



Experimental investigation of wing-propeller aerodynamic interaction in eVTOL configurations

Alex Zanotti*, Luca Menini, Alberto Savino, Donato Grassi, Luca Riccobene

Politecnico di Milano, Dipartimento di Scienze e Tecnologie Aerospaziali, via La Masa 34, 20156, Milan, Italy

ARTICLE INFO

Communicated by Damiano Casalino

Keywords:

Aerodynamics
Wind tunnel
Particle image velocimetry
Wing-propeller interaction
eVTOL

ABSTRACT

The present study is aimed at the experimental investigation of the effects of wing-propeller aerodynamic interaction in a boom-mounted configuration typically used in eVTOL aircraft. The investigation was focused on the repercussions on wing and propeller performance coming from the variation of angle of attack, advance ratio and blades sense of rotation. Moreover, particular attention was devoted to the evaluation of the effect of the propeller's longitudinal offset. Results of a comprehensive wind tunnel campaign performed on a propeller-mounted wing scaled model confirmed the advantageous effects of an inboard-up rotating propeller on lift generation and drag reduction, while outlined the opposite sensitivity of wing and propeller performances when exposed to a non-zero angle of attack. Propeller's longitudinal offset instead led to slight alterations on wing and propeller aerodynamic performance, while a noteworthy sensitivity on the mounting setup was perceived by propeller aerodynamic performance. Moreover, PIV measurements allowed to evaluate quantitatively the effects of the investigated parameters on propeller slipstream behaviour and blade tip vortices pattern.

1. Introduction

Urban Air Mobility (UAM) is one of the most prominent and prolific topic that is under investigation for the future of transportation in great metropolitan areas. Indeed, ground traffic congestion, air pollution and a new emergent sensibility about the environment have allowed numerous and different competitors to suggest, transform or enhance new solutions for urban transportation. Among these the development of electric Vertical Take-Off and Landing (eVTOL) aircraft has the potential to revolutionize urban transportation by combining the benefits of helicopters to takeoff and land vertically with the efficient cruise capabilities of airplanes. Typical eVTOL architectures are based on Distributed Electric Propulsion (DEP) technology which replaces traditional single-engine configurations with an array of smaller electric propellers distributed across the wings or the fuselage [1–3]. Different promising eVTOL concepts are emerging across renowned aeronautical players as Airbus, Archer or Vertical to cite few examples. However, this prominent design brings to forefront the complex phenomena of wing-propeller aerodynamic interaction that could impact the aircraft performance and stability, as well as noise emission and power consumption.

The interplay between wings and propellers is not a novel challenge in aviation, but it becomes even more critical in the context of eVTOLs that are typically characterised by multiple propellers and lifting surfaces [4]. Despite the interest into this aerodynamic mutual interplay comes already with Prandtl before the Second World War [5], a proliferation in scientific publications emerges only some decades after. Snyder et al. [6] evaluated the primary repercussion coming from a tip-mounted tractor propeller configuration. Authors showed how a significantly effectiveness in lift augmentation and drag reduction can be felt when propeller is moved toward the wingtip, while the influence of propeller's power into lift coefficient was due to the altered wing's angle of attack and dynamic pressure provided by the slipstream. Their research was also focused on the effect of blades rotating directions on wing performance and trailing vortex evolution. Later on, Kroo [7] and Johnson et al. [8] explored the primary outcomes coming from wing-propeller interaction for a conventional inboard layout, while the more recent work by Veldhuis [9] provides a summary of the major aerodynamic outcomes related to the employment of a propeller in front of a wing. Now going to the more recent activities related to eVTOL architectures, Sinnige et al. [10] propose a comprehensive comparative study between wingtip and inboard propeller mounting

* Corresponding author.

E-mail address: Alex.Zanotti@polimi.it (A. Zanotti).

Notation

| | | | |
|-----------|--|-------------------|--|
| CFD | Computational Fluid Dynamics | R_p | propeller blade radius..... m |
| C_L | lift coefficient | Re_c | Reynolds number based on wing chord |
| C_l | wing sectional lift coefficient | T | propeller thrust N |
| C_D | drag coefficient | U_t | blade-tip velocity m/s |
| C_{d_p} | wing sectional pressure drag coefficient | u | axial velocity component m/s |
| C_{M_y} | pitching moment coefficient | v | spanwise velocity component m/s |
| C_P | power coefficient, $= P/(\rho n^3 D_p^5)$ | UAM | Urban Air Mobility |
| C_Q | torque coefficient $= Q/(\rho n^2 D_p^5)$ | V | in-plane velocity magnitude..... m/s |
| C_T | thrust coefficient $= T/(\rho n^2 D_p^4)$ | V_∞ | wind tunnel freestream velocity..... m/s |
| D | drag..... N | $X - Y - Z$ | reference system |
| D_p | propeller diameter m | α | angle of attack deg |
| d_x | longitudinal distance between propeller disk and wing leading edge | η | propulsive efficiency $= J(C_T/C_P)$ |
| eVTOL | electrical Vertical Take Off and Landing aircraft | ψ | blade azimuthal angle..... deg |
| F.S. | full scale | ρ | air density kg/m ³ |
| J | advance ratio $= V_\infty/(nD_p)$ | σ | standard deviation |
| L | lift N | θ | blade pitch angle at 75% of the rotor radius deg |
| M_y | pitching moment..... Nm | ω | out-of-plane vorticity component..... 1/s |
| n | rotational speed RPS | <i>Subscripts</i> | |
| P | propeller power W | 0 | zero angle of attack |
| Q | propeller torque..... Nm | <i>in</i> | inboard in |
| R.O. | rated output | <i>out</i> | outboard in |

configurations. Tip-mounted setup was investigated considering both blades sense of rotation and results confirmed quantitatively the effects on the system aerodynamic performance. In particular, regarding the wing performance, inboard up rotation regime provides an advantage in terms of lift coefficient, while the interaction with propeller slipstream in outboard up rotation regime led to a penalty in terms of wing lift when compared to the prop-off condition. The same wing-propeller model was numerically investigated by Stokkermans et al. [11] and Van Arnhem et al. [12]. In particular, the latter work found an average increase of the propeller-mounted thrust coefficient at if compared to single propeller configurations. The effects of the propeller blades sense of rotation and advance ratio variation was also numerically investigated by RANS simulations in [13]. However, authors focused their attention only on the influence of propeller on the wing lift and drag coefficients, neglecting the analysis on propeller performance. Similarly, Minervino et al. [14] numerically explored the advantages arising from tip-mounted configuration and compared the obtained drag reduction with the one exhibits by an optimized winglet. More recently, Lin et al. [15] investigated the effects of propeller on wing lift and drag coefficients for tip-mounted configurations at different propeller rotational speed and angles of attack. Moreover, this work included an extensive analysis of the vortical wake and of flap effectiveness for such configuration. Cole et al. [16] numerically investigated the influence of propeller location, diameter and rotating direction in a propeller-wing system design space. Authors observed that wing performance benefits expected by inboard up propellers are not general and strictly depend upon the propeller-wing design and the interactions between those parameters. In particular, propeller's required power shown a correlation in terms of magnitude with vertical location, because of the reduction in the induced drag inside the propeller slipstream. Furthermore, Schollenberger et al. [17] investigated the influence of propeller rotational speed, number of blades and pitch angle of wingtip mounted propeller systems. Authors found that slower rotating propeller enabled to achieve a higher drag reduction, while an increase in the number of blades or pitch angle provides an enhancement of global aerodynamic efficiency. Despite the great number of activities aimed at the investigation of wing-propeller aerodynamic interaction, eVTOL architectures opened new scenario for the investigation of the effects of different parameters with respect to classical aircraft configurations. In particular,

one of the driving solution developed by different manufacturers is the design of a boom that extends beyond the wing leading edge to sustain the propellers.

The present activity was inspired by a previous work by the same authors in collaboration with Archer Aviation [18] aimed to wind tunnel testing of full-scale eVTOL components of the Maker aircraft, particularly a wing section with a boom-mounted propeller. This work represented a quite unique experiment thanks to the availability of eVTOL aircraft components to the tested and provided some interesting outcomes for the evaluation of wing-propeller interaction in eVTOL scenario. Nevertheless, due to confidentiality issues related to the employed geometries only a limited database was disseminated in this work. Thus, in the present work, a systematic series of wind tunnel tests was performed on a wing-propeller scaled system with open geometry aimed to provide an open comprehensive experimental database suitable to investigate the main parameters that characterise eVTOL flight conditions as cruise and last phase of transition. In particular, the activity was focused on the evaluation of the effects of mutual aerodynamic interaction on both propeller and wing by varying angle of attack of the system, advance ratio and particularly boom's length. Different measurements techniques were employed in this activity, from global system loads and propeller loads measurements, to pressure measurements over the wing and PIV surveys in the propeller wake. This enabled to extend knowledge in the field of wing-propeller aerodynamic interaction in eVTOL environment as well as to provide a robust database for the validation of CFD tools.

The paper is organized as follows. Section §2 describes the experimental setup, including wing-propeller system model design, measurement techniques and definition of the test parameters. Section §3 presents the discussion of the main results obtained by the experiments for the different flight configurations reproduced in the wind tunnel. Conclusions are drawn in Sec. §4.

2. Experimental set up

The experimental activity was performed at the *S. De Ponte* wind tunnel of Politecnico di Milano. The closed-loop wind tunnel has a 1 m × 1.5 m test section and can reach a maximum speed of 55 m s⁻¹ with a turbulence level lower than 0.1%.

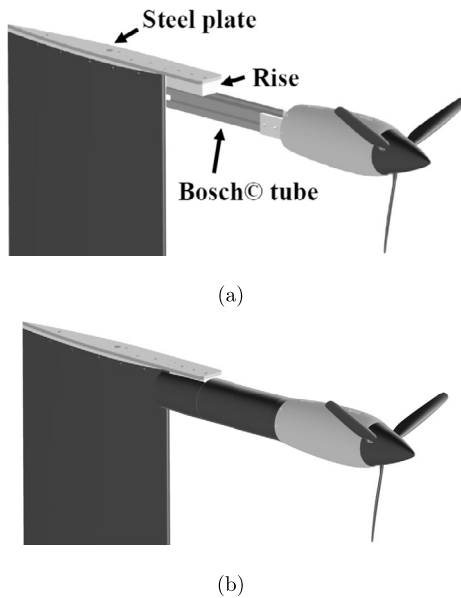


Fig. 1. Layout of the wing-propeller model.

2.1. Wing-propeller model set up

The selected wing model was made by a NACA 23015 airfoil with a chord of 300 mm and an untapered span of 930 mm. The model was manufactured using an internal aluminium structure made by four ribs and two spars and an external cover of 3 mm thickness made by thermoplastic resin. The propeller model was the same used for the test activity described in [19,20]. The propeller hub was designed using hobby-grade components. In particular, a three-bladed hub equipped with left- or right-handed VarioProp 12C blades was used, thus resulting in a propeller disk diameter D equal to 300 mm. A 65 mm diameter aluminium spinner was screwed on the propeller hub. An internal aluminium frame was designed to support the propeller driving system and a bi-axial strain gauge load cell. The propeller was driven by a Scorpion brushless motor (5.3 kW continuous power) with shaft connected directly to propeller hub. The motor was powered by an external

PWM-controlled electronic speed controller. A custom software developed in Labview was used to keep controlled both propellers at the desired rotational speed. A maximum fluctuation below 1% of the target rotational speed of the propellers was found during the wind tunnel tests. A polycarbonate nacelle with 270 mm length was manufactured using FDM technique and mounted on the internal metallic frame to shield both the motor and the load cell. The propeller model is attached to the wing by means of an outer steel plate resembling the rib shape and a 30 mm \times 30 mm squared Bosch[®] aluminium profile, as shown in Fig. 1(a). A cylindrical nylon cover made by 3D printing technique was used as a boom to shield the internal wing-propeller connection structure (see Fig. 1(b)). This set up allowed to perform tests with propeller disk at different distances with respect to the wing's leading edge by varying the length of the connecting Bosch[®] profile, thus resembling eVTOL configurations with different boom length. In particular, the axis of rotation of propeller blades is aligned with wing airfoil chord. The complete CAD configuration of the model geometry will be provided by request to the authors.

The wing-propeller model was mounted inside the wind tunnel test section by means of a steel shaft attached at wing basement rib enabling the variation of the system angle of attack around 25% airfoil chord axis. A 5 mm gap was left between the wing basement rib and test section floor. The wing-propeller model mounted inside the wind tunnel is shown in Fig. 2.

2.2. Loads measurements set up

The supporting steel shaft was connected to an external six-component strain gauge balance mounted on a heavy basement placed below the wind tunnel floor. This balance allowed the measurement of the global aerodynamic forces and moments of the modular system. The balance was calibrated in-house at the Aerodynamics Laboratory of Politecnico di Milano. Loading range and accuracy of the balance can be found in [21,22]. A Futek MBA500 strain gauge bi-axial load cell embedded in the propeller internal metallic structure was used to measure propeller thrust and torque. Load cell has a F.S. range of ± 222 N for thrust and of ± 5.7 Nm for torque (non-linearity $\pm 0.25\%$ R.O., non-repeatability $\pm 0.05\%$ R.O.). Load cells signals were acquired by a National Instrument c-DAQ system equipped with strain/bridge NI 9237 modules. Loads signals of the balances were sampled at 2.5 kHz

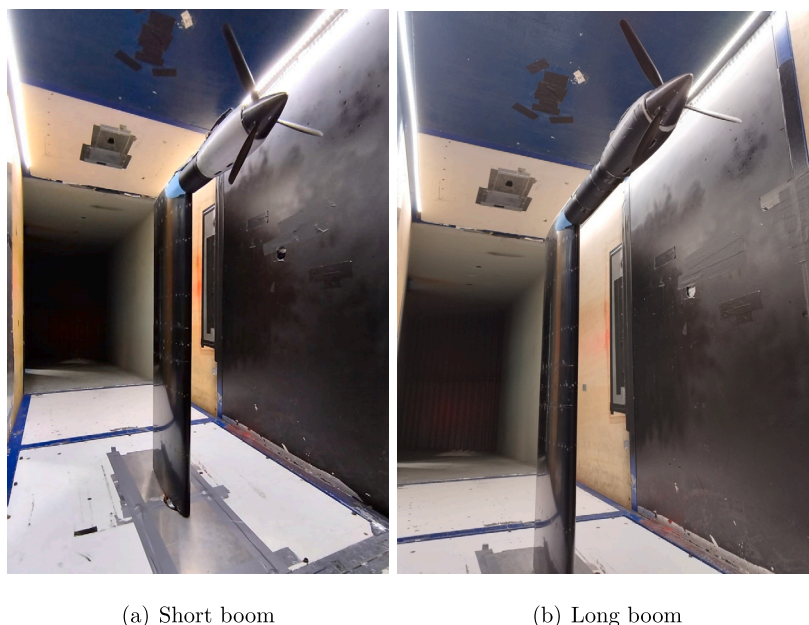


Fig. 2. Wing-propeller model mounted inside the wind tunnel test section.

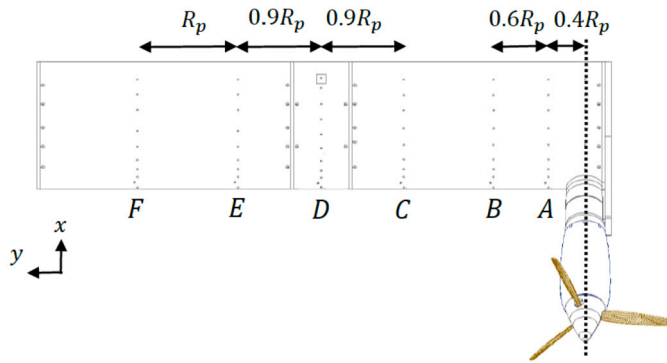


Fig. 3. Layout of the pressure taps positions on the wing model.

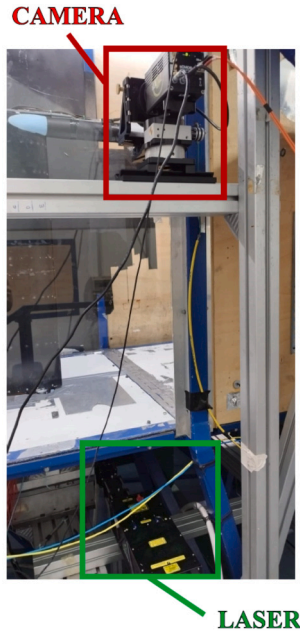


Fig. 4. Layout of the PIV setup.

and averaged over 10 seconds of acquisition time. Each test point was measured four times and results averaged.

2.3. Pressure measurements setup

Static pressure measurements were performed over 6 airfoil sections along the wing span each equipped with 21 pressure taps, for an overall amount of 126 measurement points. The positions of the pressure taps sections (A-F) are shown as function of the propeller radius R_p in Fig. 3, where also the $x - y$ axis reference system used for results presentation is depicted. Pressure signals were acquired simultaneously to loads measurements by means of five 32-ports ESP-32HD-DTC pressure scanners and a DTC Initium system at a sampling frequency of $50 Hz$.

2.4. PIV set up

Two-components PIV surveys were performed. The set up of the instrumentation is shown in Fig. 4.

A Quantel Evergreen Nd:Yag double-pulse laser with an output energy of 200 mJ and wavelength of 532 nm was positioned under the plexiglass floor of wind tunnel test section to generate a laser sheet aligned with the longitudinal $x - y$ mid-span plane by means of a 90° optic mirror. A double-shutter ILA.PIV.sCMOS camera with a 16 bit 2560×2160 pixels array was mounted on an external metallic structure around the test section. This set up allowed an investigation area in the

region between the wing leading edge and the propeller boom/nacelle junction with dimensions of $373 \text{ mm} \times 314 \text{ mm}$. A particle generator (PIVpart30 by PIVTEC) equipped with Laskin atomizer nozzles was used to fulfill wind tunnel test section with seeding. The seeding particles consisted of small oil droplets with a diameter in the range of $1\text{--}2 \mu\text{m}$. Free-run and phase-locked 2C PIV measurements respectively over 400 and 250 image pairs were performed for each test configuration considered during the wind tunnel campaign. Image pairs analysis was performed using PIVview 3C software developed by PIVTEC. Post-processing made use of the multi-grid interrogation method [23] starting from a $128 \text{ pixels} \times 128 \text{ pixels}$ to a $16 \text{ pixels} \times 16 \text{ pixels}$ interrogation window with effective 50% overlap. This methodology results in a spatial resolution between adjacent measurement points less than 2 mm. The dimensions of the output areas of investigation are shown in the results discussion. PIV recording system, i.e. camera and laser, was linked to wind tunnel and does not vary for surveys at different angles of attack of the wing-propeller. Thus, measurements windows are linked to wind tunnel reference system and aligned to freestream velocity. Details about the accuracy of the PIV measurements are reported in [24] using the same setup. In particular, considering pulse-separation time and the optical magnification used for the present tests, the maximum in-plane velocity error was below 1% of the maximum in-plane velocity component.

2.5. Wind tunnel test conditions and parameters

A systematic series of wind tunnel tests were performed over several configurations obtained by changing the boom length, the angle of attack of the wing-propeller system, the advance ratio and propeller direction of rotation. In particular, two boom configurations providing a distance d_x between the propeller disk and the wing leading edge equal to 2 (short boom) and 3 (long boom) propeller radius R_p were investigated. The two selected distances resemble eVTOL aircraft configurations as Airbus Vahana and Archer Midnight. Loads and pressure measurements were performed for each boom configuration in the range of angle of attack of the entire system α between 0° and 14° , with a step of 2° . This allowed to reproduce wing-propeller aerodynamic interaction both in cruise and in the last phase of transition of an eVTOL tiltwing configuration. Moreover, three propeller advance ratios were investigated during wind tunnel campaign, i.e. $J = 0.5$, $J = 0.75$ and $J = 0.95$, in order to reproduce flight conditions from last phase of transition to cruise of an eVTOL tiltwing aircraft. In particular, $J = 0.5$ could be considered typical of the last phase of transition manoeuvre characterised by tilting wing angles of attack in the order of 10° , while $J = 0.75$ and $J = 0.95$ can be considered typical of moderate to fast cruise flight conditions characterised by tilting wing angle of attack near to zero. Advance ratio was changed by varying the wind tunnel freestream velocity while keeping the propeller rotational frequency fixed to 7050 RPM. This RPM target value was considered to reproduce a typical tip Mach number, i.e. $M_t = 0.325$, of full-scale eVTOL aircraft propellers in airplane-mode flight condition [25,26]. Finally, both propeller blades direction of rotation, i.e. inboard up and outboard up regime, was investigated by the use of left- and right-handed blades. In particular, Fig. 5 shows the definition of inboard up propeller sense of rotation as well as blade azimuthal angle ψ .

Due to manufacturing limitation of the hobby-grade hub used for the present propeller model, the pitch angle of the blades evaluated at 75% span θ could not be the same in the inboard up and outboard up regime. An overview of the test conditions and parameters for the aerodynamic performance measurements is reported in Table 1.

PIV surveys were performed only for $\alpha = 0^\circ$ and $\alpha = 10^\circ$ to limit wind tunnel occupancy. Phase-locked measurements were performed only in the outboard up regime at three azimuthal blade angles, i.e. $\psi = 0^\circ$, $\psi = 40^\circ$ and $\psi = 80^\circ$. Indeed, this test campaign required almost a month of wind tunnel occupation.

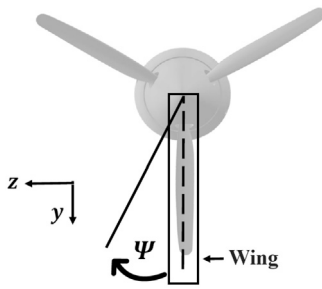


Fig. 5. Scheme of the propeller including the definition of blades sense of rotation in inboard up regime and azimuthal blade angle ψ .

Table 1
Summary of test conditions and parameters for performance measurements.

| J | V_∞ [m/s] | RPM | Re_c | θ_{out} [deg] | θ_{in} [deg] |
|------|------------------|-------------------|-------------------|----------------------|---------------------|
| 0.50 | 17.6 | 7050 | $3.52 \cdot 10^5$ | 20.5 | 22 |
| 0.75 | 26.4 | 7050 | $5.28 \cdot 10^5$ | 20.5 | 22 |
| 0.95 | 33.5 | $6.70 \cdot 10^5$ | 20.5 | 22 | |

Wind tunnel corrections were applied in order to consider solid and wake blockage effects by using a linear superimposition of effects related to model parts (wing, propeller and boom), while wing downwash effect correction was considered for angle of attack and drag coefficient [27]. Moreover, propeller thrust coefficient was corrected considering wind tunnel walls effects following the work by Werle [28].

3. Results and discussion

Wind tunnel campaign provided a comprehensive amount of experimental data. The complete database will be available on request to authors. A selection of the results are presented and discussed in this section considering the different measurements techniques involved. In particular, the discussion will consider separately the effects of propeller on wing aerodynamic performance and wing effects on propeller performance. The banded regions over the loads coefficients curves presented in the following indicated the standard deviation calculated over the four repetitions performed for each test point. Finally, flow field analysis will be included considering PIV surveys results.

3.1. Aerodynamic effects of propeller on wing

3.1.1. Lift evaluation

First of all, the wing-propeller system lift coefficient is compared to the single wing configuration in Fig. 6 for the different advance ratios and boom configurations. In the outboard up regime, the complete wing-propeller system exhibits an increase of the lift curve slope at the lowest advance ratio ($J = 0.50$). Thus, the maximum lift coefficient raises of about 7% with respect to the isolated wing in both short and long boom configurations. At higher advance ratios, a slight performance degradation effect is observable as a downward shift on the lift coefficient curves for the complete system. For this rotational regime of the blades the wing spanwise region washed by the propeller slipstream experiences a downwash due to the outboard-up propeller rotation that provide a reduction of the local effective angle of attack. This interaction effect is in contrast with the increased axial velocity provided by propeller slipstream occurring particularly at lower J , hence at higher propeller thrust, as the wing region invested by propeller slipstream is immersed in a flow with local increased dynamic pressure. At lower advance ratio this latter effect becomes dominant for high angles of attack, while at lower incidences downwash effect prevails, thus providing a higher slope of the lift coefficient curve for the

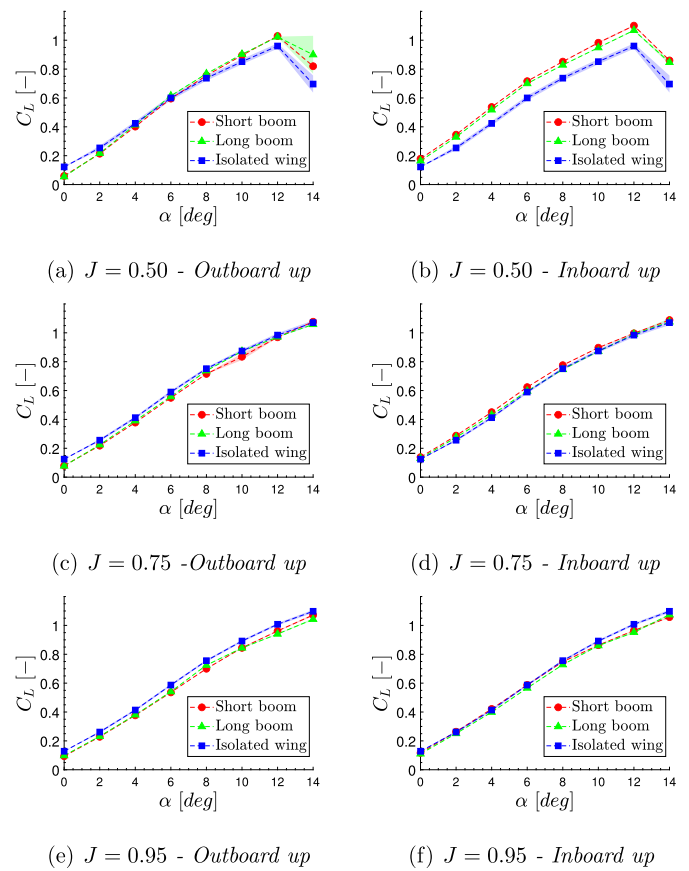


Fig. 6. Comparison of the measured lift coefficient as function of angle of attack for the three tested advance ratios. The coloured bands are representative of one σ confidence level.

complete wing-propeller system with respect to the single wing configuration. Moreover, at higher advance ratios, the local increased dynamic pressure effect becomes lower as wing airfoils experience a reduced variation of the local axial velocity due to the higher freestream velocity.

On the other hand, for inboard up blades rotational regime the interaction of propeller slipstream with the wing provides an apparent beneficial effect on lift at the lowest considered advance ratio ($J = 0.50$). This effect is observed in the whole range of angle of attack tested, even if stall can not be prevented past $\alpha = 12^\circ$. In this regime the swirl effect provided by propeller slipstream produces an upwash experienced by the airfoils invested and a consequent increase of the local angle of attack. This effect combines positively with the local increase of dynamic pressure related to the propeller slipstream accelerated flow.

For long boom configuration this latter effect decreases, as wing airfoils experience a reduced variation of the local axial velocity due to the higher longitudinal offset of the propeller disk. Thus, particularly at lowest advance ratio the long boom lift curve is slightly downward shifted with respect to the short boom one. At higher advance ratios, the lift benefit coming from propeller interaction decreases, as the axial velocity variations tends to vanish due to the higher freestream velocity. In particular, at $J = 0.95$ no beneficial effect on lift curve is observed due to propeller interaction.

A deeper insight in the flow physical effects related to the wing-propeller interaction can be deduced from pressure measurements. In the following, the wing-propeller system at $\alpha = 4^\circ$ is considered as sample configuration for pressure measurements analysis. Fig. 7 shows the comparison of pressure coefficient C_p distributions measured on an airfoil section of the wing invested by propeller slipstream, i.e. Row A. Pressure distribution measured for outboard up regime reveals, as

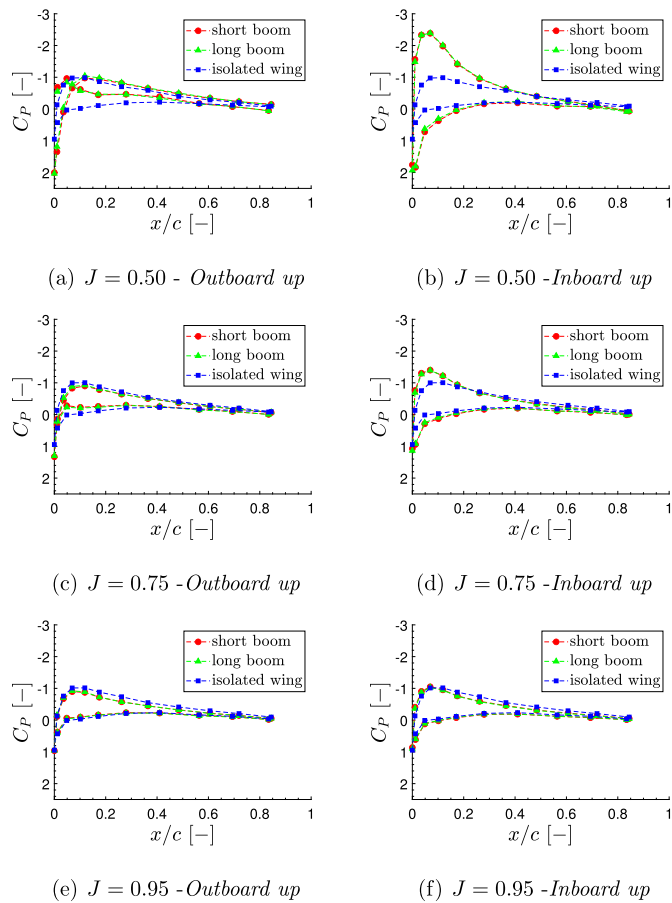


Fig. 7. Comparison of the measured pressure distribution on Row A ($y/b = 0.9$) at $\alpha = 4^\circ$.

expected, a decrease of the C_p curves areas for all the advance ratio related to the combination of the interactional effects previously described. On the other hand, for inboard up regime the propeller slipstream investing this wing section provides an amplified suction peak at leading edge region, particular apparent for the lowest advance ratio, where interactional effects are higher. This suction peak increase gradually recovers at larger cruise speeds till vanishing for the highest advance ratio tested, where the C_p curves resemble almost the same area.

A global overview of pressure measurements results on the wing is presented in Fig. 8, showing the comparison of sectional lift coefficients C_l distributions along wing span evaluated by integrating pressure coefficients measured on all the instrumented airfoil sections.

Outboard up rotation leads to a degradation of sectional lift generation along the entire wing span for all the advance ratios tested. In fact, the steep lift gradient between the washed and un-washed wing regions provides the shedding of a distorted vorticity sheet, leading to a modification of the incoming inflow angle along the entire wing span [9]. In particular, an higher freestream velocity reduces the effect of the propeller slipstream into sectional lift coefficient, particularly in the washed wing region. On the other hand, the reduction of sectional lift along the entire wing span is attenuated by the use of longer boom. For the inboard up regime a strong raise of the sectional lift was found at the lowest advance ratio in the wing spanwise region that is invested by the propeller slipstream. However, this lift increase effect is valuable along the outer half of the wing, while a slight degradation of the performance was found on the inner wing region. This trend, even if with reduced magnitude, is observed also for $J = 0.75$, while at the highest advance ratio tested the sectional lift distributions resemble the same behaviour, as the interactional effects almost vanish.

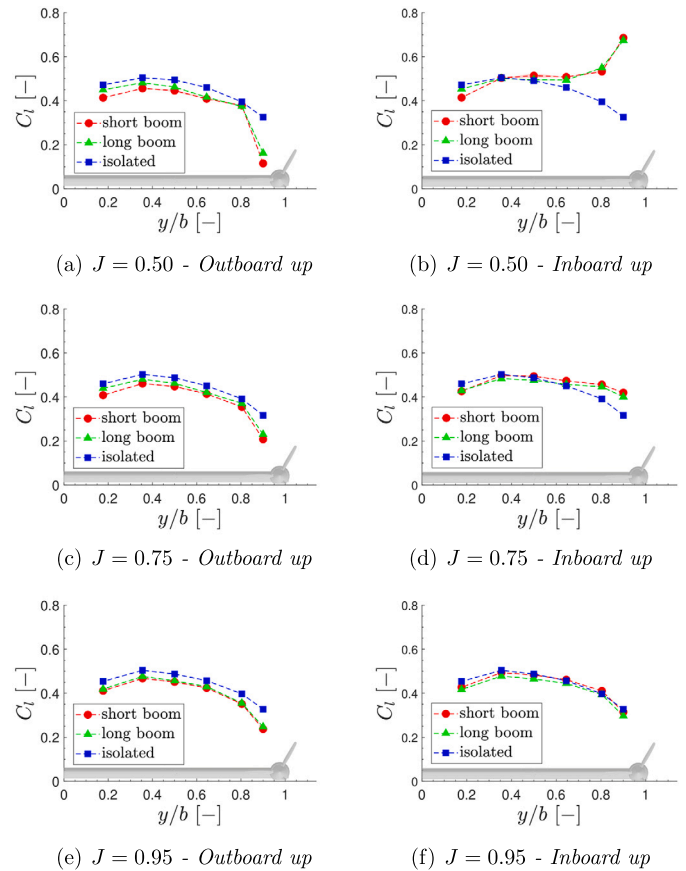


Fig. 8. Comparison of sectional lift coefficient C_l at $\alpha = 4^\circ$. Coloured band represents one σ confidence level.

3.1.2. Drag evaluation

The overall system aerodynamic drag is depicted in Fig. 9 as function of angle of attack. Propeller thrust represents the predominant force with respect to aerodynamic drag of the system, particularly at lower advance ratio where greater negative C_D values (i.e. propulsive force) are observed. The analysis of this force component highlights no noticeable differences between the short and long boom configurations, for both outboard up and inboard up rotational regimes. Nonetheless, propeller slipstream has strong impact on wing induced drag, as will be shown from the analysis of the sectional pressure drag coefficient distributions obtained by integrating pressure coefficients measured along the wing model. In particular, in order to highlight the main effects of propeller interaction on wing induced drag, Fig. 10 presents the comparison of pressure drag distributions measured at two different advance ratios for a sample angle of attack, i.e. $\alpha = 0^\circ$.

In the outboard up regime an important increase of pressure drag component can be observed in the region of the wing that is invested by propeller slipstream. In details, in this rotational regime the swirl component provided by propeller slipstream is co-rotating with the wingtip vortex, leading to an enhancement of the total amount of swirl experienced by wing sections. The swirl enhancement leads to the classical downwash effect, as lift vector is rotated backward thus causing an increase of induced drag. This effect combined with the dynamic pressure raise related to the flow acceleration provided by propeller is responsible for the greater enhancement of the pressure drag component in the wing region invested by propeller slipstream, particularly for lower advance ratio, as explained in [9,29].

On the other hand, in the inboard up regime the increase in the effective local angle of attack provided by the upwash component results in a rotation of the lift force vector leading to a reduction in the induced drag component, known as swirl recovery effect. Thus, at given C_L of

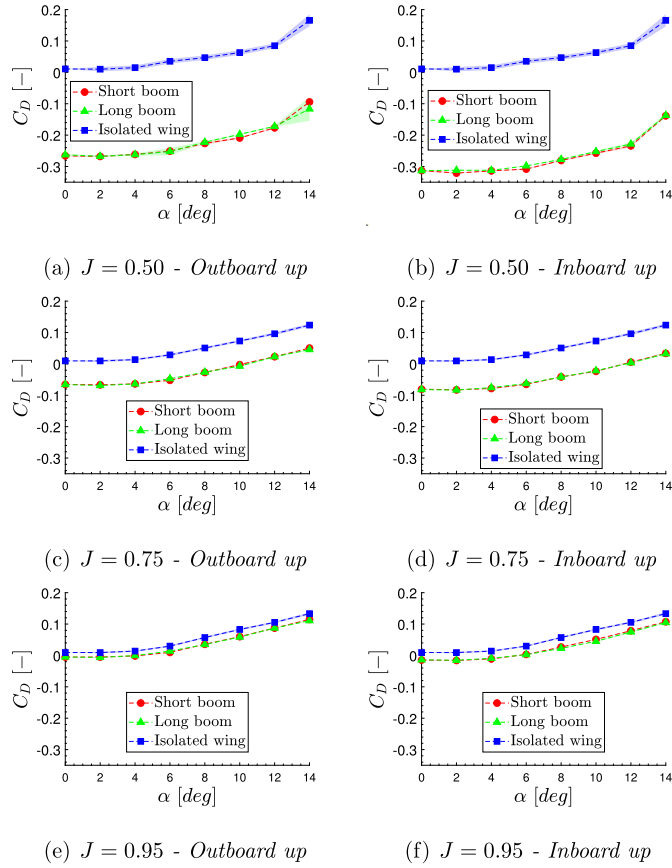


Fig. 9. Comparison of the measured drag coefficient as function of angle of attack for the three tested advance ratios. The coloured bands are representative of one σ confidence level.

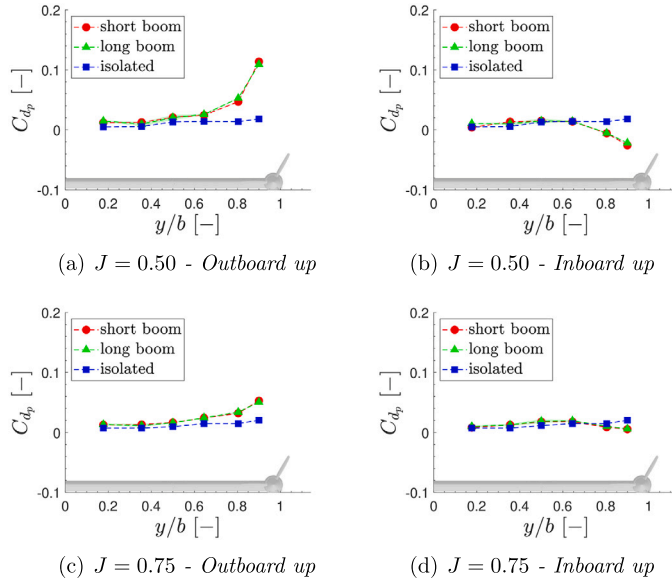


Fig. 10. Comparison of sectional pressure drag coefficient C_{dp} at $\alpha = 0^\circ$. Coloured band represents one σ confidence level.

the overall system, the angle of attack needed is reduced with respect to the isolated condition, leading to a consequent reduction of total drag. In particular, in the wing region invested by propeller slipstream the sectional pressure drag coefficient is strongly reduced, particularly at lower advance ratio, while this effect apparently decreases by increas-

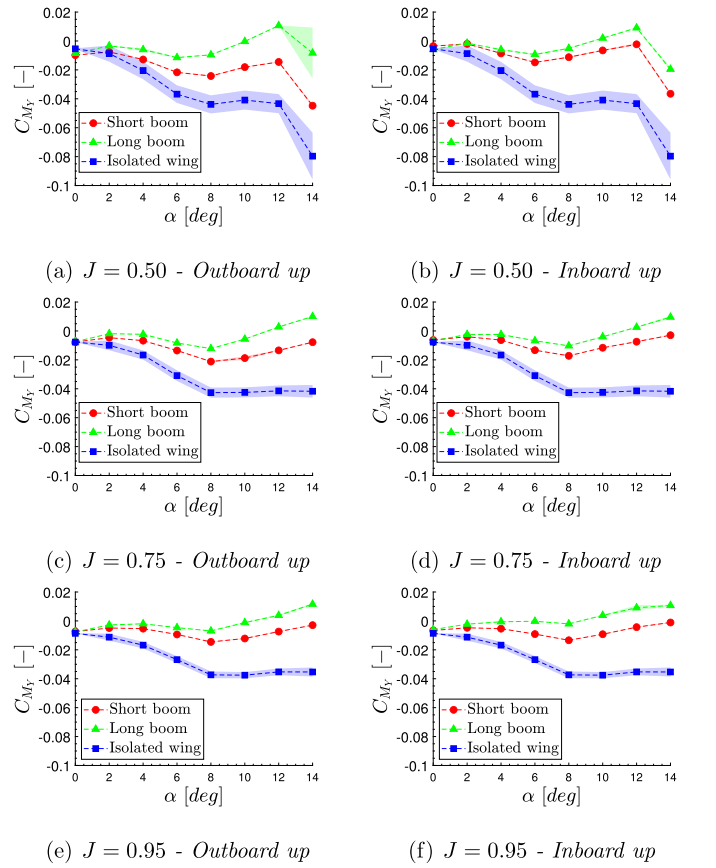


Fig. 11. Comparison of the measured pitching moment coefficient as function of angle of attack for the three tested advance ratios. The coloured bands are representative of one σ confidence level.

ing the advance ratio, as axial velocity variation provided by propeller slipstream is vanishing.

3.1.3. Pitching moment evaluation

The overall system aerodynamic pitching moment coefficient evaluated at the root airfoil quarter chord is shown in Fig. 11 as function of angle of attack. Remarkable differences related from propeller longitudinal positioning are observed concerning pitching moment evaluation. Generally, the propeller mounting provides a strong reduction of the negative slope of the pitching moment coefficient curve, thus reducing the pitching-down moment representing an advantage from a structural point of view. The trend of C_{My} curves shows also a direct sensitivity with respect to the angle of attack. Indeed, at non-null incidence both propeller and boom generate aerodynamic loads that provide an increasing pitching up moment. This effect is increased when longer boom is employed and is slightly influenced by the blades sense of rotation at all advance ratios tested.

3.2. Aerodynamic effects of wing on propeller

The presence of the wing in the investigated configuration produces an alteration of propeller performance related to blockage and circulation effects [9]. Fig. 12 shows the comparison of propeller thrust coefficient C_T as function of the angle of attack for the three investigated advance ratios. At lowest advance ratio $J = 0.5$, propeller thrust is slightly influenced by the wing in both the different rotational regimes, as shown by the flat behaviour of C_T curves. At higher advance ratio propeller thrust experiences an increase with respect to single propeller performance due to wing blockage effect. This is observed as a shift of the C_T measured with the complete wing-propeller system at zero

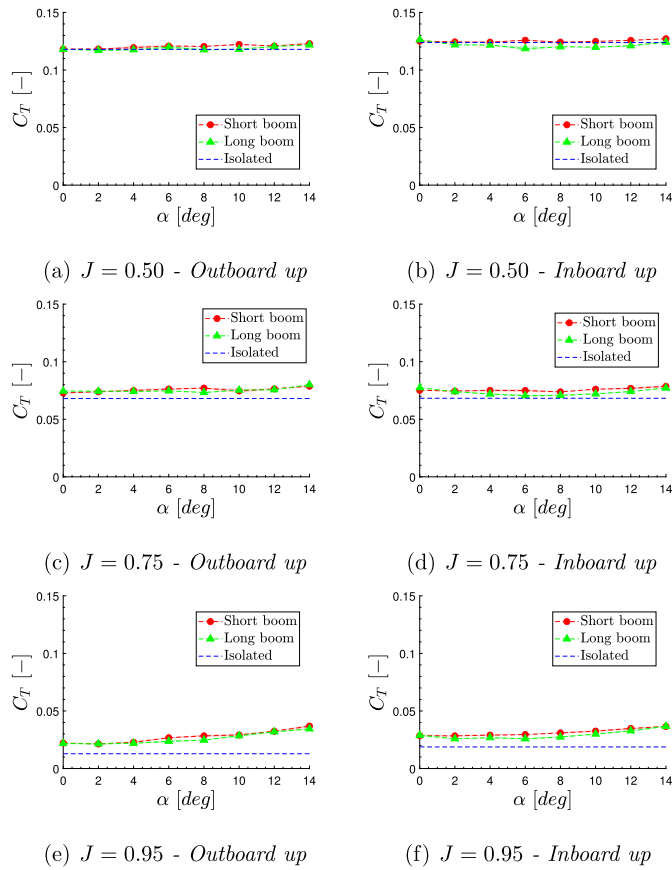


Fig. 12. Comparison of the measured propeller thrust coefficient as function of angle of attack for the three tested advance ratios. Dotted line refers to single propeller performance measured at $\alpha = 0^\circ$. The coloured bands are representative of one σ confidence level.

angle of attack with respect to single propeller configuration, that becomes higher increasing the advance ratio from $J = 0.75$ to $J = 0.95$. Generally, long boom configuration tends to reduce, in both rotating directions, the thrust increase if compared to the short boom case. Indeed, longer offsets between propeller disk and wing model reduce the amount of influence, thus decreasing the beneficial upwash effects on rotor disk performance. Moreover, propeller thrust curves in this flight conditions show an increasing trend with respect to angle of attack. This sensitivity is related to the asymmetric modification of disk loading occurring at non-null angles between freestream velocity and propeller disk, as described in [9,30,31,20].

This effect is accentuated for the outboard up region and higher advance ratio due to an upwash effect provided by the wing on the advancing blades related to the augmented wing circulation [9], as highlighted by Fig. 13 showing the ratio between thrust coefficients measured for the complete wing-propeller system and the corresponding ones measured at zero angle of attack for the short boom configuration at $J = 0.95$ in both rotational regimes. Power coefficient curves resemble a quite similar behaviour with respect to the thrust ones, thus, for the sake of consistency, in the following the propulsive efficiency curves are presented to provide an overall analysis of the effects of interactional mechanisms on propeller performance for the different test conditions.

Fig. 14 shows the comparison of propeller efficiency η as function of the angle of attack for the three investigated advance ratios. In details, regarding the lowest advance ratio $J = 0.5$, no effects on propulsive efficiency are observed in the whole range of angle of attack tested and in the different rotational regimes. At higher advance ratios the effect of the wing is apparent, providing an increase of the propulsive efficiency

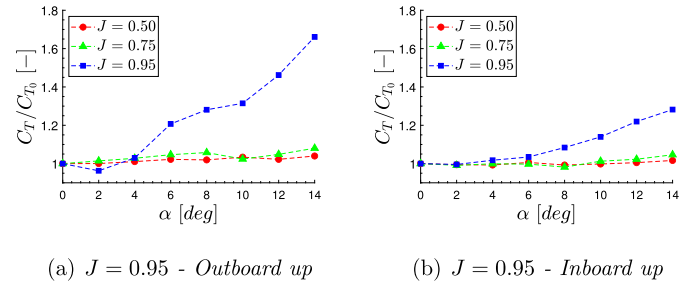


Fig. 13. Comparison of the ratio between thrust coefficients measured for the complete wing-propeller system and the corresponding ones measured at zero angle of attack C_{T_0} for the short boom configuration at $J = 0.95$.

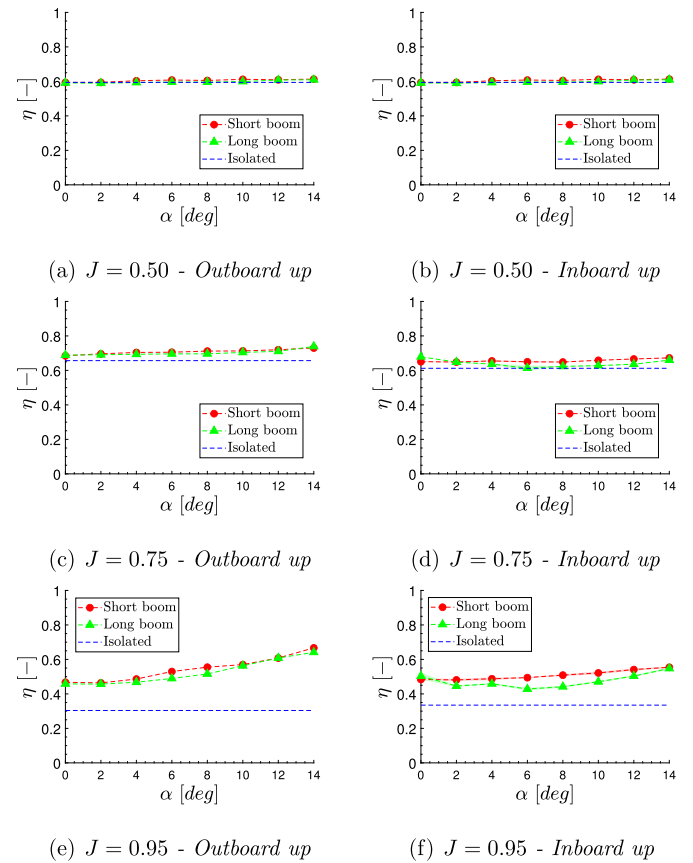


Fig. 14. Comparison of the measured propeller efficiency as function of angle of attack for the three tested advance ratios. Dotted line refers to single propeller performance measured at $\alpha = 0^\circ$. The coloured bands are representative of one σ confidence level.

with respect to single propeller configuration. This effect increases by increasing the freestream velocity in both the rotational regimes and resembles the behaviour observed for thrust coefficient with respect to angle of attack. In particular, the behaviour of the propulsive efficiency ratio shown for $J = 0.95$ in Fig. 15(a) confirmed the augmented effects of the interaction for the outboard up regime, providing an increase of more than 40% of the propeller efficiency measured at null angle of attack.

The effect of the short boom configuration is appreciable at higher advance ratio only, where an increase of few percents of the propulsive efficiency is observed with respect to the long boom configuration almost in the whole range of angle of attack tested.

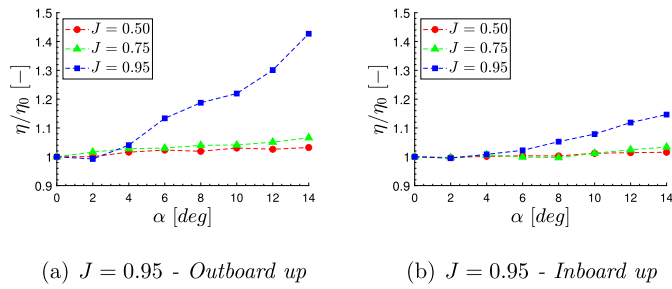


Fig. 15. Comparison of the ratio between propeller efficiency measured for the complete wing-propeller system and the corresponding ones measured at zero angle of attack η_0 for the short boom configuration at $J = 0.95$.

3.3. Flow fields analysis

This section describes the main results achieved by ensemble-averaged and phase-locked PIV measurements performed for the two considered angles of attack of the wing-propeller system, i.e. $\alpha = 0^\circ$ and $\alpha = 10^\circ$. In particular, results will be presented for the outboard up regime only, as the 2C PIV setup available for the present test campaign does not allow to evaluate the main effects of propeller blades sense of rotation related to swirl velocity component.

3.3.1. Time-averaged flow fields

Contours of the time-averaged non-dimensional axial velocity u are depicted for the three investigated advance ratios in Fig. 16 at $\alpha = 0^\circ$. Axial velocity contours provide information about the averaged flow acceleration inside the propeller wake. In particular, at lowest advance ratio $J = 0.5$, velocity inside the propeller wake reaches values in the order of 50% higher than freestream, while at highest advance ratio $J = 0.95$ the local flow acceleration provided by propeller is quite limited because of the lower induced velocity developed by propeller disk at increasing inflow speed.

Moreover, the global behaviour of the flow field inside propeller wake and near the wing leading edge is almost similar for the short and long boom configuration. Thus, in order to provide a more quantitative comparison of the effects of the two boom configurations on flow features near the wing leading edge, axial and spanwise velocity components profiles were extracted along a vertical straight line at a distance $\Delta x/R_p = 0.1$ from the wing leading and are compared in Fig. 17.

At the lowest advance ratio, axial velocity in the spanwise wing region inside the propeller slipstream is 5% lower for long boom configuration compared to the short boom one, while outside the propeller wake u -component becomes comparable between the two setups and resembles a value that is almost 10% lower than the freestream velocity. Similar considerations can be hold for the averaged spanwise velocity component, showing a reduction of 2% inside the propeller slipstream for the long boom configuration. These results allow to underline the weak mitigation of detrimental effects related to the mutual interaction between propeller and wing when an enlarged offset between them occurs. Analogously, for $J = 0.75$ long boom configuration reduces the effect on axial velocity inside propeller slipstream to about 2% with respect to short boom configuration, while negligible effects are found on spanwise velocity component. For $J = 0.95$ axial velocity profiles for the two boom configurations show a slight shift of about 1% of the freestream velocity in the whole area of investigation, while negligible variations are again observed for the spanwise velocity component.

3.4. Phase-averaged flow fields

Phase-locked PIV measurements enabled to provide an insight on propeller wake evolution for the different flight conditions and mounting settings. Fig. 18 shows the comparison of the contours of the

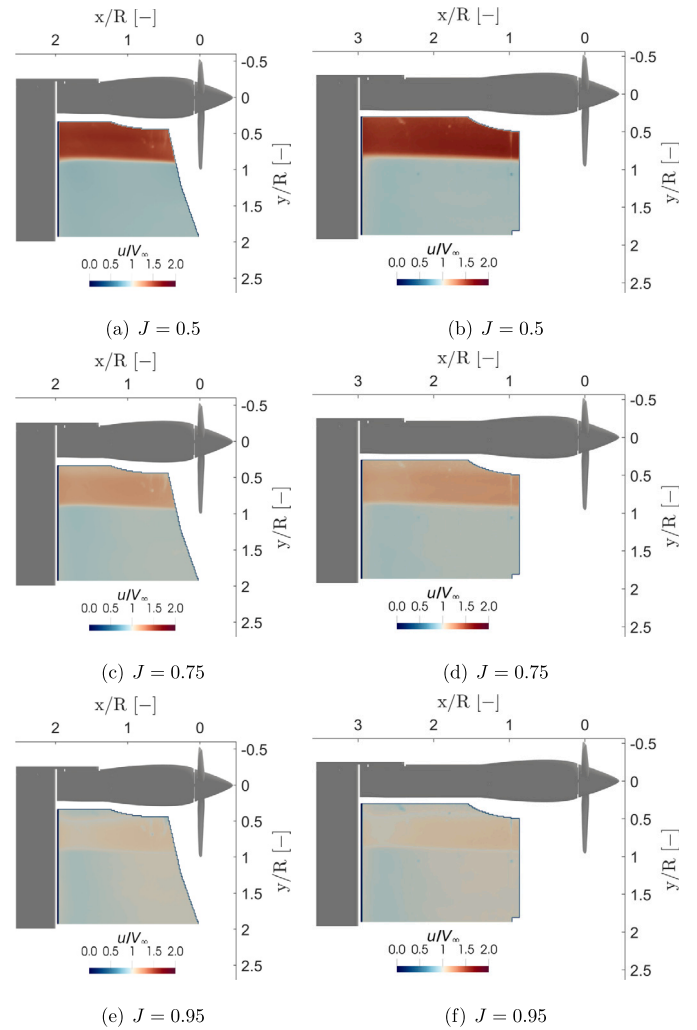


Fig. 16. Contours of the time-averaged non-dimensional axial velocity component u at $\alpha = 0^\circ$ in outboard up regime. (For interpretation of the colours in the figure(s), the reader is referred to the web version of this article.)

phase-averaged non-dimensional axial velocity u at $\alpha = 0^\circ$ and blade azimuthal angle $\psi = 0^\circ$.

Moreover, the non-dimensional out-of-plane vorticity is computed and represented in Fig. 19 for the same test conditions. This latter representation shows that, for an advance ratio of $J = 0.50$ in both short and long boom configurations, the wake contraction is more pronounced and characterised by a number of tip vortices almost doubled with respect to $J = 0.95$ with a higher magnitude of the shed tip-vorticity related to the higher blade loading. In particular, at $J = 0.50$, when approaching the wing leading edge, propeller slipstream starts to stretch towards the wing inner spanwise region. This effect is mainly due to the spanwise variation of wing circulation that provides an increase of the spanwise vortex velocity in the inward direction, as indicated by [32,33]. This is particularly evident when long boom is employed. Moreover, for this configuration at lowest advance ratio an instability breakdown of the tip vorticity [34] occurs for $x/R > 2.5$ (see Fig. 19(b)). This feature vanishes when the advance ratio is increased (see Fig. 19(d) and 19(f)), consistently to what found in Felli et al. [35]. Another important remark related to the observed features lies in the vorticity magnitude that has a slightly lower intensity near the wing for the long boom configuration at all the advance ratios due to the larger longitudinal distance of the propeller disk.

In order to provide a more quantitative comparison of the propeller slipstream behaviour, as done in the previous work [36] the positions

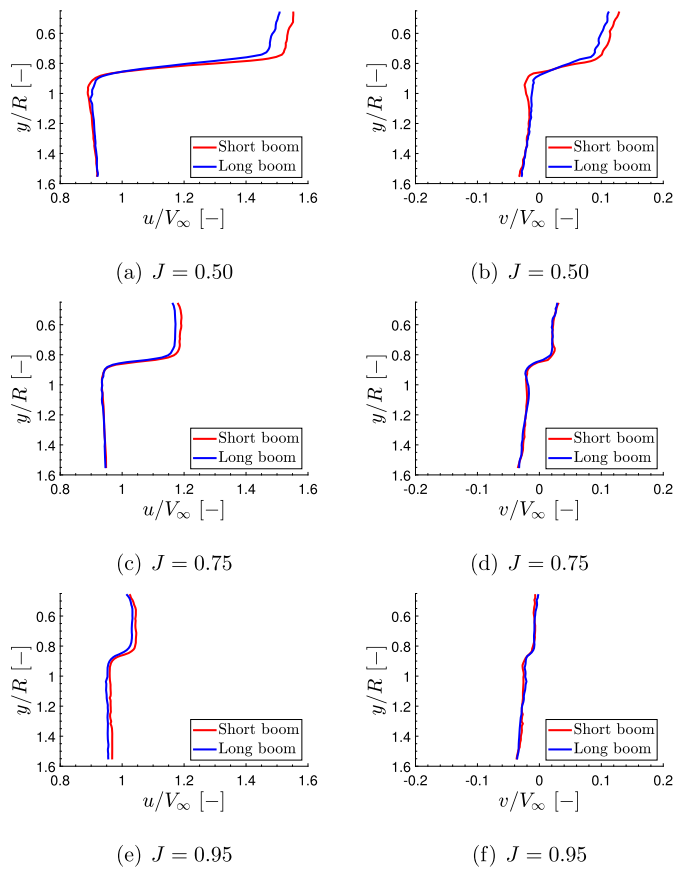


Fig. 17. Comparison of the axial and spanwise velocity components profiles in outboard up regime for $\alpha = 0^\circ$ at a distance of $x/R = 0.1$ from wing leading edge.

of the maximum out-of-plane vorticity magnitude are extracted for all the azimuthal blade angles ψ considered by the phase-locked PIV measurements and are plotted together on Fig. 20 to show the evolution of the blade tip vortex for the two propeller set up at null angle of attack at different advance ratios.

The main difference that can be observed between the two boom configurations is that the propeller slipstream for the long boom is slightly more contracted in the flow field region toward the wing leading edge. This effect is related to the higher longitudinal distance of the propeller disk that enables the wake to have more space to develop before reaching the wing leading edge. In particular, quantitative considerations can be provided if considering the longitudinal section at $x/R = 3$, corresponding to the wing leading edge. For the lowest advance ratio $J = 0.50$ corresponding to the highest blade loading, propeller slipstream for long boom configuration shows a slight expansion of about $5\%R$ due to wing interference, as previously discussed. For the higher advance ratios tested, a reduction of about 6% and 4% of the propeller radius were found respectively at $J = 0.75$ and $J = 0.95$ for long boom configuration slipstream with respect to the short boom one.

In order to provide a better understanding of the vortex paths, data for the short boom configuration depicted in Fig. 20 were shifted by $x/R = 1$ and plotted in Fig. 21 to be compared with longer boom data. This data representation shows that the vortex positions would almost match if released at same distance from the wing, thus highlighting that wing interaction on vortex path is quite weak particularly at high advance ratios. Indeed, in the overlapped region the slipstream extent shows a difference between the two boom configurations less than $2\%R$. Moreover, a phase mismatch of the vortices footprints is observed between the short and long boom configurations that could be due to the

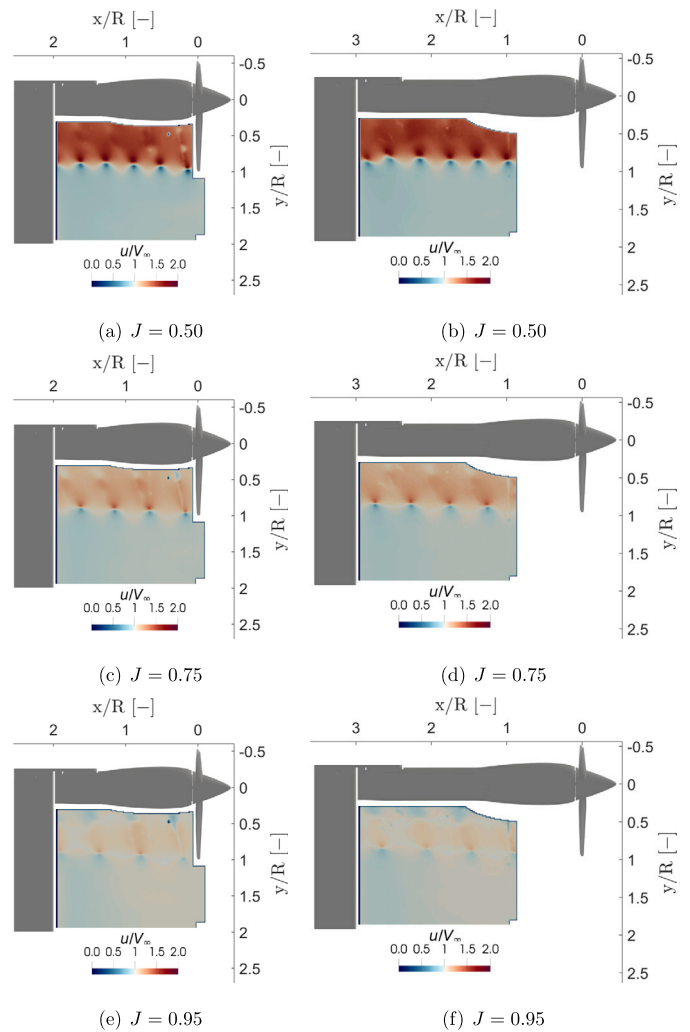


Fig. 18. Contours of the phase-averaged non-dimensional axial velocity component u at $\alpha = 0^\circ$ and blade azimuthal angle $\psi = 0^\circ$ in outboard up regime.

effect provided by the presence of the wing inducing a deceleration of the tip vortices.

Further quantitative information about the effect of advance ratio on slipstream contraction can be found from the direct comparison of blade tip vortex evolution plotted separately in Fig. 22 for the short and long boom configurations.

This representation clearly shows that for both boom configurations the propeller slipstream is more contracted by decreasing the advance ratio. In particular, at the lowest advance ratio $J = 0.50$, the behaviour of the vortices footprints shows higher oscillations with respect to the higher advance ratio ones, while an highest contraction in the order of $2\%R$ can be found particularly in the region near the wing leading edge.

In order to evaluate the effects of wing-propeller system angle of attack on propeller slipstream behaviour, Figs. 23 and 24 show the comparison of blade tip vortex evolution for the two investigated angles of attack, i.e. $\alpha = 0^\circ$ and $\alpha = 10^\circ$, in the two boom configurations.

In short boom configuration, vortex cores trajectory tends to merge when freestream velocity is increased. In particular, at lower advance ratios a larger slipstream is observed at $\alpha = 10^\circ$ that could be related to the effect provided by the transverse freestream velocity component at non null incidence. In particular, a difference extension in the order of $5\%R$ was found at wing leading edge section between the slipstreams evaluated at the two angles of attack. On the other hand, at the highest advance ratio this effect tends to vanish and the propeller wakes at $\alpha = 0^\circ$ and $\alpha = 10^\circ$ follow the same topology, even if vortex

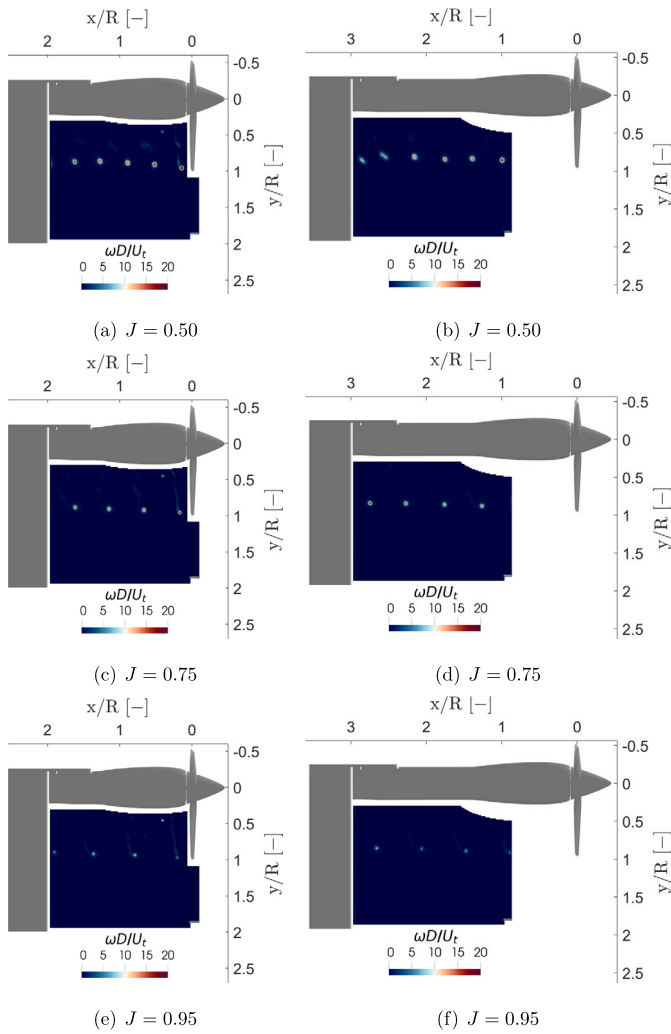


Fig. 19. Contours of the phase-averaged non-dimensional out-of-plane vorticity magnitude ω at $\alpha = 0^\circ$ and blade azimuthal angle $\psi = 0^\circ$ in outboard up regime.

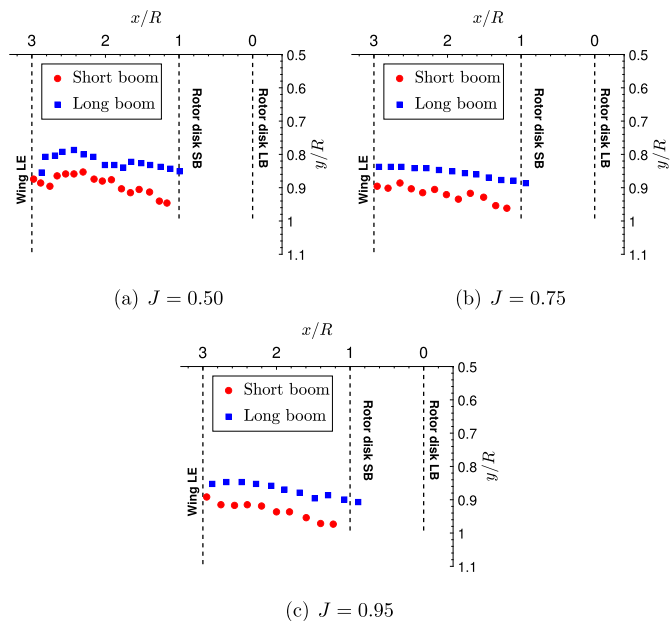


Fig. 20. Comparison of blade tip vortex evolution for the short and long boom configurations at $\alpha = 0^\circ$ in outboard up regime.

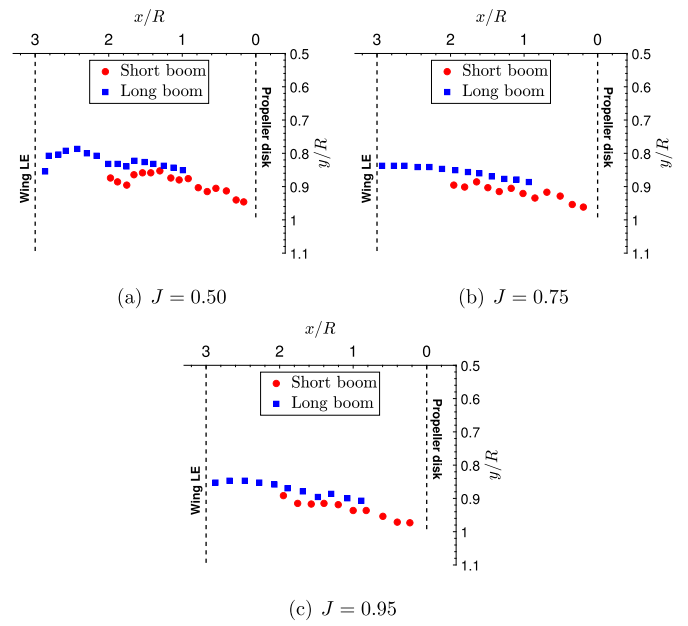


Fig. 21. Comparison of blade tip vortex evolution for three advance ratios at $\alpha = 0^\circ$ in outboard up regime with short boom data shifted upstream by $x/R = 1$.

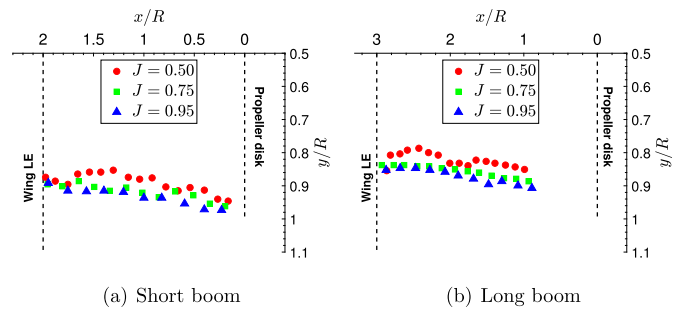


Fig. 22. Comparison of blade tip vortex evolution with respect to advance ratio at $\alpha = 0^\circ$ in outboard up regime.

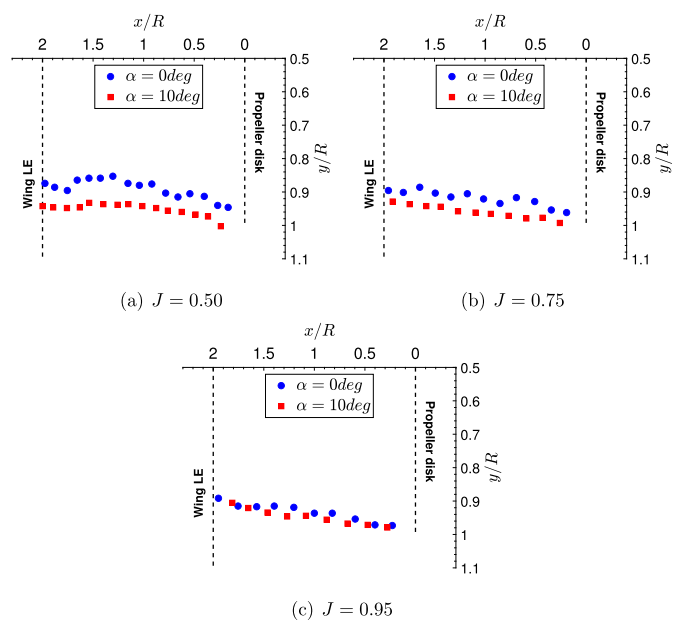


Fig. 23. Comparison of blade tip vortex evolution at $\alpha = 0^\circ$ and $\alpha = 10^\circ$ for short boom configuration at three advance ratios in outboard up regime.

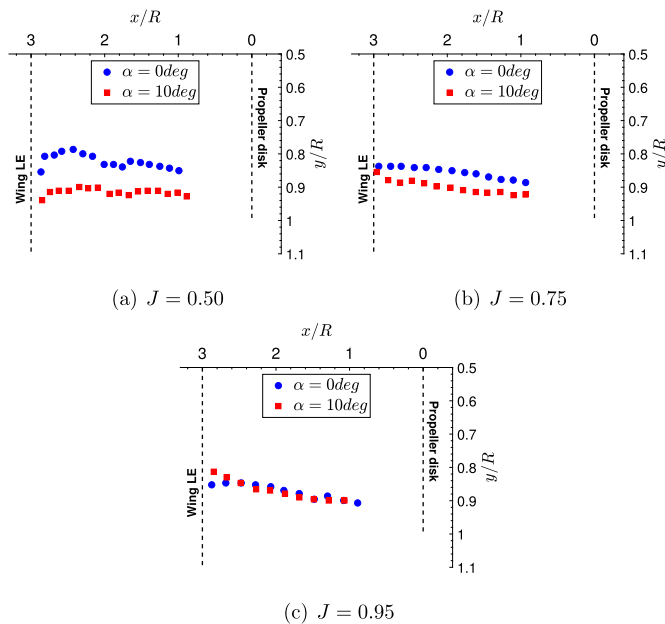


Fig. 24. Comparison of blade tip vortex evolution at $\alpha = 0^\circ$ and $\alpha = 10^\circ$ for long boom configuration at three advance ratios in outboard up regime.

core positions are out of phase due to the fact that the PIV plane cuts the slipstreams at different positions, i.e. at different vortex ages (see Fig. 23(c)). Similar consideration can be deduced for the long boom configuration, where for $J = 0.50$ differences up to $10\%R$ were found between slipstreams extent at the two different angles of attack, while at $J = 0.95$ the vortex cores appear almost overlapped (see Fig. 24(c)). In fact, when the propeller disk is further upstream with respect to the wing and at high advance ratio, the classical wake slipstream contraction is perturbed and is allowed to realign with freestream flow topology [37]. Moreover, for the long boom configuration the phase mismatch between the vortices positions tends to vanish increasing the advance ratio. This could be related to the fact that for $\alpha = 10^\circ$ at highest freestream velocity, the vortices footprints are captured on PIV plane with a time delay (i.e. later age) almost corresponding to the interval occurring between two vortices issued by adjacent propeller blades.

This quantitative representation of vortex evolution confirms the diversification of wake trajectory when subject to different inflow velocities, angles of attack or propeller disk offsets with respect to the wing and represent a thorough data base for validation of CFD tools.

4. Conclusions

The present work described and discussed a comprehensive experimental activity aimed to investigate the complex and challenging phenomena of wing-propeller aerodynamic interaction for the tip-mounted configuration. The present study aimed to focus the main effects of this interaction on system performance and flow field, with a focus on eVTOL aircraft flight conditions. In particular, the wide data base obtained with different measurement techniques as loads, pressure and velocity measurements over a free geometry represents an interesting benchmark for the validation of CFD tools. Hereafter the main outcomes of the experimental activity.

Load measurements showed that interactional effects could lead to significant improvements concerning system lift and drag coefficient when the inboard up regime for the propeller is used particularly at low advance ratio. Indeed, the combination of the dynamic pressure raise and upwash effect developed by the propeller slipstream had strong beneficial repercussion on the wing performance. Outboard up regime for blades rotation provided detrimental performance for the wing, except for the lowest investigated advance ratio. Indeed, the performance

degradation due the lower effective angle of attack provided by blade downwash effect is counterbalanced by the intense raise of dynamic pressure felt by the washed wing.

Propeller performance experienced an averaged positive influence from the upwash effect provided by the wing model in both rotating regimes, particularly at high advance ratios and higher angles of attack. Generally, advance ratio influences as well the wing performance due to the strong sensitivity to propeller disk loading. Indeed, stronger inflow speed provided lower induced velocity, i.e. axial and swirl component, that modify in a weaker way the amount of dynamic pressure and angle of attack effects on the wing.

The longitudinal offset of propeller position presents limited alterations on wing performance, except for the pitching moment coefficient. Indeed, long boom configuration can provide even worse positive slope and pitching-up moment at medium-high angles of attack, leading to a potential penalty for aircraft stability. However, a noteworthy sensitivity on the mounting setup was perceived by propeller aerodynamic performance too. Propulsive efficiency is negatively affected by the further upstream positioning of the propeller disk due to the weaker influence coming from the blockage and circulation effects provided by the wing model. Propeller longitudinal positioning also provides a slight alteration of the evolution and extension of the slipstream investing the wing, resulting in the slight variations observed on wing performance.

CRedit authorship contribution statement

Alex Zanotti: Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Luca Menini:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Data curation. **Alberto Savino:** Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Donato Grassi:** Writing – original draft, Software, Methodology, Investigation, Data curation, Conceptualization. **Luca Riccobene:** Writing – original draft, Supervision, Investigation, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This research was performed by using staff and facilities of Aerodynamics Laboratory of Department of Aerospace Science and Technology of Politecnico di Milano.

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