that can be simulated adopting the panel method. In this work the ground is modelled with a volume of squared base and constant height of $1\,\mathrm{m}$. Selection of the proper side dimension, l_{gb}, is the objective is documented in this section. A view of the model is represented in Fig. 2 where the base side is $1.5D$ and the propeller is placed at $x = 1\,\mathrm{m}$ ($z/D = 0.333$) as vertical distance from the ground. The latter ground distance is used to analyse the effect of the ground area (or l_{gb}) on the thrust IGE predictions. According to Eq.(3), the expected value of IGE to OGE thrust ratio is $\frac{T_{IGE}}{T_{OGE}} = 1.17$. Results are presented in Fig. 5 where it can be observed that for a ground area whose side is between $l_{gb}/D = 2.5$ and $l_{gb}/D = 3$ the thrust estimation is not affected by the ground model. It can also be observed that reducing the ground area could lead errors $< 10\%$ but highly sensitive to the ground area size. On the other side, adopting a very large ground area, with $l_{gb}/D > 3$, can lead to large numerical errors. The tendency presented in Fig. 5 still remains if the mesh of the ground is refined. For the present work, the area with $l_{gb}/D = 2.75$ is selected to perform the IGE to OGE thrust ratio.

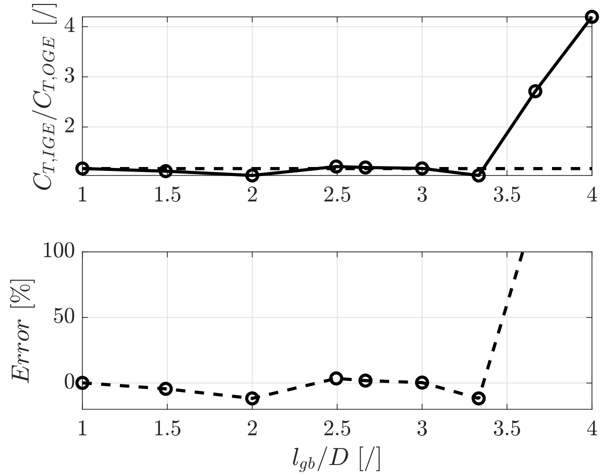


Fig. 5: Ground size influence on the prediction of the IGE to OGE thrust ratio

In Fig. 6 convergnece histories are reported for several z/D distances. When the propeller is very close to the ground ($z/D < 0.4$) the numerical solution does not reach a steady state value. The standard deviation is presented in Fig. 7.

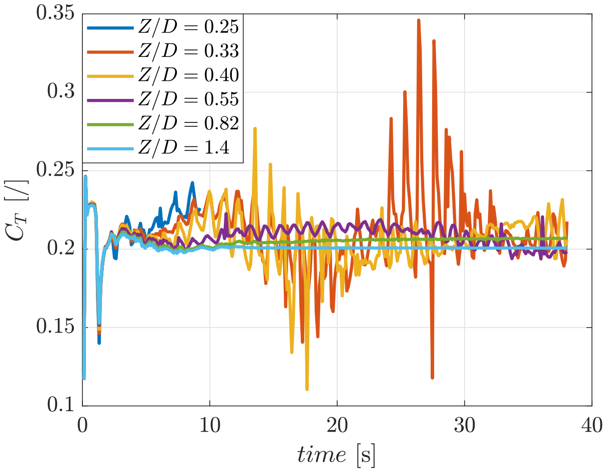


Fig. 6: Convergence history over 16 revolutions

VI. FLOW ANALYSIS

The potential flow analysis is presented in Fig. 7 considering the propeller wake whose shape is free to develop and the pressure coefficient is defined as

$$C_p = \frac{P - P_\infty}{0.5\rho_\infty V_\infty} \tag{6}$$

As the simulations proposed are in hovering condition (i.e., $V_\infty = 0\,\mathrm{m\,s^{-1}}$), a reference velocity $V_\infty = 3\,\mathrm{m\,s^{-1}}$ is assumed to present the C_p. The slipstream color of Fig. 8

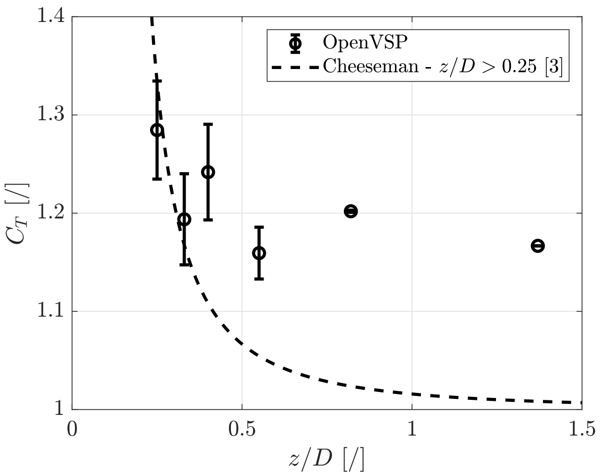


Fig. 7: Thrust prediction in ground effect using VSPAERO. Circles and bars represent the mean values the bars represent and the standard deviation respectively over the last two revolutions

does not represent the C_p. The propeller wake is affected by the presence of the solid surface as expected as shown in Fig. 8. However, after the propeller wake impacts the surface, some numerical issues arise causing large oscillations as shown in Fig. 7. The observed phenomena is more evident for $z/D < 0.5$ limiting the minimum distance between the propeller and the ground or the simulation time. The latter phenomena must be further investigated to understand if some phenomena, such as the vortex pairing [20], can be captured using VSPAERO and the proposed setup. As final observation, it can be noticed that the surface's $C_p \simeq 0$ until the propeller wake reaches the ground.

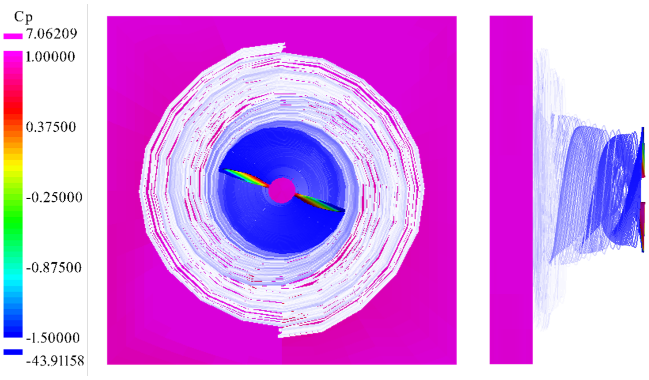


Fig. 8: Front and side views of the propeller wake in ground effect for $z/D = 0.82$ after 8 revolutions

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VII. CONCLUSION

A potential aerodynamic analysis can be useful to setup reliable aerodynamic model or to predict thrust of propellers in ground effect. In the present work, a panel code implemented in OpenVSP, developed by NASA, is adopted to model the problem of a propeller in ground effect. The ground is simulated with a box element. Due to the intrinsic nature of the panel method, the proposed model is not reliable after the propeller wake impinges on the ground, e.g. to simulate vortex pairing. The setup of the panel code is documented, and OGE and IGE results are presented. As far as $z/D > 0.33$ is concerned, even though the convergence is affected by the interaction of the propeller wake and the one coming back from the ground, the IGE is well predicted. On the other side, for $z/D > 0.82$ the wake interaction is less important but the overall IGE thrust coefficient is overestimated. To conclude, VSPAERO can be adopted for preliminary predictions of the thrust in ground effect accurately (absolute error $< 10\%$) for $z/D <= 0.5$, whereas larger errors ($> 15\%$) are observed for $z/D > 0.5$.

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