EXPERIMENTAL-NUMERICAL INVESTIGATION OF ROTOR-ROTOR AERODYNAMIC INTERACTIONS FOR eVTOL AIRCRAFT CONFIGURATIONS

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Abstract
The paper presents the description of a research activity aimed to the systematic study of the rotor-rotor aerodynamic interaction with application to the flight conditions typical of eVTOL aircraft. The activity considers a dual effort, experimental and numerical, to gather systematic parametric data on different types of rotor-rotor interactions. In particular, the paper describes the planning and set up of a wind tunnel campaign aimed to evaluate the effects of the aerodynamic interactions on the rotor performance and flow field for two propeller models both in side-by-side and tandem configuration. Moreover, the results of numerical simulations performed with a mid-fidelity aerodynamic code on both the planned test configurations are presented showing the main effects of the aerodynamic interactions on the performance of the propeller.

1 INTRODUCTION

In the recent years a great interest and development effort has been devoted to new designs of unconventional aircraft with the ultimate goal of creating a novel short-range personal concept of aviation as an effective alternative to ground transportation in overcrowded metropolitan areas. While the development of this new urban air mobility VTOL aircraft based on electric distributed propulsion was driven by the mature state of different technological areas such as electric motors and batteries [1], these new aircraft architectures pose unprecedented challenges to engineers in several different areas.

From an aerodynamic standpoint the design of these novel configurations introduces a series of challenges mainly due to interactional aerodynamics. The concurrence in a single vehicle of different aerodynamic elements typical of different classical configurations such as fixed lifting surfaces, lifting rotors, and thrusting propellers with in addition usually the change of configuration occurring between take off, cruise and landing, lead to multiple interactions of complex flows. These interactional effects characterize the flow around such eVTOLs and strongly influence loads, performance, handling qualities and noise.

The ability to understand and predict interactional aerodynamics effects is a vital tool to develop better, more efficient and quieter urban air mobility vehicles. For this reason the investigation of interactional aerodynamics for eVTOL aircraft configurations has become in the recent years a strategic research topic of the Department of Aerospace Science and Technology of Politecnico di Milano. In particular, a novel medium fidelity aerodynamic open-source software, called `DUST` [2], has been recently developed as the result of a collaboration between Politecnico di Milano and A^3 by Airbus LLC. The specific aim of `DUST` development was to obtain a fast, flexible, and accurate tool capable of performing aerodynamic simulations of complex aircraft configurations by providing a reliable and robust representation of interactional aerodynamic phenomena.

`DUST` [3, 4] is a flexible aerodynamics tool which allows to simulate complex models with different levels of accuracy by integrating in a single formulation thick surface panels, thin vortex lattices and lifting lines to model solid bodies and panels and vortex particles for the wake. The vortex particles wake is accelerated by a fast multipole method and was developed to obtain a robust and accurate wake model when interactional aerodynamics phenomena occur, i.e. when the wake interacts with other wakes or solid bodies. This formulation allows `DUST` to be employed to simulate a variety of configurations, from conventional aircraft and helicopters to novel eVTOL configurations. The code was validated against experiments and high fidelity CFD on different configurations, from simpler test cases to the full Vahana eVTOL vehicle developed by A^3 by Airbus LLC [2, 5] and is in a state of maturity which allows it to be used to gather insights on novel aircraft configurations.

The architectures designed by the companies involved in the development of these new urban air mobility vehicles are quite different between them but the rotor-rotor interaction is one of the novel key phenomena which characterize the flow around eVTOLs and their performances. The investigation of this problem has begun to gather great interest in the scientific community in particular with application to hover conditions typical of multirotor drones. Indeed,

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several works were performed both in experimental and numerical fields about the side-by-side rotor-rotor interaction in hover [6, 7, 8, 9]. Despite this effort, there is a lack in literature of a systematic study aimed to obtain parametric data on the different types of rotor-rotor interactions that characterise the eVTOL vehicles, particularly for cruise conditions.

Consequently, a novel research activity was started at Politecnico di Milano aimed to fill this gap by means of a dual effort, both experimental and numerical. In particular, the experimental and numerical analyses of this activity are focused on the investigation of the aerodynamic interactions between two rotors in side-by-side and tandem configurations, representing classical features of eVTOL aircraft architectures, as highlighted in Fig. 1 showing the Vahana aircraft layout designed by A^3 by Airbus LLC. The results of this activity will be a valuable tool for the eVTOL community when evaluating different multi-rotor configurations for the different flight conditions that characterise the aircraft mission.

Figure 1: Layout of Vahana aircraft showing possible rotor interactions for an eVTOL aircraft.

2 EXPERIMENTAL SET UP

The test rig for the investigation of rotor-rotor interactions is designed for the *S. De Ponte* wind tunnel of Politecnico di Milano, having a 1 m $\times$ 1.5 m test section and a maximum speed of 55 m/s with a turbulence level lower than 0.1%.

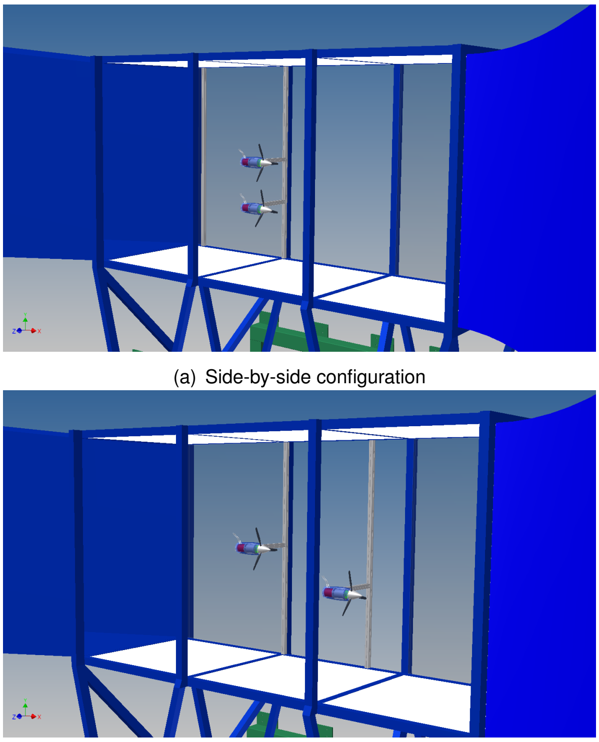
Two propeller models were designed and manufactured for the test campaign. The varioProp 12C three-bladed propellers with a diameter of 300 mm equipped with a 65 mm diameter aluminium spinner are used for the present test set up. Their rotor hub allows the adjustment of the collective pitch angle of the blades. The internal layout of the propeller model is shown in Fig. 2(a). An internal aluminium frame was designed and manufactured to support the driving system and the internal strain gauge load cell. In particular, the propeller is driven by a brushless motor equipped with a Hall effect sensor that provides the 1/rev signal to measure the rotational speed. A Futek MBA500 strain gauge bi-axial load cell (50 lbs F.S.) is used to measure the propeller thrust and torque. A polycarbonate nacelle manufactured with FDM technique is mounted on the metallic frame to cover the motor and the load cell, as shown in Fig. 2(b).

(a)

(b)

Figure 2: Layout of propeller model.

The experimental campaign is aimed to evaluate the effects of the aerodynamic interactions on the rotor performance, summarised in terms of thrust and required power and to investigate the flow physics related to such interactions both for the side-by-side and for the tandem configuration. With this aim, the two propellers models are positioned in the wind tunnel test section mounted on a thin metallic strut that allows the modification of their relative distance, in radial and axial directions, enabling the analysis of both side-by-side and tandem rotor configurations, as shown in Fig. 3.



(a) Side-by-side configuration

(b) Tandem configuration

Figure 3: Layout of the rotor-rotor interaction test rig at the *S. De Ponte* wind tunnel.

The test matrix parameters are selected to reproduce the typical parameters of the cruise flight condition of an eVTOL aircraft. The rotational speed of the propellers is fixed to 7000 RPM, while their advance ratio is changed during the tests modifyng the wind tunnel freestream velocity in the range from 16 m/s to 35 m/s. In the first test campaign, the rotors are placed in side-by-side configuration with a lateral distance between the rotor hubs (D_y) ranging from 2.05 to 3 rotor radii. In the second test campaign, the rotors in tandem are investigated considering two different longitudinal distances (D_z), respectively of 2.5 and 6 rotor radii in order to reproduce the typical distance of different classes of eVTOL vehicles. In this campaign, the rotors are tested from an overlapped configuration to a lateral distance between the hubs of 2.5 rotor radii. The rotor loads are collected in a comprehensive database considering also the variation of the pitch angle of the blades in order to provide a deeper insight of the aerodynamic interactions in eVTOL flight, a parametric description of the rotor performance for flight dynamics and a reference for numerical tool validation.

The flow field of the most peculiar test conditions highlighted by load measurements is then detailed by means of Particle Image Velocimetry (PIV). The PIV system is constituted by a Litron NANO-L-200-15 Nd:Yag double-pulse laser with an output energy of 200 mJ and wavelength of 532 nm, and two Imperx ICL-B1921M CCD cameras with a 12-bit, 1952×1112 pixel array. The laser is positioned under the floor of the wind tunnel test section to provide a laser sheet aligned with the freestream direction. The cameras are mounted on a metallic strut attached to one of the lateral wall of the test section and are positioned in tandem to cover the area of interest of the surveys. In this test campaign phase-locked 2C measurements are planned for different azimuthal angles of the blades. The flow fields are then time averaged to evaluate the mean behaviour of the interacting wakes of the rotors and phase averaged in order to investigate the evolution in time of the vortices released by the blades and their interactions. For the side-by-side configuration the area of interest is the region betwen the rotor hubs past the rotors disks, while for the tandem configuration the two cameras are used simultaneously to investigate the flow regions before and past the rear propeller disk.

3 NUMERICAL SIMULATIONS

Mid-fidelity numerical simulations are performed with `DUST` covering the planned experimental configurations for the analysis of the rotor-rotor aerodynamic interaction, both in tandem and side-by-side configurations. The aim of these simulations is to obtain a preliminary insight about the loss of performance due to the rotor-rotor interaction. Due to the low computational effort of this mid-fidelity approach, the simulations allow to explore and enlarge the whole space parameters planned for the experimental activity and to highlight the most interesting conditions to be be deeply investigated in the wind tunnel campaign. Moreover, the comparison between load experimental measurements and `DUST` mid-fidelity results will be useful for assessing the limits of such a mid-fidelity numerical approach in rotor-rotor interaction analysis.

The numerical model of the propeller was build using non-linear lifting line elements for the rotor blades, naturally including the viscosity contributions to aerodynamic loads through tabulated sectional aerodynamic data obtained by XFoil simulations and using the Viterna method [10] to obtain the post-stall behaviour of the two-dimensional aerodynamic loads coefficients curves between $\pm 180^\circ$ angle of attack. The blade geometry was reconstructed using the 3D scanning technique, thus obtaining the airfoil geometry, the chord and twist distributions along the span. The spinner-nacelle surface is modeled with surface panel elements. The layout of the numerical model including the reference system used is shown in Fig. 4.

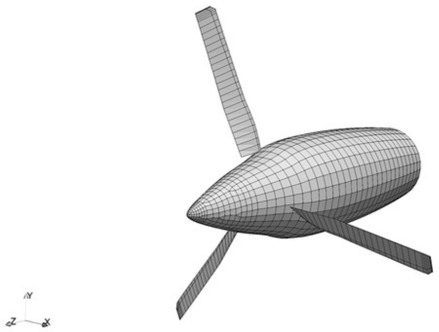


Figure 4: Layout of propeller numerical model and reference system.

4 RESULTS

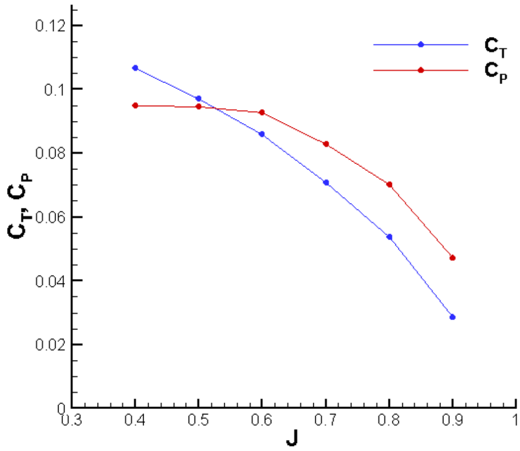
This section presents the results of the preliminary numerical simulations performed for investigating the main features of the aerodynamic interactions between the two propellers. The simulations were performed considering parameteres corresponding to flight conditions of a eVTOL vehicle. The RPM of the propellers was fixed to 7000 RPM corresponding to a Reynolds number based on the rotational speed and the blade chord at 75% of the rotor radius of 9.7×10^4 and a tip Mach number of 0.32. The blade pitch evaluated at 75% of the rotor radius is fixed to $\theta = 25.5°$. The simulations were run over 10 rotor revolutions with a discretization in time of $5°$ of blade azimuthal angle. The loads results presented in the following are averaged over the last 3 rotor revolutions.

4.1 Single propeller configuration

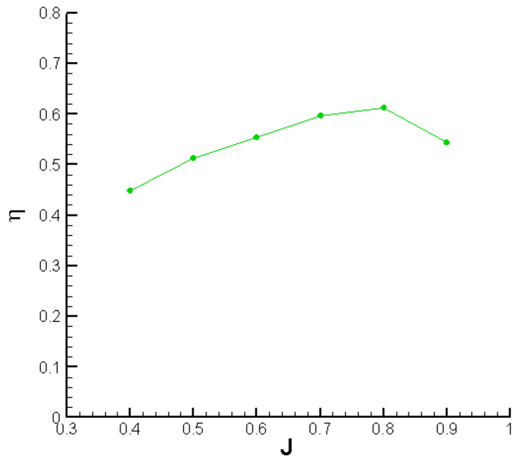
Before the interacting propellers simulations, a preliminary simulation of the single propeller was performed to obtain the reference performance for comparison. Figure 5 shows the thrust coefficient C_T, the power coefficient C_P and the propulsive efficiency η of the single propeller for a sweep of advance ratio J between 0.4 and 0.9. As can be seen from Fig. 5(b) the peak of the propulsive efficiency is obtained for $J = 0.8$ corresponding to a freestream velocity of 28 m/s, representing a typical cruise velocity for eVTOL aircraft.

4.2 Tandem configuration

After the analysis of the performance of the single propeller, the tandem configuration was investigated by numerical simulations. In particular, the two co-rotating propellers are positioned with a longitudinal distance between the rotor disks of 6 rotor radii ($D_z = 6$). In the simulations, a sweep in lateral direction was considered, ranging from the overlapped configuration of the rotor disks ($D_y = 0$) to a distance between the rotor hubs of 2 rotor radii ($D_y = 2$).



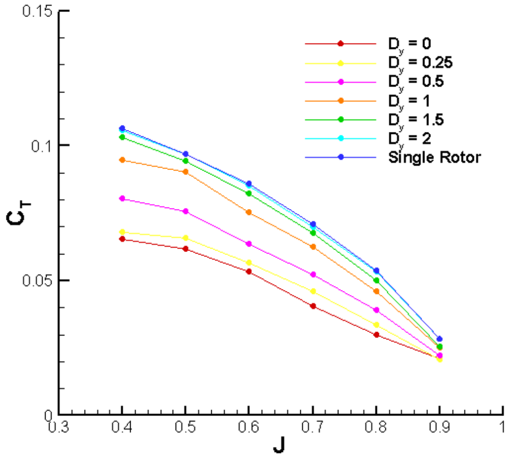
(a)



(b)

Figure 5: Results of the numerical simulations for the single rotor, $\theta = 25.5°$, rotational speed 7000 RPM: (a) thrust (C_T) and power coefficient (C_P) as function of the advance ratio (J), (b) propulsive efficiency η as function of the advance ratio (J).

Figure 6 shows the thrust coefficient C_T, the power coefficient C_P and the propulsive efficiency η of the rear propeller at different lateral distances D_y for a sweep of advance ratio J between 0.4 and 0.9. As can be observed from the comparison of the curves shown in Fig. 6, the performance of the rear propeller strongly decrease by reducing the lateral separation between the axis of the two propeller. In particular, a higher loss of performance is obtained when the two propeller disks are overlapped ($D_y = 0$), as the inflow of the rear propeller is strongly influenced by the front propeller slipstream reducing the effective angle of attack of the rear propellers blades. On the other hand, for lateral distance of $D_y = 2$ the performance curves of the rear propeller resumes the behaviour the single rotor curves, thus confirming that for this lateral separation the interactional aerodynamic effects are negligible as the rear rotor is quite unaffected by the front rotor slipstream.



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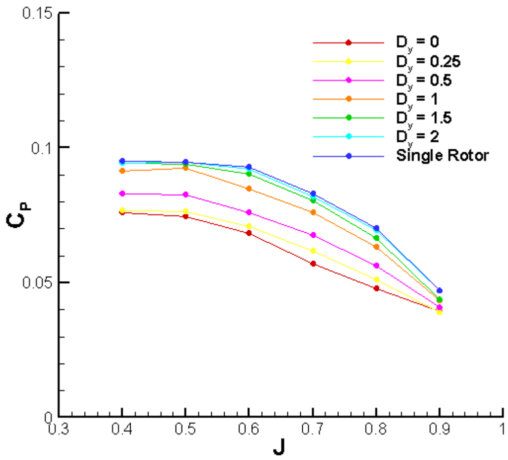

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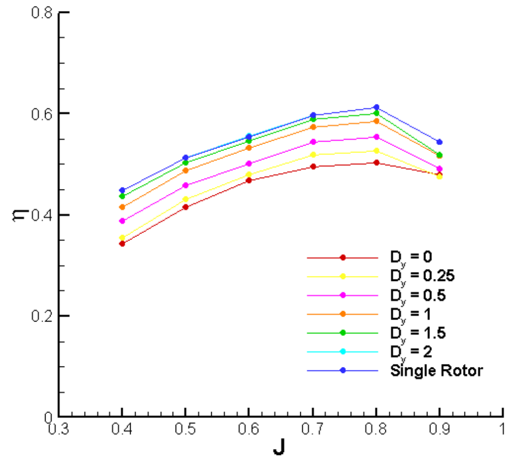


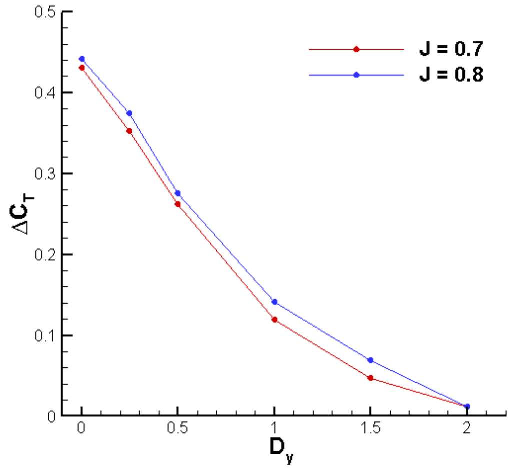
(c)

Figure 6: Results of the numerical simulations on rear propeller for the tandem interacting case, $\theta = 25.5^\circ$, rotational speed 7000 RPM, $D_z = 6$: (a) thrust coefficient (C_T) as function of the advance ratio (J), (b) power coefficient (C_P) as function of the advance ratio (J), (c) propulsive efficiency η as function of the advance ratio (J).

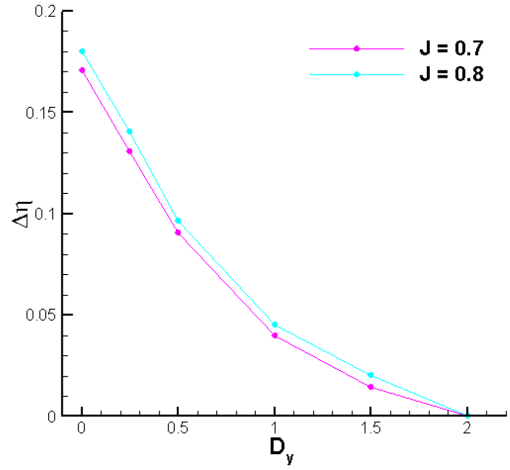
The peak of the propulsive efficiency curves remains at $J = 0.8$ for all the interacting configuration analysed with different lateral distances. A quantitative evaluation of the loss of performance is shown in 7 in terms of two loss factors defined for the thrust coefficient and for the propulsive efficiency as follows:

$$\Delta C_T = \frac{C_{T_{sr}} - C_{T_{rp}}}{C_{T_{sr}}}; \Delta\eta = \frac{\eta_{sr} - \eta_{rp}}{\eta_{sr}} \tag{1}$$

where the subscripts sr and rp are referred respectively to the single rotor configuration and to the rear rotor in tandem configuration. This analysis was performed for two advance ratio, $J = 0.7, 0.8$, as they corresponds to the operational conditions where the propeller provides higher propulsive efficiency.



(a)



(b)

Figure 7: Results of the numerical simulations on rear propeller for the tandem interacting case, $\theta = 25.5^\circ$, rotational speed 7000 RPM, $D_z = 6$: (a) thrust coefficient variation with respect to the single rotor (ΔC_T) as function of lateral distance (D_y), (b) propulsive efficiency variation with respect to the single rotor $\Delta\eta$ as function of the lateral distance (D_y).

As shown in Fig. 7, a decrease of more than 40% of the thrust and of about 20% of the propulsive efficiency is observed for the rear propeller when the propeller disks are overlapped. In particular, the gradient of the performance loss is higher for lateral distances between $0 < D_y < 1$.

4.3 Side-by-side configuration

The side-by-side configuration investigated by numerical simulations consists of two counter-rotating propellers ($D_z = 0$) sweeping in lateral direction from $D_y = 2.05$ to $D_y = 4$. For this interacting case only the advance ratio $J = 0.8$ corresponding to the peak of the propulsive efficiency shown by the single rotor results was considered. Figure 8 shows the thrust coefficient C_T, the power coefficient C_P and the propulsive efficiency η of one of the propellers normalized with respect to the corresponding parameters evaluated from the single rotor configuration results.

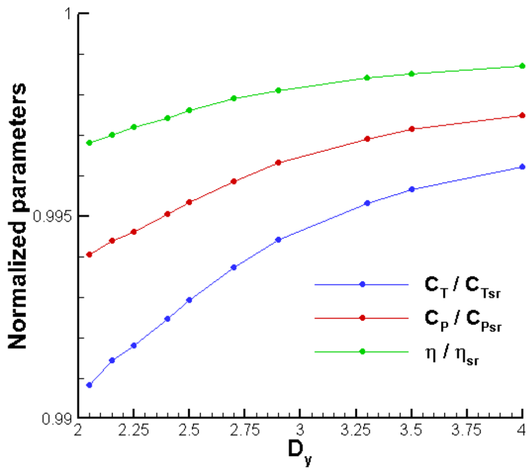


Figure 8: Results of the numerical simulations for the side-by-side interacting case, $\theta = 25.5°$, rotational speed 7000 RPM, $J = 0.8$: thrust (C_T), power coefficient (C_P) and propulsive efficiency η normalized with respect to the single rotor configuration parameters as function of the lateral distance between the propellers hub (D_y).

As can be observed from Fig. 8, the performance of the propellers in side-by-side configuration are negligibly affected by the aerodynamic interaction. Indeed, a loss of performance lower than 1% with respect to the single propeller configuration is observed for the thrust, the power and the propulsive efficiency when the propellers hubs are at a lateral distance equal to 2.05 rotor radii. Increasing the lateral distance D_y the propeller resumes the performance of the single propeller configuration. These results are in line with the outcomes of the work by Alvarez et al. [8] for a similar interacting test case.

5 CONCLUSIONS

In the present paper a complete overview of a novel research activity aimed to obtain parametric data on the different types of rotor-rotor interactions that characterise the eVTOL vehicles is provided. The present activity consists of both wind tunnel tests and numerical simulations performed with a mid-fidelity aerodynamic code. The preliminary numerical simulations show that a robust loss of performance is obtained for the rear propeller in tandem configuration, while for the side-by-side configuration the effect of the aerodynamic interaction on the propeller performance is low. These results will be compared with the wind tunnel results when available in order to confirm quantitatively the effects of the interaction on the propeller performance and to evaluate the capabilities of a mid-fidelity aerodynamic code to reproduce these complex configurations.

Copyright Statement

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