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NLR-TP-2019-082 | February 2019

# Wind turbine wakes and helicopter operations

An overview of the Garteur HC-AG23 activities

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## Problem area

The effects of a wind turbine wake on General Aviation and the behaviour of helicopters in the tip vortex of large fixed-wing aircraft has been topic of research in the past years, but less is known about the interactions of helicopters operating in a wind turbine wake. A dedicated GARTEUR Action Group, HC-AG23, consisting of European universities and research institutes was formed to investigate helicopter behaviour in a wind turbine wake and to study the consequences for helicopter handling and safety of flight

## Description of work

The research activities are structured in work packages addressing wind turbine wake identification, wake experiments and computations, offline and piloted simulations and management and dissemination activities. This paper presents an overview of the partners' activities and provides a short overview of the results that have been achieved in the past three years.

### REPORT NUMBER

NLR-TP-2019-082

### AUTHOR(S)

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### REPORT CLASSIFICATION

UNCLASSIFIED

### DATE

February 2019

### KNOWLEDGE AREA(S)

Helicopter Technology  
Computational Physics and  
Theoretical Aerodynamics  
Safety  
Computational Mechanics  
and Simulation Technology

### DESCRIPTOR(S)

Helicopter Flight Dynamics  
Wind Turbines  
Flight Safety  
Pilot Performance

## Results and conclusions

The GARTEUR HC-AG23 Action Group consists of nine research institutes and universities, each using a variety of methods and tools to capture the physics of wind turbine wakes and helicopter dynamic interactions, and each having simulation facilities in various layouts, model fidelity and hardware characteristics at their disposal. This allowed for a broad spectrum of experience and knowledge to be shared and to progress the partners understanding of the physics involved.

## Applicability

The wind turbine wake data survey shows that relevant analytical wake models are available and it also disclosed sources of experimental data. Due to the fact that most partners dispose of airwake models in their own simulation tools, it was preferred to update and improve them in-house. Findings have been discussed and preliminary results on wake structure, wake velocities, methodologies were shared between the partners. The wind turbine wake models are fit to be used for further investigation into helicopter – wind turbine wake interactions.

### GENERAL NOTE

This report is based on a presentation held at the European Rotorcraft Forum, TU-Delft, The Netherlands, September 18-21, 2018.

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<b>CUSTOMER</b>	Netherlands Aerospace Centre
<b>CONTRACT NUMBER</b>	-----
<b>OWNER</b>	NLR + partner(s)
<b>DIVISION NLR</b>	Aerospace Vehicles
<b>DISTRIBUTION</b>	Unlimited
<b>CLASSIFICATION OF TITLE</b>	UNCLASSIFIED

APPROVED BY :																			
AUTHOR					REVIEWER					MANAGING DEPARTMENT									
R.J.J. Bakker					P.J.A. Booiij					J.F. Hakkaart									
<i>Approved</i>					<i>Approved</i>					<i>Approved</i>									
DATE	1	4	0	2	1	9	DATE	1	4	0	2	1	9	DATE					

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# Abbreviations

ACRONIEM	OMSCHRIJVING
AG23	Action Group
CAA	UK Civil Aviation Authority
CAP	Civil Aviation Publication
CETI	Control Equivalent Turbulence Input
CFD	Computational Fluid Dynamics
ERF	European Rotorcraft Forum
GARTEUR	Group for Aeronautical Research and Technology in Europe
HOST	Helicopter Overall Simulation Tool
L2R	Left to Right
MTE	Mission Task Elements
NREL	National Renewable Energy Laboratory
NLR	Nederlands Lucht- en Ruimtevaartcentrum
OEM	Original Equipment Manufacturer
RANS/LES	Reynolds Averaged Navier Stokes/Large Eddy Simulation
R2L	Right to Left
SCAS	Stability and Control Augmentation Systems
VFR	Visual Flight Rules
WP	Work Package
WT	Wind turbine



## WIND TURBINE WAKES AND HELICOPTER OPERATIONS AN OVERVIEW OF THE GARTEUR HC-AG23 ACTIVITIES

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### Abstract

The effects of a wind turbine wake on General Aviation and the behaviour of helicopters in the tip vortex of large fixed-wing aircraft has been topic of research in the past years, but less is known about the interactions of helicopters operating in a wind turbine wake. A dedicated GARTEUR Action Group, HC-AG23, consisting of European universities and research institutes was formed to investigate helicopter behaviour in a wind turbine wake and to study the consequences for helicopter handling and safety of flight. The activities are structured in work packages addressing wind turbine wake identification, wake experiments and computations, offline and piloted simulations and management and dissemination activities. This paper presents an overview of the partners' activities and provides a short overview of the results that have been achieved in the past three years.

## 1. INTRODUCTION

Recent interest in renewable energy has led to an increase in the number of wind turbines and installation of onshore and offshore wind energy parks. The wind energy production grows year by year<sup>1</sup>, (Figure 1) and is expected to continue to do so in the near future. In addition, new developments in technology enable the increase of the rotor size of wind turbines, with rotor diameters ranging up to 448 ft (137 m) and a total height of 808 ft (246 m).

The likelihood of air traffic encounters with wind turbine wakes is increasing due to the nature of the operations such as providing medical air services or performing aerial logistics required for the maintenance of offshore wind energy parks. In addition, wind turbine placement close to an airfield, may cause the wake to interfere with airport safety regulations and is a reason for concern.

The effects of a wind turbine wake on General Aviation and the behaviour of helicopters in the tip vortex of large fixed-wing aircraft has been investigated in the past<sup>2,3,4</sup>. Safety authorities have identified the lack of knowledge for helicopter and wind turbine wake encounters, showing the need for a study on the interactions of rotorcraft in a wind turbine wake.

The UK Civil Aviation Authority (CAA) mentions on-going research activities<sup>5</sup> but until recently no results have been published. Existing legislation addressing wind turbines and aircraft flight is primarily related to the disturbing effect that the wind turbine structure has on the radar signature<sup>6</sup>.

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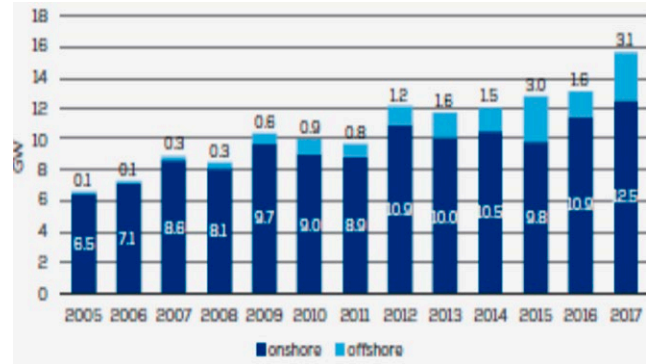


Figure 1 Annual offshore (light blue) and onshore (dark blue) wind energy installations 2005-2017 in GW.

Source: Wind Europe.

Obviously for Visual Flight Rules (VFR) flights these restrictions may not be applicable or may be inappropriate for helicopter flight. The imposed limitations with respect to the distance to the wind turbine might be too stringent.

## 2. DESCRIPTION OF HC-AG23 ACTIVITIES

The activities are executed under the umbrella of GARTEUR (Group for Aeronautical Research and Technology in Europe). GARTEUR is a multinational organization for aeronautics research and technology collaboration in Europe, both civil and military. The organisation is based on a government-to-government agreement (MoU) between seven European Nations with major research and test capabilities in aeronautics.

GARTEUR initiates collaborative, precompetitive research in the field of aeronautics, carried out by dedicated Action Groups composed of aeronautical experts from academia, research establishments and industry. The HC-AG23 action group was established in November 2014 with a planned duration of three years, extended by one year. The partners include;

- CIRA, Italian Aerospace Research Centre
- DLR, German Aerospace Centre
- NLR, Netherlands Aerospace Centre
- NTUA, Technical University of Athens
- ONERA, French Aerospace Lab
- TU Delft, Technical University of Delft
- TU Munich, Technical University of Munich
- UoL, University of Glasgow
- UoG, University of Liverpool.

## 2.1 HC-AG23 Objectives

The aim of the Action Group HC-AG23 is to set up a team of researchers from research institutes and universities to perform the following activities:

- Conduct a survey of available experimental and analytical wake data for typical wind turbines. Collect and assemble the data to produce a database of wind turbine wake properties. Identify appropriate wake characteristics with regard to the effect it may have on the helicopter flight characteristics.
- Define representative test cases for a wind turbine and helicopter combination, depending on the available experimental data, helicopter models and data, and simulation facilities.
- Perform off-line computations and piloted simulator experiments and analyse the effects of a wind turbine wake on the stability, handling qualities and safety aspects of a helicopter.
- Validate the results of the computational tools and simulator trials with available experimental data.
- Provide recommendations for legislation and disseminate the findings to the appropriate authorities and parties concerned.

## 2.2 Work Package description

In order to achieve the objectives the project is structured in five work packages. A description of the work packages is given below.

### 2.2.1 WP0 Project management

This work package aims at the coordination dissemination activities of the Action Group activities. The analyses of helicopter flight into a wind turbine wake and the results of the piloted simulations and theoretical models will provide the information to support the development of directives, issuing guidelines, rules and limitations for helicopter flight near a wind turbine.

The findings will be disseminated to the appropriate authorities and relevant stakeholders, through contacts, reports, journals and conference papers.

### 2.2.2 WP1 Wind turbine wake identification

Wind turbine wake data is available from a variety of sources. A survey of available data will explore the experimental databases to identify the detail, completeness and quality of the data. Existing datasets either experimental or generated through

analytical or engineering methods or through Computational Fluid Dynamics (CFD) reduces the effort of generating such data by the partners themselves.

If existing data sets should not contain enough information, the partners will consider efforts for additional flow computations or measurements. These activities will take place in work package WP2 'Wind turbine wake experiments and computations'. Because wind turbines vary in geometry and performance, effort will be put in creating a generic wind turbine wake or in defining scaling parameters so results are valid for a large range of wind turbine geometries.

To perform off-line computations and conduct simulations of helicopter-wake interaction, relevant flow phenomena should be identified and quantified. Preliminary findings show a differentiation in a near and far wake and a transition zone. Key physical mechanisms that are considered are the velocity deficit in wind turbine wake, the velocity distribution in the near and far wake and turbulence<sup>7,7</sup>. In case of the near wake, data is required on the blade vortex structure and vortex tube geometry; the tip vortex trajectory, its strength and vortex core size.

### 2.2.3 WP2 Wind turbine wake experiments and computations

The goal of the WP2 activities is to generate a complete set of relevant wind turbine wake data that can be used for representative flight dynamics analyses for helicopter – wind turbine wake encounters, either by making use of the available (experimental) data, or by developing or improving existing wake (analytical) models and computer codes.

If specific, indispensable data of wind turbine wakes is not available, not detailed enough or particular information is still missing this may be acquired by dedicated wind tunnel tests, full-scale measurements or by additional (theoretical) analyses and CFD. Beside the improvement and extension of wind turbine wake codes, the partners will also perform activities aimed at the implementation and integration of those codes in their simulation software.

### 2.2.4 WP3 Helicopter-wind turbine wake offline simulations

This work package addresses the off-line simulations to assess stability and handling qualities on the basis of objective criteria. To facilitate the analyses, a combination of a representative wind turbine and helicopter is to be

defined, together with a set relevant test conditions. The helicopter weight and geometry will be dependent on the partners' available helicopter data and models, the model fidelity and on the partners' simulation facilities.

A detailed analysis of the results should disclose helicopter stability and handling quality characteristics for hands-off and controlled flight. If available then partners will also apply a pilot model. In order to allow comparisons an assessment of the handling characteristics of partners' simulation models is included in the activities.

Test conditions will include flight speed, wind, position and track with regard to the wake, distance from turbine disk, approach path angle etc.

### 2.2.5 WP4 Helicopter-wind turbine wake piloted simulations

Piloted simulations are planned by some of the partners. The same wind turbine - helicopter combination as in WP3 will be used.

To assess the handling qualities of the helicopter a set of objective criteria should be selected. Hazard severity criteria should be developed and suitable handling qualities criteria and pilot rating scales should be chosen. The ADS-33E-PRF MTE (Mission Task Elements) requirements for final approach can serve as guideline. The piloted experiments should be conducted with and without Stability and Control Augmentation Systems (SCAS).

A detailed analysis of the results should disclose the helicopter stability and handling quality characteristics, the control margins for overcoming a wake encounter, the relation with pilot intervention time and will identify the effect of the SCAS etc. Pilot feedback will be valuable help to clarify some of the issues. Additional conditions such as degraded visual environments and day/night conditions may also be considered.

## 3. PARTNERS ACTIVITIES AND PRELIMINARY RESULTS

This chapter presents the partners activities and gives a short overview of achieved results. The group addressed several topics with a variety of methods, tools and methodologies for wake modelling, flight mechanics codes, aerodynamic interaction both analytical and simulated, and piloted simulation. The following paragraphs will discuss the reference model and test case, the partner's development activities on wind turbine wake modelling and will provide a description of

the simulation tools with results from the offline and piloted simulation sessions.

### 3.1. Reference model and common test case definition

As a representative wind turbine – helicopter combination, the NREL 5MW wind turbine, combined with the BO105 helicopter was selected, suited for the anticipated analyses and the simulation activities.

In case of the NREL 5MW wind turbine (NREL5), a comprehensive set of data on the geometry, the aerodynamic parameters and performance is publicly available<sup>9</sup>. The most important parameters of the NREL5 are listed in Table 1.

Rating	5 MW
Rotor Orientation, Configuration	Upwind, 3 Blades
Control	Variable Speed, Collective Pitch
Rotor, Hub Diameter	126 m, 3 m
Hub Height	90 m
Cut-In, Rated, Cut-Out Wind Speed	3, 11.4, 25 m/s
Cut-In, Rated Rotor Speed	6.9, 2.1 rpm
Rated Tip Speed	80 m/s
Overhang, Shaft Tilt, Precone	5 m, 5°, 2.5°

Table 1 Parameters of the NREL 5MW reference wind turbine

In addition, most of the GARTEUR partners are familiar with the BO105 helicopter (Figure 2) as this type has frequently been subject of GARTEUR Action Group research. A large amount of geometry and performance data is readily available with the partners.



Figure 2 BO105 reference helicopter

A principal test case that was defined consisted of the perpendicular crossing of a wind turbine wake at a downstream range of 2 and 5 rotor diameters

for the rated wind speed of 11.4 m/s (22 kts), combined with a helicopter speed of 33 m/s (64 kts). The crossings will be at hub height, plus or minus (half) the wind turbine rotor radius, so at heights of 60, 90 and 120 m above ground level.

### 3.2. Experimental activities

The Technical University of Munich (**TUM**) in cooperation with the Politecnico di Milano (**PoliMi**) dispose of an experimental facility owned and operated by PoliMi, which could be used for scaled wind tunnel experiments with single or multiple wind turbines and including interactions (Figure 3). In detail, tests were conducted in the past with two set of scaled wind farm models. The first one composed of G2 (Generic 2 meter diameter rotor) wind turbine models and the second one composed of G1 (Generic 1 meter diameter rotor) models. Both models were conceived to satisfy the following design requirements:

- a realistic energy conversion process enabled by good aerodynamic performance, both at airfoil and rotor level;
- active pitch and torque control (as well as yaw on the G1s), for the testing of modern control strategies;
- a comprehensive on-board sensor suite of the machine, including measurements of blade, shaft and tower loads;

The models used already within several projects<sup>10</sup>,<sup>11</sup> have been operated under different conditions, such as power settings and yaw misalignments. Moreover, the wake shed by the models has been measured at several locations downstream of the rotor by means of hot-wire probes<sup>12</sup>.

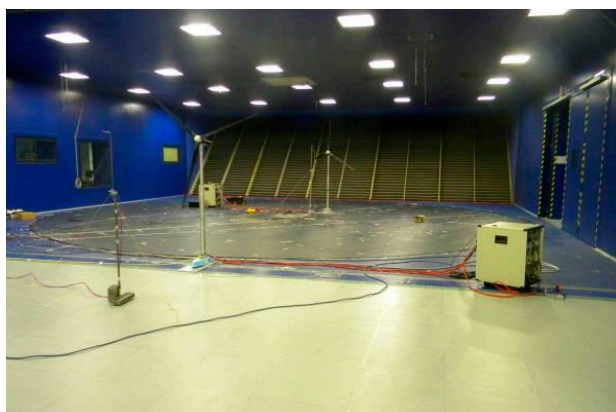


Figure 3 G2 models in the PoliMi wind tunnel

The data have been made available to partners, so as to allow the validation of the wake models described in the following sections.

### 3.3. Wind turbine wake modelling

The survey in WP1 indicated that experimental data on a wind turbine wake was available albeit, for smaller wind turbines. In other cases the experimental data, including the bigger ones, was proprietary and not allowed to be used by all partners. Since most of the partners' simulation tools are well equipped to include wind turbine air wake models, partners preferred to develop or upgrade their existing airwake models.

The University of Glasgow (**UoG**) investigated turbulence models to extend their existing CFD wake code. A typical wake for a wind turbine can be computed with steady-state CFD or with a BEM method; it captures the basic flow features but lacks frequency content, and shear due to the atmospheric boundary layer. Moreover the wake is stochastic in nature. UoG employed different numerical methods in order to compute turbulence characteristics of the WT wake. Guidelines with respect to grid density have been provided to partners. The use of the so-called "Mann box" technique<sup>13</sup> is recommended since it was found to provide an effective way to generate a representative turbulent wake (Figure 4). The results show a wake that is resolved enough for the application at hand and showed decent frequency content with the low frequencies that may be of interest. In addition, the effect of adding the atmospheric turbulence was to reduce the length of coherent part of wake and promoted its breakdown to finer flow scales. This is a positive effect since helicopter blades respond in a milder way to encounters of small flow structures.

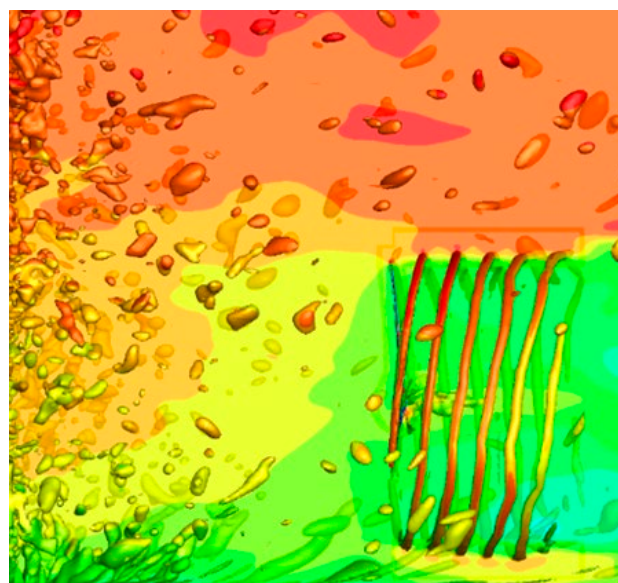


Figure 4 Turbulent wake using Mann's box

**CIRA** updated its unsteady, free-wake panel code RAMSYS with the aim to study helicopter and rotor blade airloads and performance during a

wind turbine wake encounter. The velocity and vorticity magnitudes of a wind turbine wake were computed. An atmospheric boundary layer based on a logarithmic-law model was implemented in the code.

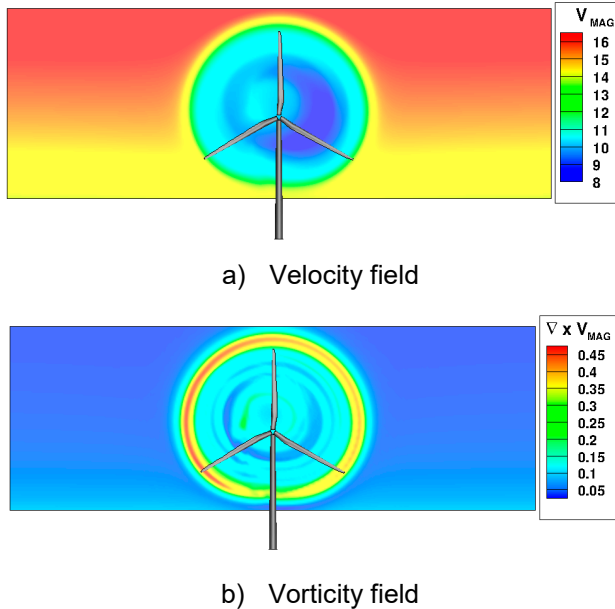


Figure 5: Wind turbine axial velocity(a) and vorticity(b) distribution,  $V$  in m/s

Wind turbine wake data derived from extensive off-line CFD calculations was implemented in the UoL's HELIFLIGHT-R Motion Base Flight Simulator in order to assess Handling Qualities criteria according to ADS-33E-PRF.

NLR has developed a simulation model of the NREL5 wind turbine in its FLIGHTLAB development environment. After comparison of the wind turbine performance parameters with reference data, the model was used to create the wind turbine wake, making use of existing vortex wake models of FLIGHTLAB. The generated wake is based on a time-accurate, periodic, free vortex wake model.

NTUA computed the turbulent wake of the NREL 5MW wind turbine using RANS/LES method (Figure 6). The resulting velocities are then transferred to particles used in the Vortex Particle Method (VPM) that enter the computational domain, in order to quantify the impact of this wake on the attitude of the helicopter flying through this wake.

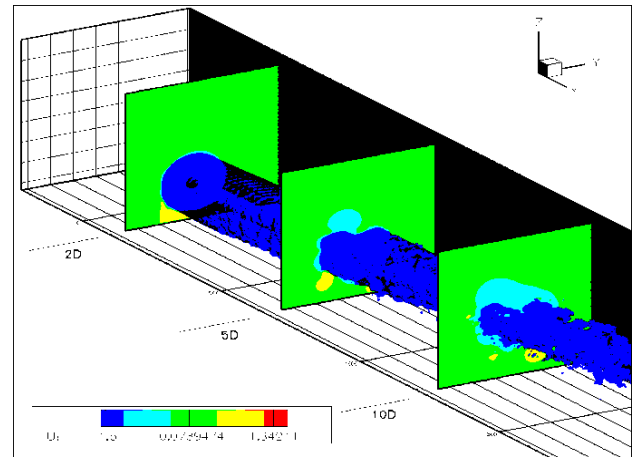


Figure 6 Impression of the NREL5 wind turbine wake at 8m/s wind speed

ONERA's CFD code elsA, based on the Navier-Stokes equations with finite-volume formulation, provides a high fidelity representation of a wind turbine airwake and has been previously used by the aerodynamic department for detailed studies of wake physics (Figure 7).

However, for the purpose of this Action Group, an analytical real-time wind turbine wake model has been developed. It is based on the Larsen's model<sup>14</sup> for the axial velocity deficit and an extension proposed by ONERA for taking into account the tangential induced velocities.

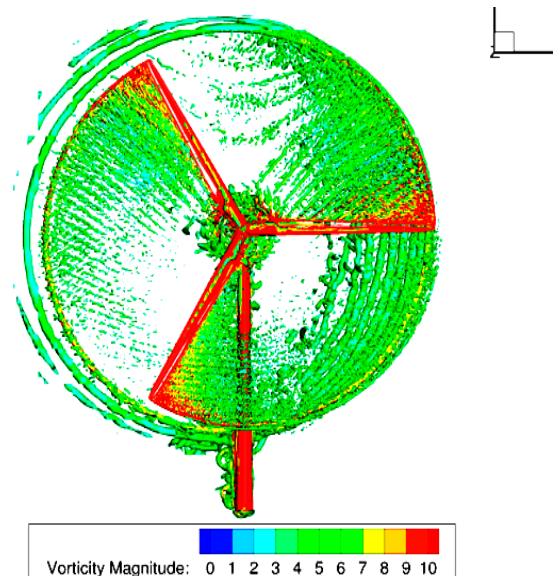


Figure 7 Sideslip effect of NREL 5MW Wind turbine computed by ONERA elsA CFD code

For this last feature, a large number of simulations with a free wake model (in-house code PUMA free wake lifting line model) have been generated.

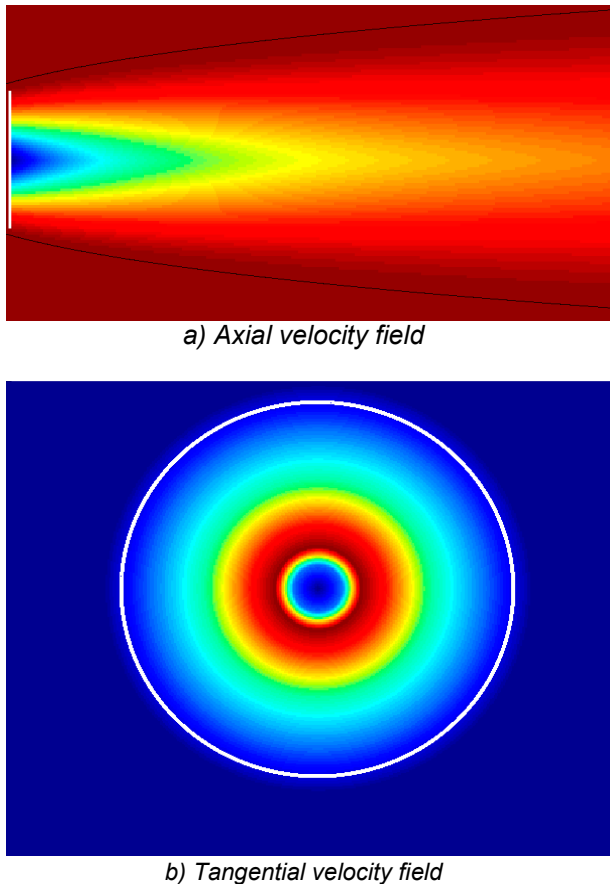


Figure 8 Impression of the ONERA analytical real-time wind turbine wake, axial and tangential velocities

It was shown that the tangential velocities within the wake have a non-linear radial dependency, but are more or less homogeneous in a certain number of cylindrical zones. The radius and thickness of these cylinders as well as the magnitude of the tangential velocities vary with the distance downstream the wind-turbine. Figure 8 shows two illustrations of this simplified analytical wind turbine wake model.

This analytical wake model has been implemented into the **ONERA's** Helicopter Overall Simulation Tool (HOST)<sup>15</sup> development code. In order to quantify the influence of the wind turbine wake on the helicopter flight dynamics, several model configurations have been tested, from a simple one where induced velocities are computed on a single point at the helicopter centre to the most advanced ones where induced velocities are calculated for multiple points on the fuselage, tail stabilizers, tail rotor as well as along the span of the main rotor blades.

### 3.4 Offline simulations of helicopter – wind turbine wake encounters

Several analyses were conducted by **CIRA** using the updated RAMSYS code<sup>16</sup> to assess the air loads on the helicopter. Helicopter forces and

moments on the BO105 rotor blades at different blade radial stations were computed and analysed (Figure 9).

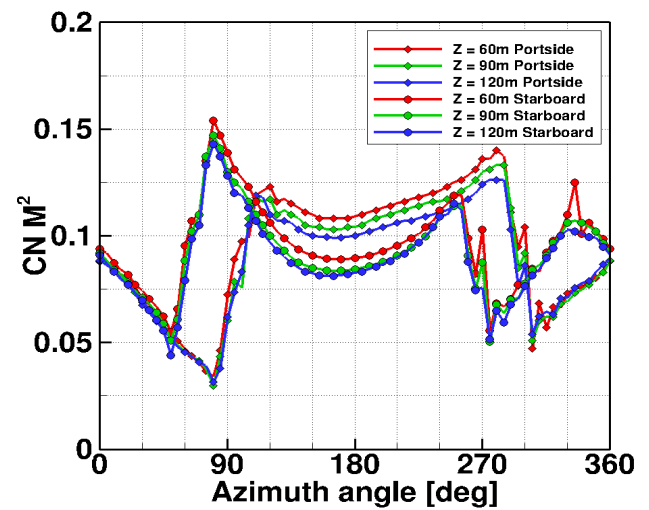


Figure 9 The CNM2 distribution on a helicopter blade radial station, at different height crossings

The analyses indicated that on entering the WT wake, a helicopter pilot is subjected to an increase in workload in order to keep a trimmed flight of the aircraft. Significant differences can be observed if the rotor crosses the WT wake leaving the WT disk on its portside (R2L) or on its starboard side (L2R), Figure 9. The flight altitude produces moderate changes while the effects on the flapping angles, loads and moments become important inside the WT wake, with peaks generally located around the WT hub position. The conicity slightly increases with about the same amount for the two flight directions. Regarding the longitudinal flapping, the flight direction L2R produces a significant reduction of it. Instead, the flight direction R2L produces fluctuations of smaller amplitude. The effect on the pitching moment is direct: a significant rotor nose-up can be observed during L2R flight. The flight direction R2L produces an increase in the lateral flapping, whereas the flight direction L2R produces some fluctuations. The effect on the rolling moment is direct: a positive roll (port side-down) can be observed during R2L flight. The yawing moment slightly increases inside the wake with a maximum around the WT hub position. No difference can be observed by changing the direction of flight; the thrust increases significantly, while the torque reduces, independently of the flight direction.

The focus of investigations by **DLR** was to identify the pilot controls required to keep the rotor trim constant when being subjected to the influence of a wind turbine (WT) blade tip vortex, i.e., how

much main rotor collective and cyclic controls would be required to mitigate the vortex impact on thrust and hub moments. In addition, it is of interest how much change in thrust, rotor blade flapping and associated hub moments would result if no pilot action was performed.

The investigations were executed three-fold by analytic estimate using blade element momentum theory as detailed in<sup>17-23</sup>. The analytic results for the isolated main rotor were cross-checked and verified by DLR's high resolution comprehensive rotor code S4<sup>24</sup> and the Helicopter Overall Simulation Tool (HOST)<sup>15</sup> of Airbus Helicopters for the complete helicopter.

The fundamental interaction occurs for a helicopter entering the WT vortex wake either at the top or bottom of the wake spiral, or it enters at half WT height. At top or bottom position the vortex lies planar in the rotor disk, its axis oriented in longitudinal rotor direction, inducing velocities normal to the rotor disk (Figure 10) When flying from downstream towards the WT, or in wind direction away from the WT, the vortex will still be planar in the helicopter rotor disk, but the vortex axis orientation then is lateral instead of longitudinal. In either case the vortex-induced velocities are normal to the rotor disk, thus mainly affecting the blade element angle of attack and with it the lift distribution along span and azimuth.

A flight into the wake at half height of the wind turbine causes the vortex axis to be vertical and the vortex swirl generates in-plane velocities at the helicopter rotor blades. In this case the induced velocity component acting in the local blade element chordwise direction needs to be computed. It primarily affects the total dynamic pressure at the blade element, thus the local lift, and to a lesser extent the section angle of attack. Therefore, this kind of interaction with the vortex normal to the rotor disk can be judged as less important compared to the vortex lying planar in the rotor disk.

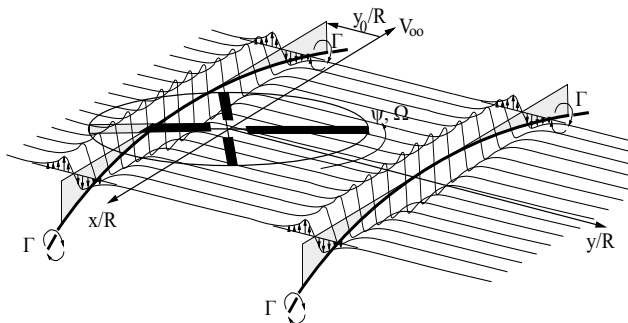


Figure 10 Schematic of the helicopter rotor – wind turbine wake vortex model

Analytic results have been obtained for a variation of core radii and vortex positions relative to the hub centre. The vortex is oriented with its axis in flight direction and lies planar in the rotor disk. The pilot controls required for mitigating the vortex impact on thrust and hub moments are computed. Figure 11 shows the collective control angle required in fast forward flight at an advance ratio of  $\mu = 0.3$ .

Similar analyses have been conducted for longitudinal control and for blade flapping in relation to mechanical limits such as to avoid tail strikes.

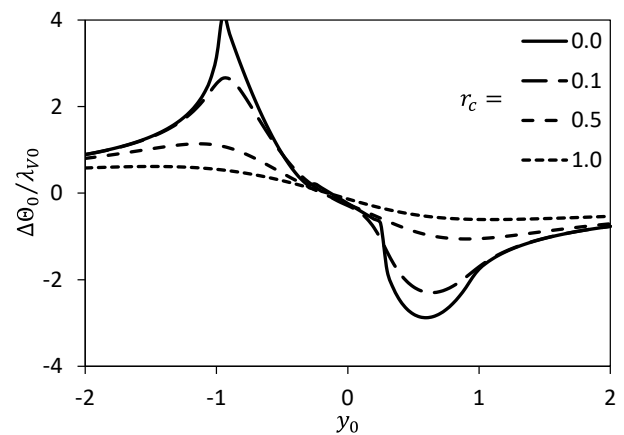


Figure 11 Collective control angle for a forward flight,  $\mu = 0.3$

The analytical investigations have shown that at the distances of 2D or more behind a 5 MW wind turbine in a worst condition, a helicopter of the BO105 class experiences noticeable disturbances that are increasing with flight speed, but are well below uncontrollable limits. Pilot actions in the order of one degree of control angle inputs are needed, or a flapping of the same amount would develop. The closer to the wind turbine the larger becomes the hazard. Rotors of slower tip speed, such as autogiros or ultra-light helicopters, are more sensitive, because an essential parameter is the ratio of vortex swirl velocity to rotorcraft tip speed.

**TUD** contribution consists of offline and piloted simulations on effects of a wind turbine wake on helicopter operations. Focus is on control power; a measure of the total moment or force available to the pilot for manoeuvring the helicopter. The combination of control sensitivity and damping governs the ability of the pilot to make precise manoeuvres or to hold the helicopter steady in gusty air. The MIL-H-8501 standard defines boundaries of control sensitivity.



The response in pitch attitude was calculated for a helicopter disturbed in pitch as a result of an encounter with a vortex core aligned in the same helicopter direction. For values of the wind turbine vortex speed and helicopter advance ratios, it was seen that as the helicopter enters the wind turbine wake, it is lifted up (increase of coning angle) and pitches down (as a result of longitudinal disc tilt), Figure 12.

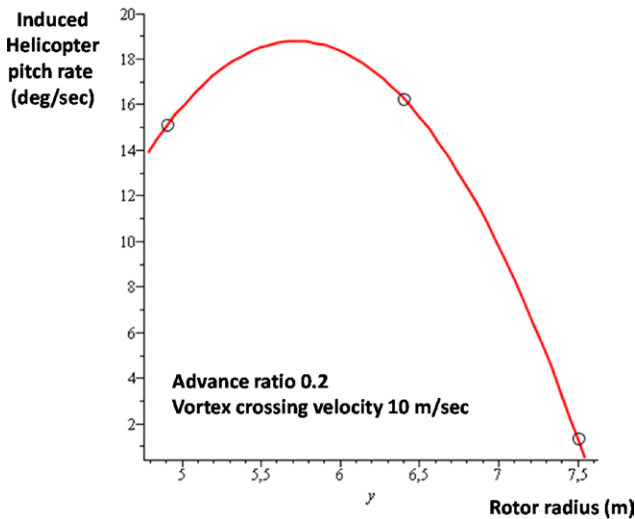


Figure 12 Induced pitch rate when encountering a vortex, for different lateral positions w.r.t rotor hub

Recent activities aim at deriving analytical formula in order to quantify the amount of collective pitch angle change when the helicopter is immersed into an orthogonal wind turbine wake.

UoG showed some initial results of a simulation of a Sea King helicopter model attempting to hover at the edge of the wake. The setup included performing a hoisting operation while an upstream wind turbine is operating at rated power of 10 MW (Figure 13). The simulation showed increased auto-pilot activity. The computations are expensive for coupled CFD/Flight Mechanics simulations. A simpler response model for the helicopter is needed to efficiently obtain results, albeit with reduced accuracy and realism.

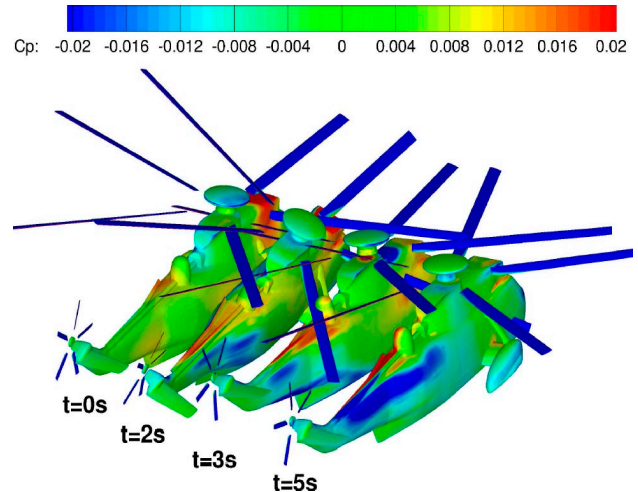


Figure 13 Simulation of helicopter in a wind turbine wake

UoL conducted offline experiments involving the WTN 250 wind turbine and perpendicular crossings of the wake by the BO105 (Figure 14)<sup>26</sup>. The test conditions include downstream locations of 3 and 5 wind turbine diameters, wind speeds of 20 and 30 knots and helicopter speeds of 20, 30, 40, and 50 knots. The Virtual AirDyn\* method<sup>27</sup> was used to compute helicopter dynamic parameters, attitude and attitude rates. Important findings were the coupled, multi-axis response in the wake, with the largest changes happening in yaw; maximum yaw angle changes in (ADS-33) level 3 for 30 knot wake indicating a serious effect on performance.

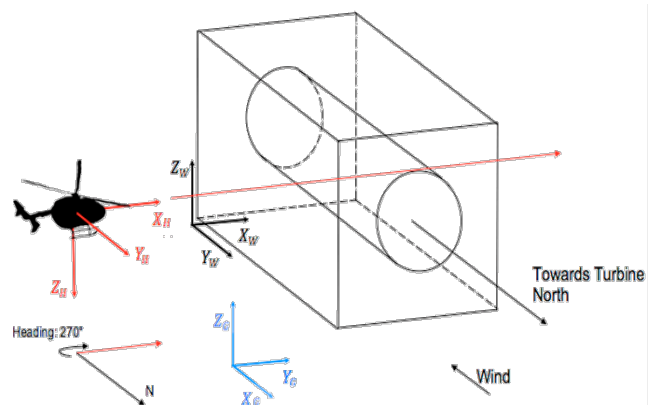


Figure 14 Schematic of the offline experiments WTN 250 wind turbine

UoL also assessed the handling qualities of the partners' BO105 simulation models to be able to do comparisons of the helicopter handling characteristics in a wind turbine wake, later in the program (Figure 15).

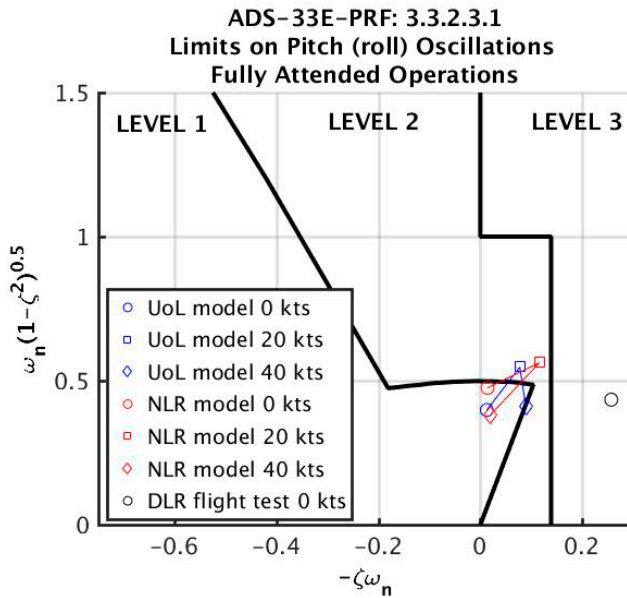


Figure 15 Comparison of pitch/roll oscillations of partners' BO105 simulation models

A wind turbine wake based on a time-accurate periodic free vortex wake was used for offline simulations with NLR's FLIGHTLAB. The BO105 helicopter trajectory was computed for a trimmed forward flight without control input.

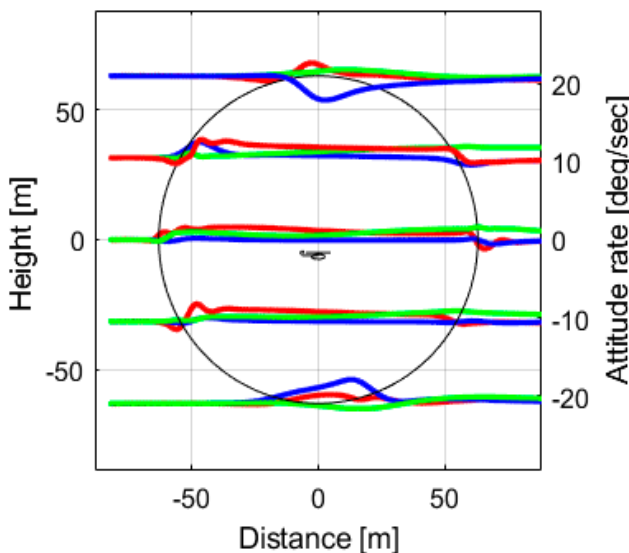


Figure 16 BO105 Attitude rates in roll (red), pitch (blue) and yaw (green), superposed on the initial heights of 0, +/-1/2R and +/-R, while crossing wake at 2D downstream

The computed attitude rates while crossing the wind turbine wake were compared with the minimum control power requirements from ADS-33E-PRF, to identify whether the imposed attitude rates requires limited, moderate or aggressive manoeuvring. For the defined test case the attitude rates required only limited manoeuvring

(Figure 16). Aggressive manoeuvring was found for conditions of higher wind speed combined with low helicopter speed; 26 m/s (50 kts) and 20 m/s (39 kts). Attitude rates reach maximum values when crossing at the upper or lower side of the wake.

NTUA performed offline analyses using their turbulent wind turbine wake, where the flight velocity was assumed constant and the trajectory straight. The wake of the helicopter is allowed to be distorted during the passage. Both controlled and uncontrolled crossings of the wake were studied, as depicted in Figure 17 for the collective pitch.

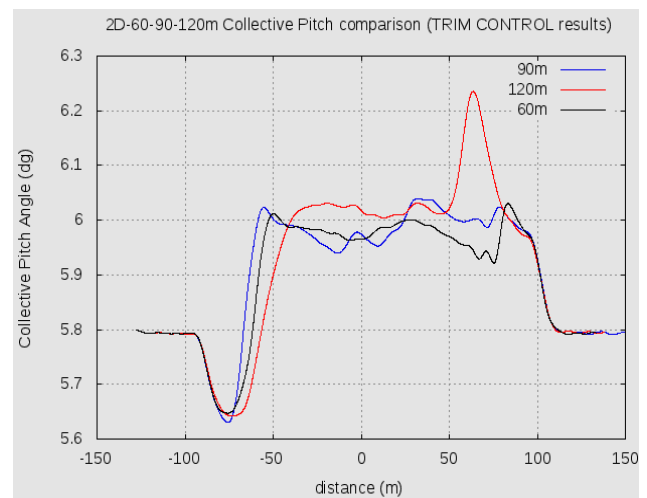


Figure 17 Collective pitch comparison for wake crossings at different heights

The simulations without trim control indicate that axial velocity principally affects roll moment and circumferential velocities affect thrust and pitch moment. The roll moment has higher fluctuations of about 15%. The trim control manages to keep thrust in the target level. Trim control also manages to keep roll moment at the target levels except when the helicopter enters or exits the wake (Figure 18).

The turbulent wind turbine wake velocity field for the NREL5 wind turbine, computed by NTUA for common test case conditions is made available to the partners and is used to perform the helicopter flight dynamics analyses.

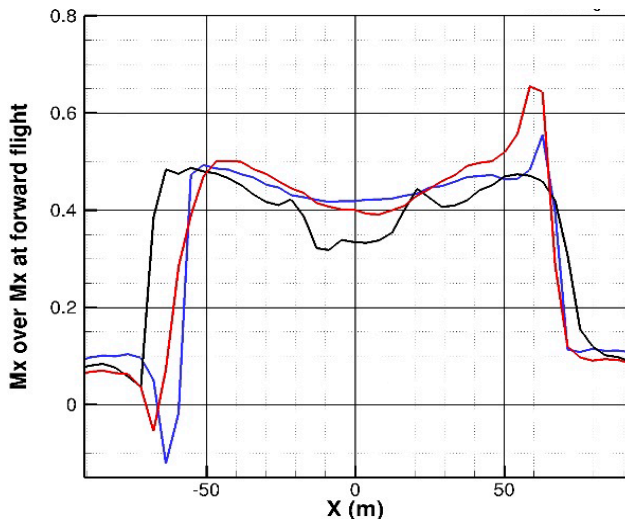


Figure 18 Roll moment while crossing the wind turbine wake at 60 (blue), 90 (black) and 120m (red)

ONERA's HOST development code with the analytical wind turbine wake model was used for an assessment of the influence of the helicopter's height and speed when crossing perpendicularly the wind turbine wake at different distances downstream from the wind turbine. The investigation has been performed mainly at the nominal (rated) upstream wind (11.4 m/s), but also at other wind speeds. An example for lateral controls is shown on Figure 19 with multiple fuselage and rotor blade computational points, a crossing at D/4 downstream the wind turbine, at the level of the wind turbine hub centre ( $Z=90$  m) and for three helicopter horizontal speeds ( $V_h=5$ , 60 or 120 kts). Similar analyses have been done for collective lever control, longitudinal pitch control, yaw control, the bank angle and longitudinal pitch attitude angle.

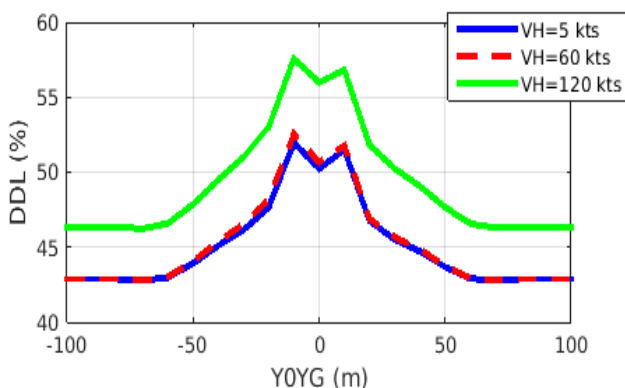


Figure 19 Helicopter lateral controls for different flight speeds while crossing the WT wake at hub centre height

Performing off-line and real-time simulations for further studies on the effect on the helicopter flight dynamics in the wind turbine wake are ongoing.

### 3.5 Piloted simulations of helicopter – wind turbine wake encounters

ONERA has implemented a simple wake model (Larsen's model augmented with swirl effect) in its simulator PycsHel (Figure 20). Pilot-in-the-loop simulations with the BO105 and NREL5 have been done for fixed controls for an initial straight steady level flight to study of the effect on the trajectory, and a piloted trajectory through the wake to investigate the effect on the control activity. First results for a lateral crossing of the wind turbine wake show that for fixed controls, the more the crossing is done close to the wind turbine and at lower speeds, the higher is the sensitivity on the trajectory deviation. With regard to the piloted trajectory, roll and yaw controls are required for coping with the axial velocity deficit. Actions on pitch and collective controls are required for coping with the vertical variations of velocity, due to tangential component (induced swirl).



Figure 20 ONERA PycsHel simulator including the NREL5MW wind turbine

UoL performed piloted simulations of helicopter-wake interaction of a helicopter on an approach path next to a 250 kW wind turbine (Figure 21). A Wake Vortex Severity rating scale, formerly used for helicopter-aircraft vortex encounters was used to classify the encounters<sup>28</sup>. One of the conclusions was a serious degradation of handling qualities levels. Pilot findings show unfavourable ratings for the small wind turbine, most likely because of the close vicinity of the ground, but are expected to be more relaxed towards the higher wind turbines such as the NREL5 due to the increased response time needed for corrective actions. Considerable pilot effort was required at lower helicopter speeds with 30 kts wake.



Figure 21 Piloted simulations 250KW Wind turbine

With regards to real-time simulation a wake field was implemented into **DLR's** simulation facility (Figure 22) for investigations on pilot workload near wind energy parks<sup>24</sup>. In addition the stochastic CETI (Control Equivalent Turbulence Input) turbulence method was improved to enable more realistic helicopter behaviour in a wind turbine wake.



Figure 22 DLR helicopter simulations facility

The test case of a BO105 helicopter crossing the NREL5 wind turbine wake was implemented in **NLR's** Helicopter Pilot Station (HPS) simulator facility, and was used primarily to demonstrate the real-time capabilities of piloted flight using a stationary wind turbine vortex wake (Figure 23).



Figure 23 NLR Helicopter Pilot Station and NREL5 wind turbine wake

Piloted tests are also planned in **TUD's** SIMONA simulator, studying how wind turbine disturbances affect pilot controls and handling qualities.

#### 4. CONCLUSIONS

The GARTEUR HC-AG23 Action Group consists of nine research institutes and universities, each using a variety of methods and tools to capture the physics of wind turbine wakes and helicopter dynamic interactions, and each having simulation facilities in various layouts, model fidelity and hardware characteristics at their disposal. This allowed for a broad spectrum of experience and knowledge to be shared and to progress the partners understanding of the physics involved.

The wind turbine wake data survey shows that relevant analytical wake models are available and it also disclosed sources of experimental data. The data did not always suit the purposes or could not be disclosed to all partners. Due to the fact that most partners dispose of airwake models in their own simulation tools, it was preferred to update and improve them in-house. Findings have been discussed and preliminary results on wake structure, wake velocities, methodologies were shared between the partners.

Simple wake models have been used to assess the basic characteristics of the wake and how they may affect flight trajectory, loads and helicopter handling. More complex wake models, including models that incorporate turbulence have been developed by the partners and have been used in more exhaustive analyses of helicopter dynamic characteristics and behaviour in a wind turbine wake. The acquired knowledge with recommendations on turbulence modelling issues and grid structure has been shared. An unsteady turbulent velocity field has been computed by one of the partners with the intent to make it available for the other partners, and to implement it in their own flight mechanics tools.

Wake models have been implemented in flight dynamics codes to investigate how helicopter flight is affected by the wind turbine wake. Air loads in the form of forces and moments on the vehicle and on rotor blades have been determined and analysed. Offline analysis of helicopter-wake encounters provided insight in basic helicopter flight mechanics behaviour. In a limited assessment the partner's helicopter simulation models have been compared with objective criteria from ADS-33E-PRF.

Piloted simulations have been executed by a few partners. Results so far indicate that for the common test case, based on rated wind speed and moderate helicopter speed, the implications

on safe flight are limited and there is no reason for concern. However, for a more critical case at extreme conditions such as very close to the wind turbine, high speed winds and relatively low helicopter speed or even hovering within the wake, first indications show that the situation may be different. Also, it was found that for small wind turbines pilot corrective actions, on account of being close to the ground, may prove hazardous. These critical conditions are still subject of research.

The various investigations enabled the exchange of experience and knowledge on wake physics, analytical and numerical modelling, dealing with large spatial and temporal differences; a relatively large, slow rotating wind turbine rotor combined with a small, fast rotating helicopter rotor system.

The results so far show that relevant and useful information has been obtained, which can be used to support stakeholders such as aviation safety authorities, the OEM and helicopter operators, in setting up guidelines to promote safe helicopter flight near wind turbines.

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