Rotor Wake impinging a finite-span cylinder by Time-Resolved PIV measurements

G. Ceglia¹*, T. Astarita², F. De Gregorio¹

¹CIRA Italian Aerospace Research Centre, Aerodynamic Measurement Methodologies Laboratory, Capua, Italy
²University of Naples “Federico II”, Department of Industrial Engineering, Naples, Italy
g.ceglia@cira.it

Abstract

The dynamical behavior of a rotor wake impinging on a finite-span cylinder has been investigated by means of Time-Resolved Particle Image Velocimetry (TR-PIV). The rotor wake was generated by a four-bladed isolated rotor of radius \( R = 360 \text{ mm} \), the rotating frequency was set either at \( \Omega = 26.6 \text{ Hz} \) or 29.9 Hz. The experiments were conducted in hover conditions with the rotor wake impinging on a finite-span cylinder with a diameter of 100 mm representative of a slung load. It is found that, on average, the wake remains attached over most of the cylinder curvature. The modal analysis through Proper Orthogonal Decomposition (POD) of the velocity field elucidates the large-scale coherent structures impinging over the cylinder surface and pulsating predominantly at the rotor frequency. These structures influence the flow behavior over the cylinder surface and the so-formed wake further downstream. Furthermore, the periodic characteristics of the incoming rotor wakes impose bursts of the intensity of instantaneous vertical velocity. This in turn energizes the flow in the proximity of the cylinder surface, promoting the reattachment. Small-scale vortices participate in the build-up of the turbulence.

1 Introduction

The need of transporting bulky loads outside the fuselage of helicopters or drones has gained intensive efforts for unveiling their dynamical behavior (Bernard and Kondak 2009). In rotorcraft operations, it is often required the transportation of suspending loads underneath the rotorcraft, that can significantly affect the aerodynamic performances. Most of these slung loads behave like non-aerodynamic bodies promoting instabilities in forward flight or hover conditions. The mutual interaction of the rotor wakes investing the slung load can trigger undesired fluctuations that, under certain conditions, diverge in catastrophic effects. From a merely dynamical consideration, the pendulum movements of the suspended load interfere with the smooth operation of the helicopter to form an unstable system. Gupta and Bryson (1976) proposed a mathematical model for the control of a helicopter carrying a slung load in hovering or in slowly forward flight. It was considered the presence of an intrinsic damping featuring the model stemming from a coupled system composed of helicopter-hanging. It should be underlined that the dynamics of this system are more sophisticated than simple point-mass dynamics (Bernard and Kondak 2009). There are several complications to consider, one of them relies on the role of the flow investing the slung load (Theron et al. 2006, Visingardi et al. 2017, De Gregorio et al. 2018, 2021). Theron et al. (2006) studied via numerical simulations the aerodynamics of a helicopter with a slung load carrying out a flow field characterized by massively separated flows around the bluff body. Visingardi et al. (2017) elucidated the basic understanding of the aerodynamic forces undergone by obstacles invested from rotor wakes. They outlined the three-dimensional organization of the rotor wakes and the dissipation of the coherent vortical structures shed from the rotor blades encountering an obstacle beneath. Successively, De Gregorio et al. (2018) explored both by numerical simulations and experiments a rotor wake generated by a four-bladed rotor impinging a finite-span cylinder, representing a slung load, at different distances from the rotor disk. They outlined that the overall effect due to the presence of the cylinder is the contraction of the rotor wake if compared to the case of the free rotor wake. It is evident from the present brief survey that studies devoted to understanding these
effects are needed for investigating the main dynamical characteristics of the wake flow imping a bluff body as representative of a slung load.

The present work focuses on the dynamics of the wake flow generated by a four-bladed rotor impinging over a finite-span cylinder placed at approximately one radius from the rotor disk. The rotor rig and the cylinder coincide with that already presented by De Gregorio et al. (2018 and 2021). To unveiling the flow evolution, time-resolved particle image velocimetry (TR-PIV) has been used to resolve simultaneously in space and time a region in the vicinity of the cylinder. This allows for the inspection of the dynamics of the coherent structures participating in the flow field.

2 Experimental setup

The experiments were carried out at the Aerodynamic Measurement Methodology laboratory in CIRA. A four-blade rotor of an existing commercial radio-controlled helicopter model (Blade 450 3D RTF) was operated in hover conditions. It is worth to underline that the tail boom and tail rotor were removed. The blades have a rectangular planform with a span length of $R = 0.36$ m, thus covering a diameter of $2 \times R = 0.72$ m, and chord length of 0.0327 m. The airfoil section follows a NACA 0013 shape along the span direction. The root cut-out is at 16% of the radius, thus resulting in a rotor solidity of 0.116. The maximum rotational speed attains to $\Omega = 30$ Hz in a clockwise direction, able to vary the collective pitch angle between $0^\circ$ up to $12.2^\circ$.

On the other hand, the slung load is represented by a finite-span cylinder with a diameter of 100 mm and a span length of 200 mm, immersed in the rotor wake. In Figure 1 (left), it is placed at $x = 205$ mm ($x/R = 0.57$) and $z = -412$ mm ($z/R = -1.14$). The reference system origin is located at the center of the rotor hub, with the $x$-axis oriented horizontally along the rotor blade, the $y$-axis planar to the rotor disk and orthogonal the $x$-axis and the $z$-axis vertically upward directed.

The inspection of the evolution of the rotor wake impinging the cylinder was performed by time-resolved (TR) two-component PIV measurements. Aerosolized diethylhexylsebacate (DEHS) droplets of diameter less than 1 $\mu$m were used as tracer particles. A homogenous concentration of the particles populated the testing room. The illumination was provided by a Photonics DM 30 dual head Nd-YLF laser with a pulse energy of 20 mJ at the wavelength of 527 nm for an operating frequency of $f_s = 720$ Hz. The time separation between the laser pulses was set at 60 $\mu$s. A high-speed camera was installed by imaging half-part of the cylinder as illustrated in the iso-contour of Figure 1 (right). The model was a Phantom VEO 640L, 1400 frame rate, 2560 × 1600 pixels, 12-bit, pixel dimension 10 $\mu$m, and it was equipped with a Zeiss lens with a focal length of 100 mm set at an aperture of $f\# = 2.8$. The final measurement region covers a field of view (FOV) of size of $117 \times 187$ mm$^2$, yielding a spatial resolution of 13.62 pixel/mm. The periodic phenomenon was sampled by synchronizing the TR-PIV system through a hall effect trigger that was also used to monitor the rotational speed of the rotor rig. Two rotational speeds were considered either $\Omega = 26.6$ Hz or 29.9 Hz; 50 cycles were captured by discretizing each one in 26 or 22 phases, resulting in a phase resolution of 13.9$^\circ$ and 16.4$^\circ$, respectively for an acquisition time of 1.67 s. The acquisition and the computation of pre- and post-processing analyses were conducted using DaVis 10.1 by LaVision. The quality of the raw images was improved by subtracting a sliding background. The undesired reflections of the laser light impinging on the cylinder surface were masked-off to avoid the presence of spurious vectors. The particle displacement was calculated by an iterative multi-pass cross-correlation algorithm ending at $32 \times 32$ pixels and 75% overlap (Wereley and Meinhart 2001; Westerweel et al. 1997). A sub-pixel accuracy for the detection of the correlation peak was obtained by using a three-point Gaussian fit (Willert and Gharib 1991). The resulting vector pitch attains to 0.588 mm.

Furthermore, the hover induced velocity $V_h$, evaluated from the momentum theory, reads as in Eq. (1).

$$V_h = \Omega R \sqrt{C_T / 2}$$

(1)

where, $C_T = 5.5 \times 10^{-3}$ indicates the thrust coefficient, which is retrieved from earlier measurements conducted by Ceglia and De Gregorio (2022).
Results and discussion

3.1 Flow characterization

For both rotating speeds, the flow patterns are dominated by the wake impinging on the cylinder; hence, for conciseness, only the case of $\Omega = 29.9$ Hz is discussed. In Figure 2 are shown, for the time-average flow field, the stream lines and the iso-contours of the vertical velocity component $\bar{W}/V_h$ in panel (a) and the iso-contours of the root mean square (rms) of the velocity fluctuation $w_{rms}/V_h$ in panel (b). The impinging flow remains attached over the cylinder surface till detaching at an angle of approximately $138^\circ$, where the null angle is located at the cylinder stagnation point. The stream traces underline the curvature of the flow influenced by the presence of the cylinder. The vertical velocity component intensifies in the proximity of the cylinder where the maximum expansion of the flow is expected. The inspection of $w_{rms}/V_h$ reveals a dominant peak activity approximately at the rear recirculation region of the cylinder. It can be ascribed to separation phenomena occurring at $138^\circ$. Slightly weaker peaks of turbulent concentrations are detected further downstream the cylinder $-1.36 \leq Z/R \leq -1.30$, and downstream the expansion of the flow $-1.39 \leq Z/R \leq -1.22$ at $X/R = 0.80$. This indicates the presence of large-scale coherent structures that participate in the build-up of the flow.

3.2 POD analysis

The dynamic behavior of the flow fields reflects the periodicity of the rotor wake. The large-scale coherent structures are retrieved by means of a POD analysis, conducted on the instantaneous velocity fields for the two rotor speeds. The spectra of the POD eigenvalues are plotted in percentage of the total kinetic energy across the modes for $\Omega = 26.6$ Hz and $29.9$ Hz in Figure 3 (a) and (b), respectively. The first mode captures either $\sim 15.0\%$ or $\sim 16.4\%$ for $\Omega = 26.6$ Hz or $29.9$ Hz, respectively, with a smooth decrease of the kinetic energy across the higher modes, indicating the absence of pairing between the most energetic modes.
Figure 2 Iso-contours of the time average flow field with stream-traces color coded with the vertical velocity component $\bar{W}/V_h$ (a) and corresponding rms of the velocity fluctuation $w_{rms}/V_h$ (b) for $\Omega = 29.9$ Hz.

Figure 3 Spectra of the POD eigenvalues in percentage across the first 20 modes for the rotor frequency $\Omega = 26.6$ Hz (blue) and 29.9 Hz (green).

Since the flow fields are inherent to time-resolved measurements, the corresponding time coefficients $\mu_i(t)$ preserve their correlation in time, including spectral information intrinsic to the evolution of the coherent structures. From the inspection of the frequency content of each $\mu_i(t)$ (correspondent to the most energetic ones), it is found that the rotor wake impinges over the cylinder surface with a characteristic flow
pulsating at the rotor frequency. For $\Omega = 26.6$ Hz, modes #6, #10 and #12 capture the dominant pulsation at the rotor frequency; whereas, for $\Omega = 29.9$ Hz, it occurs for modes #7, #10 and #12. Figure 4 shows for each $\mu_i(t)$ the power spectral density (PSD), where $i = 6, 10, 12$ for $\Omega = 26.6$ Hz or $i = 7, 10, 12$ for $\Omega = 29.9$ Hz. It should be noted that secondary frequencies are captured, which concur with the build-up of the flow structure at the selected kinetic energy.

Figure 4 Power spectral densities (PSDs) of the time coefficients $\mu_i(t)$, where $i = 6$ (a), 10 (b), 12 (c) for $\Omega = 26.6$ Hz, and $i = 7$ (d), 10 (e), 12 (f) for $\Omega = 29.9$ Hz. Dominant peaks are indicated by texted arrows.

The corresponding spatial structures are illustrated in Figure 5 for $\Omega = 26.6$ Hz and 29.9 Hz, along the first and the second lines, respectively. The spatial organization of the modes #6 and #7, shown in panels (a) and (d), respectively, describe large-scale structures located at the right-top side of the FOV; smaller ones are detected at the bottom and in the proximity of the cylinder surface. Interestingly enough, these structures favor the flow separation over the cylinder surface, as testified by the orientation of the velocity vectors in that proximity. In Figure 5 (b), a large-scale recirculation locates further downstream of the cylinder at coordinates $X/R = 0.66$ and $Z/R = -1.51$, characterizing the decomposition for $\Omega = 26.6$ Hz. On the other hand, for $\Omega = 29.9$ Hz mode, #10 describes spatial structures leading to the reattachment of the flow over the cylinder surface, as highlighted by the vectors following the cylinder curvature at coordinates $X/R = 0.67$ and $Z/R = -1.24$ in Figure 5 (e). For both investigated rotor speeds, mode #12 exhibits large-scale structures scattering in the FOV, describing vortices coming from the rotor wake (Figure 5 c) or recirculation flow due to flow separation (Figure 5 f).
Figure 5 POD modes #6 (a), #10 (b), #12 (c) for $\Omega = 26.6$ Hz and #7 (d), #10 (e), #12 (f) for $\Omega = 29.9$ Hz of the velocity field describing large-scale structures pulsating dominantly at $f = 26.6$ Hz and 29.9 Hz, respectively. Iso-contours of $\frac{W}{V_h}$ with in-plane velocity vectors are shown every twelve measured points.

3.3 Instantaneous flow field

Three realizations of the instantaneous velocity field for the rotor speed at $\Omega = 26.6$ Hz are reported in Figure 6, in which the burst of induced velocity imposed by the rotor slipstream over the cylinder surface is clearly depicted. It is worth underlining that the argumentations explored in the following for the case $\Omega = 26.6$ Hz can be outlined similarly for $\Omega = 29.9$ Hz; hence, for conciseness not reported herein. In Figure 6 (a), the flow in the proximity of the cylinder remains attached to the surface experiencing the increment in intensity of the velocity vector. Whereas, moving away from the cylinder wake, the shear layer embeds small vortical structures as highlighted by the iso-lines of positive $QR^2/V_h^2$. Here, the Q criterion (Jeong and Hussain 1995) is used for the vortex visualization. In Figure 6 (b), the rotor wake releases its momentum content by means of a burst in the intensity of the vertical velocity, this, in turn, energizes the flow in the vicinity of the rear side of the cylinder. This effect culminates with a remarkable increment of the velocity intensity promoting the reattachment of the flow in the rear of the cylinder as shown in Figure 6 (c). At the boundary of the velocity burst, small vortices scatter indicating the turbulent features triggered by the incoming rotor wake. This phenomenon is intermittent, which destabilizes the flow delaying separation events at the rear of the cylinder.
Figure 6 Iso-contours of instantaneous flow field color-coded with the horizontal velocity component with in-plane vectors shown every twelve measured points at $tV_h/R = 0$ (a), 44.6 (b) and 160.5 (c) for $\Omega = 26.6$ Hz. Iso-lines of positive $QR^2/V_h^2$ describe the organization of the vortical structures.

4 Conclusions

An experimental investigation of the rotor wake flow impinging a finite-span cylinder has been carried out by means of TR-PIV measurements. The main flow, on average, remains attached on most parts the cylinder surface, leaving a small rear part under recirculating flow. It is found a dominant activity of turbulent concentrations in the proximity of the rear side of the cylinder.

The dynamical behavior of the rotor wake manifests the presence of large-scale coherent structures, captured by a POD analysis, being the most prominent at a pulsating frequency corresponding to that of the rotor. It is found that these large-scale structures influence the separation event of the flow over the cylinder and participate in the build-up of the cylinder wake further downstream.

The inspection of the flow evolution by means of the instantaneous velocity field reveals the periodic characteristics of the rotor wakes which impose bursts of intensity of vertical velocity. These periodically energize the incoming flow impinging over the cylinder surface, promoting reattachment. Furthermore, small-scale vortices scatter along the boundary of the burst front. The present findings testify that the flow around a slung load, which here is represented by a finite-span cylinder, is strongly influenced by the rotor wake.

References


