Evolution of flow structures in twin-rotors wakes in drones by time-resolved PIV

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Abstract.

An experimental investigation of the noise emissions of a twin-rotor together with the evolution and spatial organization of the flow structures wakes has been carried out by means of aeroacoustics and time-resolved PIV (TR-PIV) measurements. Each rotor is characterized by three bladed propellers with diameter D=393.7 mm running at four different rotational speeds (2620, 3500, 4360, 5200 RPM). Intricate flow patterns characterized by periodic vortical structures are formed in the wake of the rotors in twin configuration at the rotor-to-rotor distance of 1.02D. Their interaction determines a strong impact on the aerodynamic performances as well as on the noise generation. Hence, the need for TR-PIV measurements relies on what is the role of these instantaneous flow patterns to unveil the spatial organization and the dynamic behaviour inspected by imaging the region between the rotors. It is found that the flow organization and the interaction between evolution of vorticity intensity of tip vortices characterize the twin-rotors wakes.

1. Introduction

Drones are often identified as Unmanned Aerial Vehicle (UAVs) or Micro Aerial Vehicle (MAV). In the most interesting configurations, drones are already designed with vertical or horizontal take-off and landing capabilities, and can be manoeuvred with extremely high versatility and speed. MAVs are often used in tactical surveillance missions or for reconnaissance purposes. The noise footprint of these vehicles is highly important even when employed in civilian roles, due to their flight proximity to populated urban areas. To give an idea of public acceptance of large-scale use of drones in residential areas, information about the effects on the population of a large-scale test drone for delivering can be found in an article from the Wall Street Journal: "Delivery Drones Cheer Shoppers, Annoy Neighbors, Scare Dogs" [1]. Indeed, drone noise is indicated as the main obstacle to widespread public acceptance of this technology. For this reason, the scientific community has been studying the phenomenon very carefully in the last few years. Specifically, since the main source of drone noise are the rotors, significant efforts are focusing on the aeroacoustic studies of the blades. In the past, the topic of rotor noise has been extensively addressed also on helicopter rotor, but these studies cannot be directly extended to drone rotors. This hindrance is strongly connected to the difference in scale of the
drone blades compared to helicopter ones. The use of small scale blades on drones implies that
the Reynolds number assumes values between $10^4$ and $10^5$ [2]. This range of values is
associated with transitional fluid dynamic fields, where Tollmien-Schlichting instability and recirculation
bubble dynamics play an important role in term of generation of pressure fluctuations [3].
The scientific community has tackled the study of drone aeroacoustics by following mainly two
strategies: the study of the phenomenon associated with the single rotor (isolated rotor), or the
investigation of the noise generated by the complete drone. Zhou et al. performed an experi-ential
investigation on the impact of the distance between the twin rotors on both the thrust force
and noise level [4]. Tinney and Sirohi assessed the aerodynamic performance and the near-field
acoustics of an isolated rotor, quadcopter, and hexacopter configurations through a six-degree-of-freedom load cell and an azimuthal array of microphones to demonstrate the effects of the
number of rotors [5]. Jia and Lee investigated the interactional aerodynamics and acoustics of
the coaxial rotor and quadrotor VTOL aircraft using high fidelity CFD simulations [6, 7]. In
addition, Ko et al. have analysed the noise directivity patterns depending on the diamond and square miltirotor configuration [8]. Recently Lee and Lee performed a numerical aeroacoustic study of rotor-rotor interaction by varying their mutual distance [2].
Although, several studies on the multirotor UAVs have been extensively conducted through ex-periments and numerical simulations, the analysis of the interactional aeroacoustics have not yet
been discussed in detail. In particular, the rotor interactional phenomena occurring around the
multirotor vehicles are significantly influenced by the separation distance between the adjacent
rotors.
In this manuscript, the aim is to study from an experimental point of view the aeroacoustic be-haviour of a couple of rotors by varying the separation distance, in this way the phenomenon is
simplified compared to the study of a complete drone. It deals with the interaction between two
adjacent rotors. In fact, the aeroacoustic performance of small UAVs is not simply proportional
to the number of rotors. Particular attention is given to the directivity of the noise due to the
rotor-rotor interaction. Moreover, an experimental investigation on the evolution and spatial
organization of the flow structures in twin-rotors wakes has been carried out. A preliminary
analysis of the tip vortices was performed on the instantaneous vorticity maps with the aim to
detect the location of the vortex centers measuring the main characteristics [9, 10]. In this case,
the rotor-to-rotor distance was retained constant, but the rotation speed was varied in a typical
range for drones applications.

2. Theoretical Background

Generally, the propeller aerodynamic noise is split into two main components: narrow and
broad-band contributions [11]

$$p'(x, t) = p'_{NB}(x, t) + p'_{BB}(x, t)$$

where $p'_{NB}$ is the narrow-band (or tonal) component of pressure fluctuations, whereas $p'_{BB}$
is the broad-band counterpart.

To further clarify this aspect, the two components have been represented in the Fourier
domain in Figure 1. Narrow (or tonal) components are directly associated to the periodic motion
of the blade in the surrounding fluid. Therefore, the frequency and magnitude of the radiated
noise is related to the rotational regime. For thin blades and low Mach numbers ($M < 1$), the
narrow-band contribution is given by the sum of a sound source related to blade thickness, $p'_T$,
and one related to aerodynamic loading, $p'_L$: 

$$p'_{NB}(x, t) = p'_T(x, t) + p'_L(x, t)$$
the thickness term takes into account the fluid displacement due to the body shape, while the loading counterpart takes count of the unsteady force distribution over the blade surface. On the other hand, the interaction of turbulent flow structures with the blade edge is responsible for the broad-band noise radiating from the propeller leading/trailing edge or from the blade tip. Therefore, the main sources that generate this component are:

(i) noise related to the turbulence of the incoming flow (LE noise) [12];
(ii) noise produced by the interaction of the turbulent boundary layer over the blade surface with the trailing edge (TE noise);
(iii) noise generated by the possible separation of the flow (Separation noise) [3]

Therefore, the broad-band contribution can be further divided as follows:

\[ p'_{BB}(x,t) = p'_{LE}(x,t) + p'_{TE}(x,t) + p'_{S}(x,t) \] (3)

where \( p'_{LE}(x,t) \) is the leading edge component, \( p'_{TE}(x,t) \) is the trailing edge component and \( p'_{S}(x,t) \) is the due to laminar separation bubble term.

3. Experimental Setup

3.1. Aeroacoustic setup

The aeroacoustic measurements campaign was performed within a semi-anechoic chamber at Niccolò Cusano University. A test bench was realized as described in the following, in order to measure the near field noise generated by the interaction of the twin propellers in hover condition. Three bladed propellers, type KDE-CF155-TP (15.5” × 5.3”), were mounted on vertical supports that allows to modify the distance \( d \) between them (see Figure 2). The rotor characteristics were diameter \( D = 393.7 \text{ mm} \) and the chord \( c = 28.5 \text{ mm} \). Since the blade was tapered and swept, \( c \) was referred at the mean aerodynamic chord (MAC). The resulting rotor solidity value was equal to \( \sigma = 0.138 \). The rotor solidity is defined as:

\[ \sigma = \frac{bcR}{A} = \frac{bcR}{\pi R^2} \] (4)
where \( b \) is the number of the blades of propeller, \( c \) is the mean aerodynamic chord, \( R \) is radius of the propeller and \( A \) is the rotor disk area.

Both propellers rotated counterclockwise at rotational speed \( \Omega = 2200 \text{ RPM} \), placed at three different distances \((d = 1.07D, 1.2D, 1.3D)\). Rotational speed was measured by using a Kubler incremental encoder characterized by 500 \( ppr \) (pulses per revolution).

**Figure 2.** Picture of the experimental setup located within the semi-anechoic chamber (an anechoic wall was used as a background only to take the present picture).

The rotors were driven by a KDE4012XF-400 engines and two KDEXF-UAS55 electronic speed controllers. A NI LabVIEW software was implemented to control the engine, measure the rotational regime and acquire the pressure fluctuations time series. Pressure fluctuations were sampled by using a Microphone Gefell M360 and an ACQ board type NI cDAQ-9174. All signals were acquired for 30 \( s \) at sampling frequency \( f_s = 51200 \text{ Hz} \). The microphone was mounted on a manual rotation stage in order to characterize the rotor noise directivity pattern, with a polar angle ranging from 0° to 230°, to measure the pressure fluctuations in the inflow field and wake regions as sketched in Figure 3.
3.2. TR-PIV measurement system

An experimental investigation on the evolution and spatial organization of the flow structures in twin-rotors wakes has been carried out using time-resolved PIV (TR-PIV). For this reason, a new rotor-rig has been designed and implemented (see Figure 4). The twin propellers, placed at the distance of \( d = 1.02D \) from each other, were mounted on custom-made horizontal support in order to perform TR-PIV measurements. The distance of the rotor rig from the floor was \( H = 4.37D \) to avoid ground effect.

The twin rotor was operated in hover condition at four different propeller speeds, respectively at \( \Omega_1 = 2620 \text{ RPM}, \Omega_2 = 3500 \text{ RPM}, \Omega_3 = 4360 \text{ RPM} \) and \( \Omega_4 = 5200 \text{ RPM} \). The twin rotors downwash characteristics were measured by a time resolved two-components PIV measurement system with an acquisition frequency of 2160 double frames per second equivalent to 49 images per revolution at \( \Omega_1 = 2620 \text{ RPM} \) or 25 images at the highest speed of \( \Omega_4 = 5200 \text{ RPM} \). The set up was composed by a Photonics DM 30 dual head Nd-YLF laser with an average power value of 45 W at the maximum repetition rate of 3 kHz. At the operating frequency of 2.16 kHz, the laser provided a pulse energy of about 20 mJ per pulse at the wave length of 527 nm. A system of three high speed cameras was installed consisting of two Phantom VEO 710L (7400 frame rate, \( 1280 \times 800 \text{ pixels} \), 12-bit, pixel dimension 20 \( \mu \text{m} \)) and one Phantom VEO 640L (1400 frame rate, \( 2560 \times 1600 \text{ pixels} \), 12-bit, pixel dimension 10 \( \mu \text{m} \)).

Figure 3. Sketch of the experimental setup.
In order to fully exploit the operative laser repetition rate, the VEO 640 was operated to the resolution of $1280 \times 800$ px. In order to track the blade tip vortices in the proximity to the rotor disk, the two VEO 710 cameras were equipped with a Nikkor lens featuring a fixed focal length of $200\,mm$ and the f number was set to $f\# = 5.6$ while the VEO 640 used a Zeiss lens with a fixed focal length of $100\,mm$ and the f-number was set to $f\# = 2.8$.

The sight of view of the upper camera was orthogonal to the laser plane, the lower cameras were slightly tilted with respect to the plane. For the latter cameras, Scheimpflug systems were used to avoid the out of focusing of the lateral regions.

The reference system origin was located in the rotor centre with the x-axis laying horizontally along the rotor blade, the y-axis vertically and upward directed and the z-axis following the right-hand rule (Figure 5). The measurement region was located immediately below and between the two propeller disks on a vertical plane radially ranging between $x/D = -0.115$ and $x/D = 0.125$. The dimensions of field of view (FOV) were $90 \times 130\,mm$. In order to follow the wake interaction, all cameras were mounted horizontally and the region of interest were partially overlapped. The three cameras were stitched together covering a vertical region in the range from $y/D = 0.075$ to $y/D = -0.27$. 

**Figure 4.** The TR-PIV experimental setup.
The image calibration and perspective distortion correction of the three cameras was performed using a 3D calibration plate having two planes spaced by 2 mm. The pinhole camera model was used for the calibration and distortion correction [13]. This yielded a spatial resolution of about $17.3 \text{px/mm}$ in image plane. The separation time between the laser double-pulses ranged between 40 $\mu$s to 60 $\mu$s according to the propeller revolution speed. As tracer particles, aerosolized diethylhexylsebacate (DEHS) oil was used. A seeding generator with 20 Laskin nozzles provided oil droplets with a size of less than 1 $\mu$m. The full test room was seeded in order to have a homogenous concentration of particles. The PIV images were pre-processed by applying a background grey-level subtraction. Davis 10.1 (by LaVision) was used to record and process the particle images. The particle images were further pre-processed using a sliding background subtraction and a particle intensity normalization in sliding windows of $5 \times 5 \text{px}$, to account for inhomogeneities in the laser light sheet and the varying particle intensity. The analysis consisted in an iterative multi-pass cross-correlation algorithm ending at $32 \times 32 \text{px}^2$ and 75% overlap [14][15]. A sub-pixel accuracy for the detection of the correlation peak was obtained by using a three-point Gaussian fit [16]. The results presented a velocity spatial resolution of $\Delta x = 0.46 \text{mm}$. The random noise of the PIV cross-correlation procedure can be preliminarily estimated as $0.1 \text{px}$ as a rule-of-thumb (Raffel et al. [17]). Using the current values for the optical resolution ($17.3 \text{px/mm}$) and the laser double-pulse delay (form 40 $\mu$s to 60 $\mu$s), this related to a velocity error of $\Delta V$ ranging between 0.14 m/s to 0.09 m/s for the measurements.

4. Results
In this section, the results of the aeroacoustic and aerodynamic measurements are reported. The aeroacoustic results related to the lower rotational regime (2200 RPM) and three different distances are presented and hereafter discussed. Instead, the aerodynamic results concern that ones pertaining to four different rotational regimes of the propellers at constant distance $d = 1.02D$. 

Figure 5. Cartesian coordinate system.
4.1. Aeroacoustic results

In order to characterize the noise emissions of a twin-rotor, the Overall Sound Pressure Level (OASPL) has been calculated. The OASPL is defined as follows:

$$ OASPL = 10 \log_{10} \left( \frac{\langle p'^2 \rangle}{p_{ref}^2} \right) $$

where $\langle \cdot \rangle$ denotes an ensemble average and $p_{ref}$ is a reference pressure equal to $2 \mu Pa$.

The OASPL is represented on a polar diagram of the for the three different rotor distances $d$ equals to $1.07D$, $1.2D$ and $1.3D$ (see Figure 6). For all the cases, there is an asymmetry in the angular region ranging from $0^\circ$ to $180^\circ$. OASPL exhibits the same behavior for the distances $d = 1.07D$ and $1.2D$, presenting an increment in the range between $0^\circ$ to $90^\circ$ followed by a reduction between $90^\circ$ to $100^\circ$ and a constant behavior up to $180^\circ$. Between $210^\circ$ and $230^\circ$ the sound pressure level present an increment due the wake effect. Different behaviour is observed by increasing the distance between the rotors, from $1.2D$ to $1.3D$. The OASPL trend results constant between $0^\circ$ and $90^\circ$, whilst it increases from $90^\circ$ to $180^\circ$, and the wake effect appears at smaller angles with respect to smaller distance $d$. Hence, the reduction of the distance between the rotors dramatically alters the directivity of the noise generation, promoting a reinforcement of it in the right side of the inflow region and, conversely, a reduction in the left inflow one. In other words, the interaction between rotors results in directivity angular rotation.

![Figure 6. Overall Sound Pressure Level upon the polar angle represented for the three different distances between rotors.](image-url)
Afterwards, a spectral analysis was performed in order to inspect how the interaction between the propellers affects the tonal component of the noise. The value assumed by the Sound Pressure Spectrum Level (SPSL) at an HBPF=1 (Harmonics of the Blade Passing Frequency) upon the angular position is represented in Figure 7.

\[
SPSL = 10 \log_{10} \left( \frac{PSD \Delta f}{p_{\text{ref}}^2} \right)
\]

\[
HBPF = \frac{2\pi f B}{\Omega}
\]

where PSD is the Power Spectral Density, \( \Delta f \) and \( p_{\text{ref}} \) are the reference frequency and pressure equal to 1 Hz and 20 \( \mu \)Pa respectively, \( B \) is the number of the blade and \( \Omega \) the rotational speed of the rotors.

![Figure 7](image)

**Figure 7.** Polar diagram of the SPSL calculated for HBPF=1 for all distances.

The asymmetry, already described in Figure 6, is more evident for propellers at the distance \( d = 1.07D \); conversely, this effect weakens for the cases of the propellers at higher distance. The distance between rotors plays a key role on the tonal noise, the effect is twofold, i.e., generation of a lobed pattern in the propagation of the noise and SPSL reinforcement.

In light of these considerations, flow field measurements were performed by inspecting two rotors at the configuration of minimum distance \( d = 1.02D \) and running at four rotational speed.

### 4.2. Aerodynamic results

In order to investigate and characterize the interaction between the two rotor wakes, TR-PIV measurements were carried out. In the following, the distribution of the velocity downstream of the rotors will be shown, and by velocity is mean the magnitude of the velocity vector, thus defined:

\[
V = \sqrt{v_x^2 + v_y^2}
\]

Figures 8 and 9 show the maps of the mean and root mean square (rms) velocity field, respectively, in hover condition at the four rotational speeds. The reference system (reported in Figure 5) is centered at the mid distance between the two rotors, the x and y axis are normalized with
respect to the propeller diameter, the rotor wakes follow the y-axis direction. The flow patterns exhibit typical features of that observed in rotor wakes. Interesting enough, a strong deflection of the flow direction is detected for the second test case ($\Omega = 3500\text{ RPM}$). This deflection is about $12^\circ$ with respect to the vertical direction. It is due to the phase difference between the rotor speeds. Moreover, it is observed that, for $\Omega = 2620\text{ RPM}$, the two propellers have the greatest contraction of the rotor wake, highlighted by a greater area of undisturbed flow (blue area in the Figure 8(a)).

**Figure 8.** Mean velocity fields at $\Omega = 2620\text{ RPM}(a)$, $\Omega = 3500\text{ RPM}(b)$, $\Omega = 4360\text{ RPM}(c)$ and $\Omega = 5200\text{ RPM}(d)$ at distance between the propellers of $d=1.02D$.

**Figure 9.** Root mean square (rms) velocity distributions at $\Omega = 2620\text{ RPM}(a)$, $\Omega = 3500\text{ RPM}(b)$, $\Omega = 4360\text{ RPM}(c)$ and $\Omega = 5200\text{ RPM}(d)$ at distance between the propellers of $d=1.02D$. 
The rms velocity contour (Fig. 9) highlights that most of the velocity fluctuations are associated with the generation of the tip vortices and their interaction at a distance $y = -0.08D$ from the rotor disks. Furthermore, as already mentioned, the case at $\Omega = 2620 \text{ RPM}$ (Fig. 9(a)), shows a large area of quiescent flow due to the wake contraction.

In addition, the distributions of the velocity magnitude $V$ in the $y$-direction and in the $x$-direction have been extracted from the mean velocity fields. In Figure 10, the distributions of the velocity profiles as a function of $y$ axes at five points and at fixed $x$ coordinate are illustrated. The data extraction is set along the vertical line passing through the center of the reference system ($x/D = 0$). Two lines at the tips of the blades ($x/D = \pm 0.01$) and other two ones at $x/D = \pm 0.078$ (section of the blade relative to 86% of its distance from the center of the rotor).

At the left side of the plot (Fig. 10(b)), a region of quiescent flow is recognized from $y/D = 0$ to $-0.1$ as testified by the map in Fig. 10(a). Turbulent dissipation mechanisms participate to the interaction of the incoming rotor wakes. The flow undergoes an increment of the velocity magnitude leaded by viscosity effects as testified by the overlapping of velocity profiles at the bottom side of the investigated region. In Figure 10(b), the flow exhibits symmetric wake patterns (solid red and blue lines).

**Figure 10.** Velocity magnitude colour map (a) and velocity profiles at different locations (b) at $\Omega = 2620 \text{ RPM}$. Please refer to Fig. 8 for colorbar.

In Figure 11, the distribution of the velocity magnitude as a function of $x/D$ has been outlined for the horizontal profiles at $y/D = 0, -0.01, -0.05, -0.1, -0.15$ and $-0.2$. All the distributions indicate again the presence of rotor wakes.
Figure 11. Velocity magnitude colour map (a) and velocity profiles as a function of x/D (b) at Ω = 2620 RPM. Please refer to Fig.8 for colorbar.

At Ω = 3500 RPM, there is a strong deflection of the rotor wake. In Figure 12(b), discrepancies between the solid blue curve and red solid one result more pronounced as the vertical distance increases. The distributions of velocity profiles along the six horizontal lines (see Figure 13(b)) show the deflection of the wake.

Figure 12. Velocity magnitude colour map (a) and velocity profiles at different locations (b) at Ω = 3500 RPM. Please refer to Fig.8 for colorbar.
Figure 13. Velocity magnitude colour map (a) and velocity profiles as a function of x/D (b) at Ω = 3500 RPM. Please refer to Fig.8 for colorbar.

For the case at Ω = 4360 RPM, the rotor wakes are combined in a slight deflected flow as observed in the plots of Figures 14 and 15.

Figure 14. Velocity magnitude colour map (a) and velocity profiles at different locations (b) at Ω = 4360 RPM. Please refer to Fig.8 for colorbar.
Figure 15. Velocity magnitude colour map (a) and velocity profiles as a function of x/D (b) at Ω = 4360 RPM. Please refer to Fig.8 for colorbar.

At Ω = 5200 RPM, Fig.16(b), the symmetry is preserved as proved by the red and blue dashed line; whilst, for the region inside the wake, a slight difference of the velocity profiles is observed of about 15%. The horizontal velocity profiles denote the presence of a more prominent symmetric features (see Fig.17).

Figure 16. Velocity magnitude colour map (a) and velocity profiles at different locations (b) at Ω = 5200 RPM. Please refer to Fig.8 for colorbar.
Figure 17. Velocity magnitude colour map (a) and velocity profiles as a function of $x/D$ (b) at $\Omega = 5200\ RPM$. Please refer to Fig.8 for colorbar.

As already mentioned, the wake deflection is caused by the phase difference between the azimuthal positions of the two rotors. Herein, the symbol $\gamma$ defines the phase angle of the blades with respect to the azimuthal position of the blades when aligned with the PIV measurement plane, as shown in Figure 18. It has been measured from the time information included in the TR-PIV measurements. The results are reported in Table 1.

Figure 18. Definition of phase angle $\gamma$. 
| Case | RPM  | γ   |
|------|------|-----|
| 1    | 2620 | 30° |
| 2    | 3500 | 40° |
| 3    | 4360 | 0°  |
| 4    | 5200 | 30° |

**Table 1.** Phase angle γ between the rotors.

From this preliminary analysis, the phase between the two rotors plays a key role in the interaction between the tip vortices. An angle of about 30° reduces this interaction in term of rotor wake deflection. An analysis on the locations of the travelling tip vortices is presented on for the three rotor cycle sets. The instantaneous vorticity maps enable the detection of the vortex centers and the measurement of their main characteristics. Figure 19 illustrates the scattering of the locations of the tip vortices. The colors indicate the verse of the vorticity: red dots describe counter-clockwise verse, while the blue dots clockwise verse.

At Ω = 2620 RPM (Fig.19(a)) with γ = 30°, it is possible to observe, as seen previously from the analysis of the mean velocity fields, that between y/D = 0 and y/D = −0.05 there is a region where the contracting of the rotor downwash is maximum. After this interval, a branching of the shear layer occurs, in particular the shear layer of the second propeller is splitted into four paths highlighted in Figure 19(a). A weak vortex tip interaction takes place in a region between x/D = −0.02 and x/D = +0.02, resulting in an alteration of the classical rotor downwash shape.

The test case at Ω = 3500 RPM (Fig.19(b)) and with γ = 40°, shows a strong deflection of the rotor tip shear layer of the propeller 1 and a strong interference among the tip vortices in a region between x/D = 0 and x/D = +0.04 (dotted black rectangle). Also, in this case there is a loss of the wake’s vortex structure at y/D = −0.06. Fig.20 shows an interaction of a counter-rotating vortex pair (dashed green circle).

At Ω = 4360 RPM (Fig.19(c)) with γ = 0°, the loss of the vortex structure of the wake occurs almost instantaneously, in fact after y/D = −0.02 it is possible to observe a marked bifurcation of the shear layer of the two propellers, with an interference among the tip vortices in a wide area between x/D = −0.05 and x/D = +0.05 until the wake approaches coordinate y/D = −0.25. Finally, for Ω = 5200 RPM (Fig.19(d)) with γ = 30°, between y/D = 0 and y/D = −0.05 there is a region where the contracting of the rotor downwash is maximum, then the wake loses its preferential direction and at y/D = −0.1 it starts a slight interaction between the tip vortices in a region between x/D = −0.02 and x/D = +0.02.
Figure 19. Tip vortex scattering at $\Omega = 2620 \text{ RPM}(a)$, $\Omega = 3500 \text{ RPM}(b)$, $\Omega = 4360 \text{ RPM}(c)$ and $\Omega = 5200 \text{ RPM}(d)$. 
Figure 20. Instantaneous vorticity field at $\Omega = 3500$ RPM.

Tab.2 shows the average vorticity values for the four test cases moving away from the rotors plane, specifically for five intervals $I$ defined as follow:

$$I_1 = \{y/D \in \mathbb{R} \mid -0.05 \leq y/D \leq 0.00\}$$
$$I_2 = \{y/D \in \mathbb{R} \mid -0.10 \leq y/D < -0.05\}$$
$$I_3 = \{y/D \in \mathbb{R} \mid -0.15 \leq y/D < -0.10\}$$
$$I_4 = \{y/D \in \mathbb{R} \mid -0.20 \leq y/D < -0.15\}$$
$$I_5 = \{y/D \in \mathbb{R} \mid -0.25 \leq y/D < -0.20\}$$

Comparing these values with the Figure 19 it is possible to observe that both in case with phase shift angle $\gamma = 30^\circ$, Fig.19(a) and (d), the vortex interaction occurs in an area (interval $I_3$) where there is a loss of vorticity intensity equal to about 50% relative to vortices released at area closest of the tip of the blade.  
In the test case with $\gamma = 40^\circ$, Fig.19(b) the vortex interaction starts in an area (interval $I_2$) where there is a loss of vorticity intensity equal to only about 7%, therefore the interaction occurs between more energetic vortices.
Finally, analyzing the case in which the two propellers rotate in phase $\gamma = 0^\circ$, Fig.19(c) the vortex interaction starts in an area (interval $I_2$) where there is a loss of vorticity intensity equal to about 40% and the distribution of counter-rotating vortices occupies a major area compared to the other cases.
Therefore, it can be assumed that, with phase shift angle $\gamma = 30^\circ$, the tip vortices interaction takes place in an furthest area away from the plane of the rotor disk, where the vortices will have a lower vorticity magnitude. It is well known that the large flow fluctuation with high turbulence intensity is closely related to the aerodynamic noise generation [18]. The distributions of the high velocity fluctuation correspond well to the vortex structure. So, the tip vortex plays a major role in the flow fluctuation related to the aerodynamic noise generation.

Table 2. Comparison of the average vorticity $\omega_z$ at the y-coordinate variation. In detail $\omega_1$ at $\Omega = 2620\,RPM$, $\omega_2$ at $\Omega = 3500\,RPM$, $\omega_3$ at $\Omega = 4360\,RPM$ and $\omega_4$ at $\Omega = 5200\,RPM$.

|   | $\omega_1$ [1/s] | $\omega_2$ [1/s] | $\omega_3$ [1/s] | $\omega_4$ [1/s] |
|---|-----------------|-----------------|-----------------|-----------------|
| $I_1$ | 14172           | 18410           | 27210           | 28118           |
| $I_2$ | 8766            | 17144           | 16551           | 26161           |
| $I_3$ | 6358            | 11305           | 11421           | 14313           |
| $I_4$ | 6336            | 9333            | 8345            | 11899           |
| $I_5$ | 4548            | 8080            | 6651            | 10803           |

5. Conclusions & Future Developments

A preliminary aeroacoustic measurements campaign was performed in a semi-anechoic chamber to study the acoustic signature of twin rotors for drone propulsion. As a main outcome, the shortening of the distance between rotors induces a significant increase in noise amplitude from 0° to 90°, especially for the tonal component. The noise increase is due to rotor-rotor interaction, which is demonstrated to exhibit a strong directivity. In addition, to the increase in the noise tonal component, rotor-rotor interaction is observed to generate a further effect: the rotation of directivity as the distance between rotors is varied. For these reasons, an experimental investigation on the evolution and spatial organization of the flow structures in twin-rotors wakes has been carried out using time-resolved PIV, in order to visualise the intricate flow patterns characterized by periodic vortical structures in the wake of the rotors at the relative distance of $1.02D$. Each rotor was characterized by three bladed propellers with diameter of $D = 393.7\,mm$ running at four different speeds (2620, 3500, 4360, 5200 RPM). The analysis of the mean velocity field showed a typical structure of the flow downstream of the rotors in all test cases, although, with deflections of the rotor wakes. In addition, the rms velocity contour showed that the wake geometry and induced flow structure behind the rotor tend to be radially dragged down toward the middle point of the twin rotors due to the existence of the adjoining rotor, which consequently results in wake-to-wake interaction and the formation of asymmetric wake structures although the multirotor operates under the hovering condition. The vortex core was also found to be attracted to the nearby rotor. These phenomena are believed to be closely related to the Coanda effect that the induced airflow behind the twin rotors would be attracted and bent toward the nearby rotor. The phase angle $\gamma$, between the two rotors, has been calculated due to the high temporal and spatial resolution of TR-PIV measurement. This angle plays a key role in the interaction between the tip vortices, in particular, it was seen that $\gamma$ of about 30° greatly reduces this interaction. In fact, when the two propellers rotate with a phase of 30° between them, the interaction between the tip vortices occurs further away from the rotors themselves, and therefore with a much lower vorticity magnitude (around 50% with respect to the vortices released at the tip).

The future developments will be to perform an experimental investigation in semi anechoic
chamber at CIRA through microphones mounted on a semicircular array and perform an fluid dynamic characterization by PIV acting mainly on three parameters: distance $d$, rotation speed $\Omega$ and phase $\gamma$, in order to find an optimal phase angle to reduce the noise generated by the interaction of the tip vortices.

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