Four blades rotor model aerodynamic characterization and experimental investigation of rotor wake and sling load interaction

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Abstract. An experimental study has been carried at the Aerodynamic Measurement Methodology laboratory of CIRA (Centro Italiano Ricerche Aerospaziali). The scope of the investigation was the characterization of the loads and of the wake behaviour of a scaled rotor test rig simulating a drop test. A 3D circular cylinder was selected as representative of a typical sling load, the experimental set up having been carefully designed also with the aid of FEM analyses. The overall performances of the scaled rotor have been retrieved by the measure of its Figure of Merit and several measurements have been performed to characterize the wake and the pressure load upon the cylindrical body. The wake flow has been carefully analysed by PIV measurements and a tracking algorithm has been implemented to identify and characterize the tip vortices. The overall properties of the wake have been retrieved and a qualitative description of the tip vortices evolution and of their properties is proposed.

1. Introduction
A drop test is a method of testing the in-flight characteristics of prototype or experimental aircraft and spacecraft by raising the test vehicle to a specific altitude and then releasing it. Test flights involving powered aircraft, particularly rocket-powered aircraft, may be referred to as drop launches due to the launch of the aircraft's rockets after release from its carrier aircraft.
In the case of unpowered aircraft, the test vehicle falls or glides after its release in an unpowered descent to a landing site. Drop tests may be used to verify the aerodynamic performance and flight dynamics of the test vehicle, to test its landing systems, or to evaluate survivability of a planned or crash landing. This allows the vehicle's designers to validate computer flight models, wind tunnel testing, or other theoretical design characteristics of an aircraft or spacecraft's design.
An example of this are: the test NASA X40-A free flight test carried out in 2001 [1], followed by the German vehicle PHOENIX in 2004 [2], the European ESA-IXV in 2013 [3] and the glide test performed by Sierra Nevada Corporation Dream Chaser mock up on November 2017 [4].
Figure 1: Drop-test model of ESA's Intermediate eXperimental Vehicle - IXV (left picture) and Dream Chaser space vehicle carried by helicopter at the requested quote in order to perform is first glide test (right picture)

In these cases, the carrier helicopter releases the space vehicle to a specific altitude in order to verify the manoeuvrability and to validate the autonomous guidance and navigation systems. The starting drop test condition can be crucial for the correct fulfilment of the mission and is directly influenced by the rotor wake downwash. During the ESA-IXV test activities, it was clear that quite few information were available in literature regarding the rotor wake downwash at medium large distance from the rotor disk and the aerodynamic induced loads on the tethered test article. This shortage of information drives the interest of actual research in order to investigate the rotor wake behaviour up to 1.5 rotor diameter (D) distance from the rotor disc in hover conditions and the induced loads on a sling loads immersed in wake. The present research was carried out in the framework of the GARTEUR (Group for Aeronautical Research and Technology in Europe) Action Group 22 aimed at investigating “Forces on Obstacles in Rotor Wake” [5] that saw the involvement of several research institutes and universities in Europe (Visingardi et al in 2017).

2. Experimental Set up
The test campaign was performed in free air at the CIRA Aerodynamic Measurement Methodology laboratory. A dedicated rotor test rig was developed and built. The rotor rig was based on the R/C helicopter model Blade 450 3D RTF, but largely customized (Figure 3). The two blades rotor head was replaced by a four blades rotor head with collective and cyclic control, the chassis was re-designed with Autodesk Inventor software and a finite element analysis was performed to verify the structural integrity of the chassis.

The reference system has z-axis centred on the axis of the crankshaft with upward direction, x-axis in the direction of forward motion of the helicopter and y-axis which completes a right-handed coordinate system.

All the other components of the model which constitute a constraint of the same have been modelled, such as the support for the motor, the bearings, the motor shaft, the cogs, the servocontrols, etc. to verify the actual assembly of the whole and to verify the absence of interferences among the various components.
In order not to burden the FEM calculations and the creation of the mesh, an analysis on the assembled model excluding the rotor head and bolt connections have been carried out (Figure 2). A bounded type contact was used between the various components, the bonded contact simulates rigid bonding of faces to each other. The following mesh settings have been set:

- Average Element Size: 0.1 (The value is a fraction of longest model dimension in x, y or z direction)
- Minimum Element Size: 0.2 (Specifies the minimum distance between mesh nodes. The value is a fraction of the mesh Average Size value.)
- Grading Factor: 1.5 (Specifies the maximum ratio of adjacent mesh edges for transitioning between coarse and fine regions)

The mesh has been eventually created with curved edges and faces. With the settings outlined above a mesh of 302,653 elements with 503,283 nodes was obtained.

Two static analyses were carried out, assuming in the first case a traction of 20N (value that was chosen as the limit threshold for the tests) and a second case with traction 30N, for safety. Gravity has also been added as an external force that acts upon the entire mechanism.

The results of the analysis are shown in table 1.

| $F_z = 20N$ | Axis x | Axis y | Axis z |
|-------------|--------|--------|--------|
| Displacement Max [mm] | 0.001909 | 0.0003759 | 0.006166 |
| $F_z = 30N$ | Axis x | Axis y | Axis z |
| Displacement Max [mm] | 0.002633 | 0.000578 | 0.009255 |

Table 1: Results of finite element analysis

Figure 2: Displacement along axis z with $F_z = 20N$
The chassis was realized using thermoplastic ABSplus by means of an additive material three dimensional printer. In order to withstand the rotor thrust once fixed to the six-component load cell, the tail boom and the tail rotor were removed.

The rotor had a radius of $R = 360 \text{ mm}$, equipped with four straight (no-swirled) rectangular blades with chord length of $c = 32.7 \text{ mm}$ and NACA0013 airfoil, resulting in a rotor solidity value of $\sigma = 0.116$. The rotor maximum speed was $\omega = 1780 \text{ RPM}$ and the collective pitch angle varied from 1 to 11.3 degree. A six components balance (ATI MINI40) equipped the rotor rig and one hale sensor (Figure 4) measured the rotating frequency and provided a trigger TTL signal in order to allow phase locked measurements.

A 3D circular cylinder having length $l = 200 \text{ mm}$ and diameter $d = 100 \text{ mm}$ was selected as representative of a typical sling load, such as the oil drums or the engine canisters investigated by Gobel and Wilson in 1968 [6] and Prosser and Smith in 2014 [7]. The cylinder is equipped with 19 pressure taps: 15 taps azimuthally equally spaced ($\Delta \phi = 20^\circ$) on the symmetry plane and 5 taps spanwise distributed at the top of the cylinder (Figure 5). A ZOC33/64 differential pressure transducers, with a full scale value of 2488 Pa and measurement accuracy of 0.2% of the full scale, was connected to the pressure taps and installed inside the cylinder.
The test campaign foresaw:

- The four-bladed rotor hover conditions characterizations by the measurement of the figure of merit (FM) obtained by varying the rotating speed and the collective angle;
- the rotor wake downwash characterization by PIV measurements with and without the presence of the sling load, located at different vertical distances from the rotor disk (1 R, 2 R and 2.5 R);
- the measurements of the pressure distribution on the cylinder located at different distances from the rotor disk.

The rotor downwash characteristics were measured by a standard two components PIV system. The system was composed by a double head Nd-Yag laser with a maximum energy of 320 mJ per pulse at 532 nm and a single double frame CCD camera (2048 by 2048 px) with a 50 mm focal length. The camera was mounted on a two components linear translating system in order to cover the full region of interest. The light sheet was moved along the vertical direction in order to cover the full wake downwash starting from the rotor disc (Figure 6). Particle images have an approximate diameter of ~2 pixels and seeding was performed by means of DEHS oil.
The full wake measurement covered a region of about 1 $m^2$. This region was covered by generating a grid of 10 PIV region of interest (ROI) with size of 320 by 320 mm$^2$ partially overlapped. The spatial resolution was increased in the vicinity of the rotor disk chosen in order to track the blade tip vortices. These measurements were performed using a 200 mm focal length providing a measurement size of 120 x 120 mm$^2$. The different measurement regions and the area covered by the PIV ROI are shown in Figure 7 for all the investigated cases.

![PIV measurement regions](image)

**Figure 7: PIV measurement regions for the different test conditions: free wake, cylinder in the rotor downwash respectively at z= 1 R, z=2 R and z=2.5 R**

### 3. Results

#### 3.1 Rotor rig characterization

The aerodynamic behaviour of the helicopter rotor model in hover conditions was characterized by varying the rotor speed and the collective pitch angle in the full operative range. Forces and moments generated by the rotor rig were measured by means of the six components balance and particular care was taken on the measurement of the thrust (T) and torque moment (Q) in order to estimate the rotor (FM). The FM is defined as the ratio between the ideal power for a rotor in hover obtained from momentum theory and the actual power consumed by the rotor. The ideal power $P_{ideal}$ is defined as the product between the rotor thrust (T) and the induced velocity ($V_i$) $P_{ideal} = T \cdot V_i$, whereas the real power consumed is given by the product between the rotor torque and the rotating speed: $P_{means} = Q \cdot \omega$. As a result, the Figure of Merit equation can be defined as:

$$FM = \frac{T \cdot V_i}{Q \cdot \omega} = \frac{T \cdot (\omega R \sqrt{C_T})}{Q \cdot \omega} = \frac{TR \sqrt{C_T}}{Q}$$
Figure 8: Rotor figure of merit compared to the modified momentum theory discussed in Leishman 2000 and the rotor measured data from Bagai and Leishman 1992 [8]

The obtained FM is presented in Figure 8. It can be observed that the present test model FM has a behaviour similar to that of literature data (Bagai and Leishman 1992) obtained on a real helicopter in hover conditions, its magnitude increasing as $C_T$ increases up to a constant value. The maximum FM, corresponding to $F = 0.48$ at $C_T = 0.006$, was selected as the reference rotor testing condition for the flow field wake characterization and sling load investigation, presented in the following sections. More specifically, all the tests were performed at rotor thrust of $T = 12N$ and at a rotating speed of $\omega = 1740 RPM$.

3.2 Velocity Field analysis
The rotor downwash behaviour for the case of free wake is shown in Figure 9 where the velocity magnitude is reported with the streamlines superimposed.

The typical structure of the flow tube downstream of a rotor can be observed, with larger speeds near the blade tip which, moving away from the rotor disk, gradually decreases. Moreover, it is possible to appreciate the symmetrical nature of the wake, even if, given the presence of the support rod of the model, the left side is slightly deviated towards the inside.

The flow behaviour in the region up to a distance of 1.5D from the rotor is of considerable interest. It can be observed that the kinetic energy of the wake decrease, since the velocity decreases from about 8.5 m/s (near the blade) to about 6 m/s (at 1.5 D), corresponding to a reduction of about 30%.
The free wake rotor downwash behaviour and the case with the presence of the sling load located at distance from the rotor disc of $z = 0.5 \, D$ are compared in Figure 10 in terms of ensemble average velocity fields. Analogous comparison between the rotor free wake and the case with the sling load located at $z = 1 \, D$ is presented in Figure 11. The distortion of the wake due to the presence of the obstacle can be clearly observed in both cases.
The maximum distance between the cylindrical body and the rotor disk was 1.25 D and for this test case PIV measurements were made only near the sling load. The velocity field as well as the corresponding streamlines are reported in the color plot in the left of the Figure 12.

In order to compare the free wake behaviour with to respect to the cylinder flow field both frames are plotted in the right side of the Figure 12. It can be observed that the two configurations do not match with each other thus supporting the idea that the cylinder considerably modifies the topology of the rotor wake.

In the mid region of the flow tube, contrary to what happens at the edge, the velocity has a lower value near the blades and increases moving away from the rotor disk up to about 6.2 m/s.
This behaviour is due to the presence of the fuselage that hinders the formation of the wake, which acquires kinetic energy and homogenizes at about 1.2 D away from the rotor. Figure 13 reports a comparison of the velocity evolution between the free wake and the wake in the presence of the cylinder.

![Evolution of vertical component of velocity at R=0](image1.png)

**Figure 13: Evolution of vertical component of velocity at R=0**

3.3 Pressure Field analysis

The static pressure has been acquired on the cylindrical body by means of the ZOC pressure transducer, simultaneously with the velocity fields. Figures 14 and 15 shows the trends of the pressure field around the cylinder versus the PTS location at the three studied test cases. The PTS location is shown in Figure 5.

![Distribution of pressure around the cylinder](image2.png)

**Figure 14: Distribution of pressure around the cylinder**
The graph shown in Figure 14 reflects the classic trend of the pressure field around a cylinder immersed in a fluid. The slight dissymmetry of the field is due to the presence of the model's support rod. It is interesting to observe that the increment of the distance between the cylinder and the model induces a growth in the surface pressure variation $\Delta p$. This result is in full agreement with what has already been seen in Figure 13 where, in the area inside the rotor downwash, the highest speed of the wake was observed at the largest distance from the rotor disk.

### 3.4 Vortex Tip

The formation of tip vortices at the tip of the blades has been analysed through dedicated PIV acquisitions. Some parameters of the experimental set-up have been modified, since the PCO-2000 camera has been equipped with a 200 mm lens and the image frame has been reduced to $120\times120$ mm$^2$. As shown in Figure 16, the analysis of the instantaneous velocity field, highlights the vortex structures and the helical flow pattern.

**Figure 16: Instantaneous out-of-plane vorticity colour map, showing blade tip vortices**
The vortex centre has been tracked by visual inspection of the velocity field and the coordinate (x, z) of to the vorticity peak was recorded. Totally 216 tip vortices have been identified having analysed 95 images. The distribution of the tip vortices location is reported in Figure 17. From this figure, four zones can distinguished:

- Zone 1 (from 0 to -0.05 z/R): compact distribution of vortices that follows the trend of the flow tube and is characterized by high vorticity;
- Zone 2 (from -0.05 to -0.3 z/R): homogeneous distribution of the tip vortices with slightly lower vorticity values;
- Zone 3 (from -0.3 to -0.5 z/R): less homogeneous distribution, the linearity of the edge of wake is lost, vorticity decreases of about of 30%;
- Zone 4 (from -0.5 to -0.8 z/R): disordered distribution of the tip vortices with consequent relevant decrease of vorticity.

Table 2 shows the average vorticity values for each area analysed clearly highlighting the vorticity decrease for increasing distances from the rotor disc.

| Zone      | Vorticity ω [1/s] |
|-----------|-------------------|
| Zone 1    | ω = 14'420.61     |
| Zone 2    | ω = 12'486.21     |
| Zone 3    | ω = 10'395.89     |
| Zone 4    | ω = 7'311.51      |

Table 2: Vorticity values
4. Conclusions
An experimental measurement campaign was successfully performed to characterize the wake of a scaled rotor and its interaction with a sling load. Several tests have been performed, including velocity fields measurements through PIV in the wake, pressure measurements on the surface of a circular cylinder representative of a typical sling load and forces/moments measurements using a customized balance. The choice of a cylinder as a structure representative of a sling load has been made on the basis of the need for a simple geometry to be used as a reference for future numerical simulations.

The rotor wake has been characterized up to a distance of 1.5 D from the rotor disk, keeping a distance of 1D from the ground in order to avoid the occurrence of the ground effect. The typical structure of the flow tube downstream of the rotor disc has been obtained. It is characterized by high speed magnitude in the area from 2/3 the aerodynamically effective blade up to its tip and to a velocity decrease with increasing distance from the rotor disk.

The tests carried out clarified the influence of the cylindrical structure upon the wake evolution and the deformation of the velocity field due to the presence of the solid body. The flow tube shrinkage has been observed to depend on the position of the body with respect to the rotor since the greater the distance, the greater the narrowing effect. The pressure trends recorded in the test cases studied were consistent with the velocity measurements characterizing the internal part of the wake.

The properties of the tip vortices were qualitatively studied in terms of their intensity, concentration and direction and different zones are identified downstream of the rotor disc depending on their homogeneity and intensity. Further studies are currently undertaken by the authors to provide more quantitative results aimed at characterizing the tip vortices during their evolution downstream of the rotor disc and their interaction with the solid body.

5. References

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