Aerodynamic effects in multirotors flying close to obstacles: modelling and mapping

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Abstract. This paper aims to model the aerodynamic effects in the flight of aerial robots close to obstacles in the oil and gas industries. These models are presented in the form of an aerodynamic effects map which represents the changes in the thrust when an aerial vehicle flies very close to different obstacles. Although there are works related to the fly close to different obstacles in the literature, some of the effects needed to develop the aerodynamic map have not been previously studied and tested experimentally in a test stand. The paper also considers the case where the rotor is affected by more than one obstacle.

Keywords: Aerodynamic Effects, UAS for inspection.

1 Introduction

The application range of unmanned aerial vehicles (UAV) has growing quickly in the last decade [1]. Although in most of these applications the UAV accomplish perceptive tasks such as exploration, monitoring or surveillance among others, there are some of them that directly involve interaction between the UAV and the environment and which are mainly carried out by aerial manipulators [2][3][4]. These are a new concept of UAV with an integrated robotic manipulator which are used in tasks as contact inspection and sensor installation in inspection and maintenance (I&M) of infrastructures or industrial plants [5][6].

These I&M tasks usually require that the aerial platform flies very close to different obstacles, for instance, the AEROARMS [7] and HYFLIERS [8] project are focused on aerial manipulation for outdoors applications in I&M in oil and gas plants or the RESIST [9] project which is about the I&M of large civil infrastructures as bridges or tunnels using UAV. Both cases imply that the aerial platforms need to fly in the proximity or even maintain a contact with a building to carry out the I&M operations. Moreover, they need to do it without lacking accuracy or safety conditions during the operation. However, these kind of situations, which involve an UAV flying close to different structures, surfaces, or obstacles in general, changes the flow field surrounding the vehicle leading to changes in the force and torque developed by the rotors which can significantly change the performance of the aerial platform [10] decreasing the accuracy during the inspection operation.

These aerodynamic effects have been previously studied [11][12][13][14] and also by the authors. In [15] a general overview of these kinds of effects was presented and some of them were specifically studied for different applications like the ground effect in [16] or ceiling effect in [6][17]. These previous studies have shown that it is usually necessary to model this aerodynamic behaviour to guarantee that the final application produces a results which are good enough even flying very close to obstacles.

Thus, this paper is focused on the next step, which is an aerodynamic characterization of the environment and its aerodynamic effect. So, the main contribution is to present and develop a method which allows the generation of an aerodynamic effects map in an environment with multiple obstacles. These maps will be the base for future works in term of studying control solutions or planning methods in complex environments with multiple obstacles.

This paper is structured as follows: Section 2 introduces the problem analyzed in the paper and presents a brief compilation of the previous results. Section 3 is focused on the experimental modelling of the aerodynamic effects which has not been previously studied and can arise in the typical scenarios of the aerial manipulation. Section 4 introduces the assumptions that have been taken into consideration as well as the mapping results of a sample scenario. Last, Section 5 is about the conclusion and the future works in which the results of this paper can be exploited.

2 Previous Results

This section analyzes the problem of flying close to different obstacles presenting how these effects are included in the dynamic model of a multirotor. Moreover, the previous results related to the aerodynamic effects close to obstacles are presented and novel results in the typical scenarios of I&M applications.

2.1 Dynamic model with aerodynamic effects

The dynamic equations of a multirotor are known in the bibliography as follow:

$$M(\xi)\ddot{\xi} + C(\xi,\dot{\xi})\dot{\xi} + G(\xi) = F + F_{ext}$$

Where ξ is the state vector $\xi = [x\ y\ z\ \phi\ \theta\ \psi]'$, M is the generalized inertia matrix, C is the Coriolis and centrifugal terms, G represents the gravity component, F is the generalized vector force developed by the rotors and F_{ext} are the external and unknown forces. However, in case of flying under the influence of an aerodynamic effect, the generalized vector force changes because the forces change due to the relative position between the multirotor and the different obstacles of the environment, so the generalized vector forces is a function of the state of the multirotor, $F = F(\xi)$, such as it has been previously presented in other authors' papers [12]. Thus, the dynamic model is rewritten as:

$$M(\xi)\ddot{\xi} + C(\xi,\dot{\xi}) + G(\xi) = F(\xi) + F_{ext}$$

This is the reason that justifies the need of model how the aerodynamic effect changes depending on the position of aerial platform in a scenario and specifically with the relative position respect to an obstacle.

2.2 Previous aerodynamic effect results

Fig. 1 shows the most common results of the different aerodynamic effects which have been previously studied by the authors and the literature in general. These experimental results show how the thrust of a rotor changes working close to a ground, a ceiling or a wall surfaces. In the figure, T_{IGE}/T_{OGE} is the relation between the thrust "In Ground Effect" and "Out Ground Effect", T_{ICE}/T_{OCE} is the same but in term of ceiling effect and last, T_{IWE}/T_{OWE} aims to model the changes that appears in wall effect. On the other hand, z/R is the distance from the rotor to the obstacle dimensionless with the rotor radius.
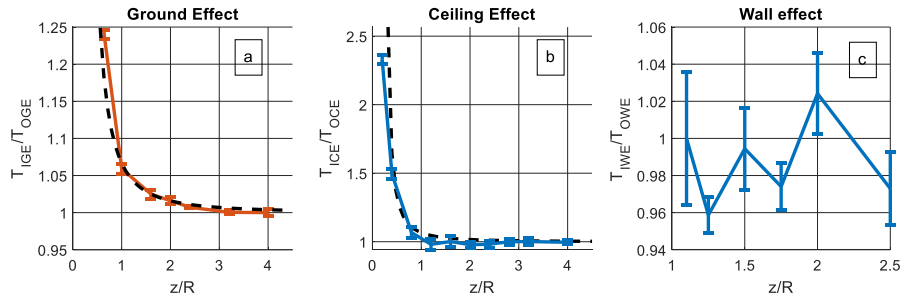

Fig. 1. Previous results in aerodynamic effect in different situations: a) Ground effect; b) Ceiling effect; c) Wall effect.

Ground Effect.

The ground effect, which is presented in **Fig. 1**.a, is the most known aerodynamic effect and it is also the widest studied in the literature. This effect arises when an aerial platform flies over a flat surface which acts as a ground. In the aerial robots, the ground effect not only appears in the take-off and landing maneuver, but also when the aerial platform need to fly over a surface, for example, during an inspection or manipulation task.

Ceiling effect.

The ceiling effect, which is shown in **Fig. 1**.b, appears when an aerial platform flies under a surface but very close to it. The results of the **Fig. 1**.b, show that the behaviour of the ceiling effect is very abrupt and unlike that the ground effect which pushes the vehicle away from the obstacle, the ceiling effect pull it toward the obstacle leading to an unsafe flight condition if it is not taken into account.

Wall effect.

Last, the experimental results of the **Fig. 1**.c shows that the wall effect can be considered negligible following the assumption of the helicopters theory which assumes that the flow is perpendicular to the rotor plane.

Paper contribution.

Although these previous results could be a starting point to model the aerodynamic effects flying close to obstacles, this paper goes beyond trying to model not only the aerodynamic effect over or under an obstacle, but also how this effect starts to be significant as a rotor approaches them.

Moreover, due to this paper is focusing on an I&M of an oil and gas industry this paper also models the behaviour of rotors working close to tubular obstacles like pipes.

Next section presents the methodology followed by the experimental results of the different cases of study of this research.

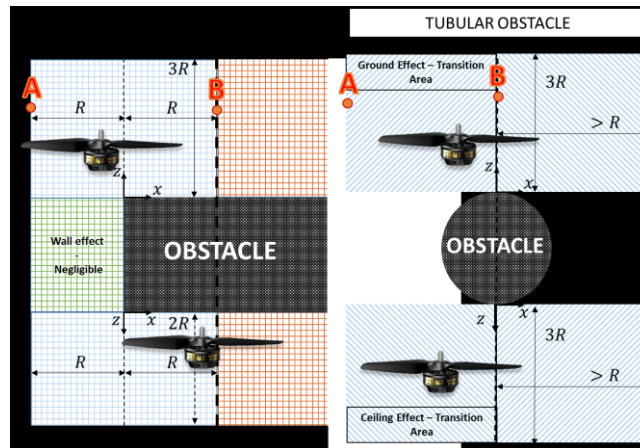## 3   Experimental Modelling

Fig. 2. Test configuration and nomenclature

Due to the typical scenario in an oil and gas inspection application includes two different obstacles, which are flat surfaces like grounds or ceilings and tubular obstacles like pipes, these will be the one taken into consideration on this work. Moreover, in contrast to the classical studies that only model the aerodynamic effect like a rotor working under or over an obstacle, this paper also models the transition part when the rotor approaches the obstacle from the rotor it is out of the effect till it is fully affected by it. These results will be obtained through several experiments in a test stand which is able to measure the thrust of the rotor. In the rectangular obstacle, the area in which the different experiments are carried out are represented in the blue areas in **Fig. 2**. This area starts when the center of the rotor placed at one radius of distance in the x axis of

the **Fig. 2** and the propeller is completely out of the obstacle (point A) and finish when the propeller is full placed over the obstacle (point B). The experiments in the tubular obstacles are also accomplished in the blue areas taking into account the symmetry conditions of the problem.

Experimental procedure.

In order to grant that the results can be compared between them, it has been necessary to define an experimental procedure common to all the experiments. In this research, a test bench with a load cell connected to an Arduino Mega 2560 which maintain a serial communication with a computer running MATLAB. In this PC, there is a graphic user interface (GUI) in which it is possible to define the experimental setup. **Fig. 3** shows the program developed to unify the experimental conditions and the settings used during the experiments.
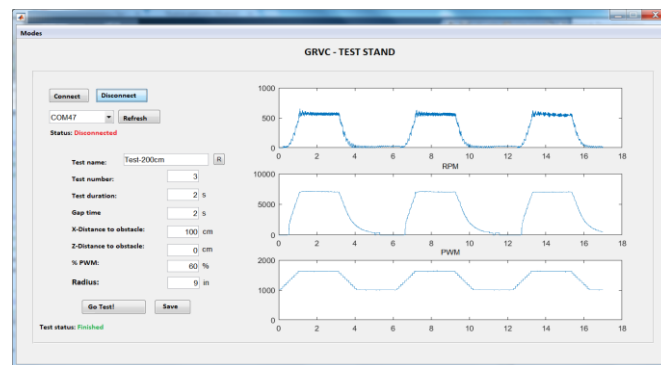

Fig. 3. Graphic user interface developed and used during the experiments.

Fig. 3 shows the GUI used to unify the experimental procedure, this system allows to select the most important variables of the experiment and show the results in the graphs placed on the right side. Some of the values which can be settable are the $\% PWM$ of the rotor, the number of iteration, the time in steady state and the gap between the different experiments.

3.1 Aerodynamic effects close to flat surfaces

Following the experimental procedure presented before, the ground and the ceiling effect has been studied taking into account the behaviour when the rotor approaches the obstacle. Due to the results of these aerodynamic effects have been previously studied in the literature and by the authors when the rotor is completely under the aerodynamic effect, it will be assumed that the effect follows the classical models because they have been validated previously. Thus, the theoretical model the ground effect presented in [18] and the experimental one of [19] for the ceiling effect will be used to create the aerodynamic effect map. The expression of both models are presented as follows:

$$\text{Ground Effect:} \quad \frac{T_{\{IGE\}}}{T_{\{OGE\}}} = \frac{1}{1-\frac{1}{16}\left(\frac{R}{z}\right)^2}$$

$$\text{Ceiling Effect:} \quad \frac{T_{\{ICE\}}}{T_{\{OCE\}}} = \frac{1}{1-\frac{1}{a_1}\left(\frac{R}{a_2+z}\right)^2}$$

Where the acronyms ICE, OCE, IGE and OGE are "in/out ceiling/ground effect" respectively. R is the radius of the rotor and z is the distance between the rotor plane to the obstacle as it is presented in the **Fig. 2**, in this case, we assume that the rotor is totally over the obstacle. The values of a_1 and a_2 were obtained through an experimental least square approach, in this case $a_1 = 6.924 \, m^{-1}$ and $a_2 = 0.03782 \, m$.

Last, the experimental results of **Fig. 3** show how the thrust changes when the rotor approaches the obstacle.

Fig. 4. Ground and ceiling effect with a flat surface - experimental results

The results of **Fig. 4** show the differences of the aerodynamic effect when a rotor approaches ground or ceiling obstacles. These results show that for the tested distances the ground effect is stronger than the ceiling which is in line with the previous results of the literature as it is presented in **Fig. 1** in the Section 2.2. This figure shows the evolution of the ground and the ceiling effect across the longitudinal coordinate but also combines it with the vertical one.

3.2 Aerodynamic effect close to pipes

The results of the aerodynamic effect which arises when a rotor is working very close to tubular objects like pipes are very relevant from the I&M of oil and gas industry point of view. In this case, it is assumed that the results will be symmetric due to the geometry of the problem, thus, the experiments will be tested with a rotor approaching the middle point of the tube as it is presented in **Fig. 2** and following the experimental procedure previously established the results are shown in **Fig. 5**
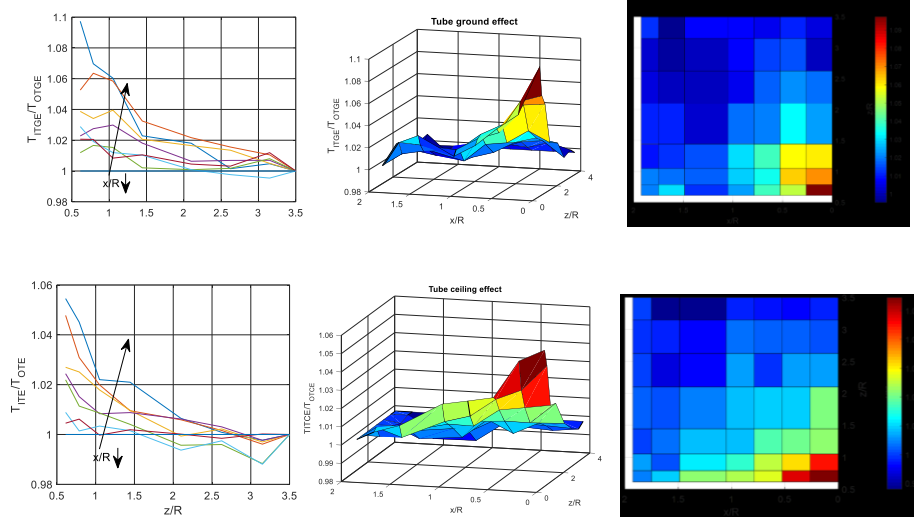
Fig. 5. Tube-ground and tube-ceiling effect - experimental results

Fig. 5 shows that the behaviour of the aerodynamic effect is the same respect to the obstacle, however, the magnitude is lower. This is the expected results because the wake of the rotor has more space and the changes in the flow field are lower. Nevertheless, during the experiments it was clear that the aerodynamic effect produced by a pipe not only depends on the relative position of the rotor respect to the pipe, but also depends on the relative size between them. A single test with two different configurations was accomplished and their results are shown in **Fig. 6** where it is possible to observe that if the rotor is very small respect to the pipe (blue line) the aerodynamic effect is more similar to the effect close to a flat surface and vice versa.
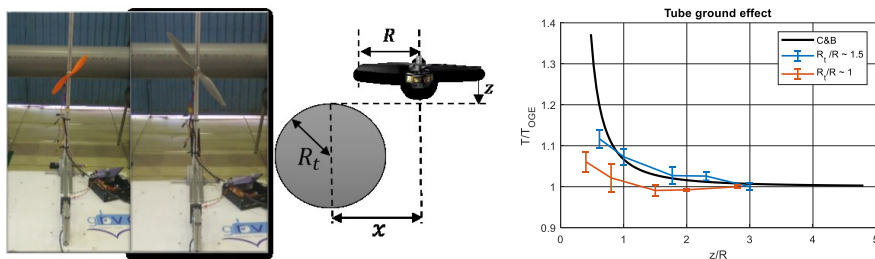

Fig. 6. Comparison with different relation between the pipe and rotor diameter

However, in this paper the aerodynamic map and the most of the test have assumed that the diameter of the rotor is 9 inches and the diameter of the pipe is 6 inches because it is the size of the most of tubes in an oil and gas industrial environment and it also was the recommendation of the industry end-users.

4 Mapping

Once the aerodynamic effects close to flat surfaces and tubes have been experimentally tested, the next step is to combine them in an aerodynamic map which could be used in a future to improve the control strategies or the planning methods taking into account this aerodynamic effect map.

4.1 Assumptions

This section is focused on defining the limits to the flying area and to establish the assumptions when the rotor is working close to different obstacles. These assumptions are established in term of defining the flyable area during the operation and how to solve the problem in the points which are under the influence of more than one obstacle.

Flyable area.
   Fig. 7 shows the flyable areas close to a flat/rectangular obstacle and a tubular one. This area establishes the limits of the map and envelope the operation area of the aerial platform.
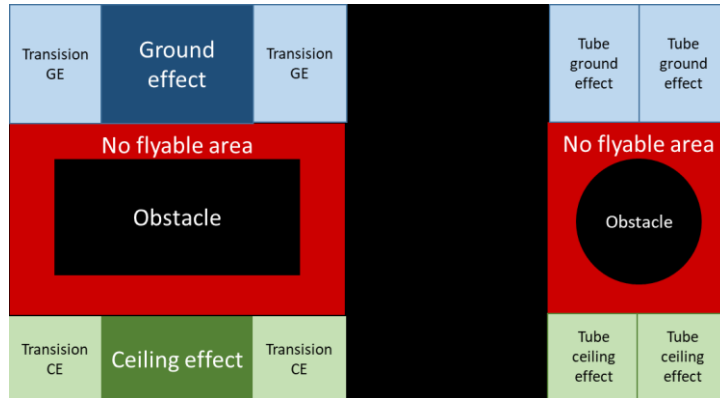

Fig. 7. Flyable area detail and forbidden zones.

The map around these obstacles will be model as it is shown in the **Fig. 8**.
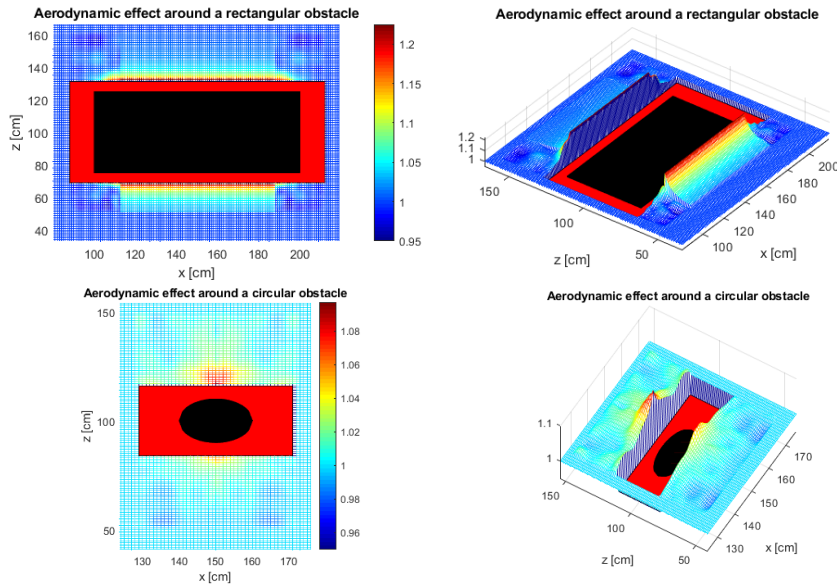
Fig. 8. Sample of aerodynamic effect close to a rectangular obstacle (left) and a pipe (right)

The flat surface where the value of the non-dimensional thrust is 0.95 is out of the flying area but it has been defined with this value to avoid infinite elements in the plot.

Obstacle overlapping.

The assumption to model the aerodynamic effect in the points of the map which are affected by more than one obstacle is that it is possible to apply the principle of super-position, however, it is assumed that the superposition method is no longer valid if one obstacle is in the shadow of another one. This is clearly explained in the **Fig. 9**, where the red area shows the influence area of the obstacle (a) and the blue area the influence of the obstacle (b). In the section in purple, it is where the principle of superposition is applicable and the grey zone is a shadow area and shows an area in which the aerodynamic effect of the obstacle (a) is considered blocked by the presence of the obstacle (b).
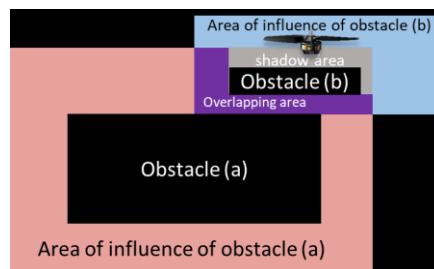

Fig. 9. Obstacle overlapping and shadows conditions

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4.2   Results

Last, this section presents the results of different aerodynamic maps in which it is represented the changes of the thrust due to the influence of the obstacles.

Fig. 10, **Fig. 11** and **Fig. 12** show the results in three different scenarios which can be used later to design different planning or control techniques.
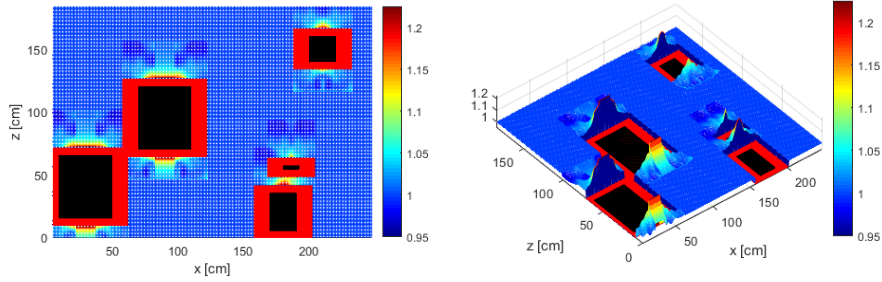

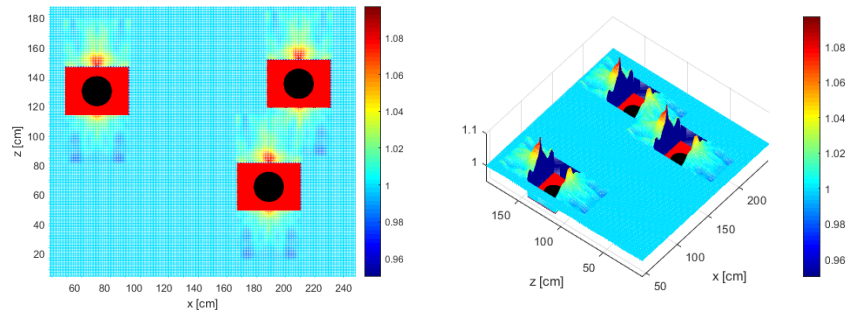
Fig. 10. Aerodynamic effect map with rectangular obstacles

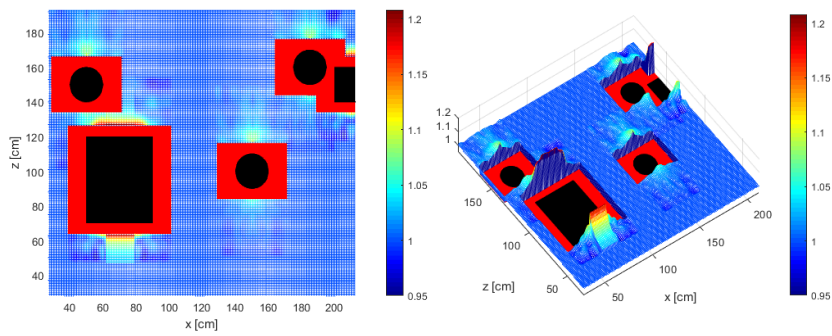**Fig. 11.** Aerodynamic effect map with tubular obstacles

Fig. 12. Aerodynamic effect map with rectangular and tubular obstacles

5 Conclusions and future applications

This paper has presented a new approach to the modelling of the aerodynamic effects that can arise during the operation of an UAV flying close to obstacles in oil and gas plants. This approach consists of creating an aerodynamic effects map which links the relative position of the vehicle with the aerodynamic effect that the environment produces in this point.

The different aerodynamic effects have been independently studied and the different assumptions about the areas under the influence of more than one obstacle are also presented.

Future work related to this research will be focused on the application of this map to design different control techniques or planning methods which take into account the aerodynamic effects on the aerial vehicle to improve its behavior or to optimize the use of resources like the power or time consumption during the operation. This kind of map has a direct application in the direction of the actual application of the UAV in the Inspection and Maintenance of oil and gas industries.

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