DETERMINING A SAFE-DISTANCE GUIDELINE FOR HELICOPTERS NEAR A WIND TURBINE AND WIND PARK

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Abstract

The Netherlands Aerospace Centre (NLR) was tasked to support the (former) Netherlands Ministry of Infrastructure and Environment to define a safe distance guideline for helicopters with respect to wind turbine parks. In an exploratory research, based on a relatively simple analytical wake model, a guideline for safe distance for helicopters is determined that can be used to support helicopter operations near offshore wind turbines and wind farms. The paper discusses the wake model, the safe distance criteria and will also consider the influence of the turbulence intensity, the wind turbine shaft height, rotor diameter of the turbine and the safe distance with regards to a multiple turbines in a wind park. A guideline for a safe distance is determined that could support directives for safe offshore helicopter operations near wind turbines.

1. INTRODUCTION

On the North Sea sizable wind farms are built in close proximity to mining platforms. These platforms are regularly visited by helicopters to drop off and pick up staff and to resupply. The wind farms may affect the helicopter operations with respect to flight safety. The question is up to what distance the wake of wind turbines has an impact on offshore helicopter operations, while traversing perpendicularly through the wake during the approach of a platform.

The UK Civil Aviation Authority (CAA) has issued a Civil Aviation Publication CAP 764 'Policy and Guidelines on Wind Turbines'[1] in the past, in which the influence of wind turbines on aviation is described. In addition to the negative impact that wind turbines have on the primary radar and on-board equipment, a wind turbine wake may also affect helicopter operations. Following the CAP 764 a study has been initiated to the influence of a wind turbine wake on General Aviation[2].

The study indicated that, based on field measurements using LIDAR (Light Detection and Ranging), statistically the wind turbine wake velocity has decreased to 90% of the undisturbed speed, at a distance of 5 rotor diameters of the wind turbine. The concerns of a wind turbine wake and the impact on helicopter operations has been picked up in the academic world through the institution of the Garteur Action Group AG23 'Wind turbine wake and helicopter operations'. Research institutes and universities from six European countries participate in this study. Also the helicopter operators recognized the challenges; on the basis of their experience, general guidelines and directives have been issued. At this time, objective and validated data that provides the necessary information to support these general guidelines is still missing.

At the start of the project there was still no specific research available on the influence of a wind turbine wake on helicopter operations. From basic examination, three fundamental phenomena can be identified. First a speed decrease downstream of the turbine (the so called velocity deficit), secondly a tip vortex tube directly behind the wind turbine blades and finally the increasing turbulence further downstream. The tip vortex tube is situated close to the wind turbine rotor disk, up to a maximum of approximately four wind turbine rotor diameters[3]. Due to the close proximity to the wind turbine disk this area will most likely be avoided by pilots and will not be considered in this study. The velocity deficit behind the turbine is more significant.

Because of the limited time span and a restricted budget, this study was meant to be exploratory and therefor limited to the effects of a velocity deficit behind the wind turbine. This defines an area at a relatively short distance from the wind turbine compared to the turbulence effects further

Presented at 44th European Rotorcraft Forum, Delft, The Netherlands, 19-20 September, 2018

downstream. The paper will consider a flight path that crosses the wake of the wind turbine perpendicularly. The decreasing wind speed wake in the wake for the helicopter bears similarities to a sudden lateral speed change or gust. To determine a safe distance guideline, a criterion is required. The base criterion that was used for the study is a maximum permissible (sudden) lateral speed decrease of 6 kts, which was first proposed in[4]. It is based on the criteria laid down for safe landing of fixed-wing aircraft, experiencing a lateral gust due to a large obstacle near a landing runway. In addition, crosswind criteria of 10.5 and 15 kts will be examined with the aim of establishing a bandwidth of lateral gust speeds.

1.1. Starting points

The study is based on the following starting points;

- The model to calculate the wake velocity is based on a single isolated horizontal axis wind turbine.
- To determine the qualitative effects of multiple wind turbines in a wind farm a limited literature study will be conducted, to investigate whether and how the arrangement of the turbines has an influence on the wind speeds in the wake.
- A highest wind speed of 70 kts will be considered, as commonly used for SAR operations.

The Department of Public Works provided the design data and the requirements for the planned 'Hollandse Kust (Zuid)' Wind Farm Zone. Geometric and performance data was available for a range of typical wind turbines[5].

Turbine	NREL	LW	DTU
Rating	5 MW	8 MW	10 MW
Rotor diameter	126 m	164 m	178.3 m
Hub height	90 m	110 m	119 m
Cut-in, Rated, Cut-out wind speed	3 m/s , 11.4 m/s, 25 m/s	4 m/s, 12.5 m/s, 25 m/s	4 m/s, 11.4 m/s, 25 m/s
Rotor speed range	6.9-12.1 rpm	6.3-10.5 rpm	6-9.6 rpm
Tower height	87.6 m	106.3 m	115.6 m
Tower top diameter	3.87 m	5 m	5.5 m
Tower bottom diameter	6 m	7 m	8.3 m

Table 1 Wind turbine properties.

1.2. Gust and crosswind criteria

The aircraft OEM's (Original Equipment Manufacturers) specify crosswind operational limits for the approach phase. For typical fixed wing aircraft, the limits are generally relatively high compared to the 6 kts and may vary between 15 to 30 kts for poor and good runway conditions[6].

The ICAO Annex 14; 'Aerodrome design and operations'[7] specifies categories of airports in the 'Aerodrome Reference Code' which are defined on the basis of a reference field length, the wing span and wheel width. In an Advisory Circular by the Federal Aviation Administration (FAA) for these categories of airports allowable crosswind components are specified. For the category A-I and B-I airports, based on a reference length smaller than 800 m, a span smaller than 15 m and a wheelbase of less than 4.5 m, an allowable crosswind component of 10.5 kts is specified. The latter criterion is used for the wind turbine wake research in relation with General Aviation[2].

The ICAO Annex 3 'Meteorological Services for International Air Navigation' dictates when and how weather reports are to be generated. In special cases such as during wind shear conditions an airport is required to issue a warning for head and tailwind changes larger than 15 kts.

The landing of a fixed wing aircraft in gusty conditions, due to presence of a local large object in the direct vicinity, for heights below 200 ft AGL (Above Ground Level) was investigated in[4]. The research focused on the response and the landing performance of the aircraft due to wind, wind shear and wind speed changes. Maximum allowable lateral and longitudinal wind speed changes in undisturbed air are recommended. The criteria can be summarized as follows:

- For an altitude lower than 200 ft, the variation in average wind speed parallel to the flight path, because of the disturbing object, may not exceed 7 kts. This velocity deficit of 7 kts should manifest itself over a distance of at least 100m.
- For an altitude lower than 200 ft., the variation in average wind velocity perpendicular to the flight path as a result of the object disturbing may not exceed 6 kts. The velocity deficit of 6 kts should manifest increase over a distance of at least 100 m.

Both criteria are prescribed for a height of 200 ft above the ground. Due to the relatively high placement of the axis of the wind turbine, a wake can reach a height higher than 200 ft. At this altitude there is more time and space for pilot and aircraft to respond to a disturbance. In the case of offshore helicopter operations the landing site is often at a height of 150 ft or higher above the ground. In this case, the criterion for AGL greater than 200 ft. is also of interest. The criteria are independent of the

Presented at 44th European Rotorcraft Forum, Delft, The Netherlands, 19-20 September, 2018

flight speed.
In the framework of the study the relevant wake velocity speeds will be based on 6, 10.5 and 15 kts as the crosswind criterion. The 6 kts criterion is based on conservative assumptions. The 10.5 and 15 kts velocities were considered in consultation with the customer and the helicopter operators CHC and NHV to address general, more practice oriented limits.

1.3. Validity of the gust criterion for helicopters

The influence of atmospheric disturbances on the response of the helicopter with respect to the operating margins and workload of the pilot is analysed[8]. A comparison is made between the handling of a helicopter in wind gusts and those of fixed wing aircraft. Through an analysis of the aerodynamic derivatives in the equations of motion it was found that the blade load is the most important parameter for a helicopter's response to a gust of wind. The much higher blade loading on rotorcraft compared with the wing loading on fixed-wing aircraft, is by far the single most significant reason why helicopter are less sensitive to gusts than corresponding fixed-wing aircraft of the same weight and size.
Because the helicopter response is inversely proportional to the blade loading, the sensitivity of a helicopter for a gust is less than equivalent fixed-wing aircraft. The higher the blade load, the less the helicopter rotor blade is affected by a disruption. This finding, combined with the existing gust limit for aircraft, can be taken as a starting point for determining a safe distance.

2. ANALYSES

2.1. The Ainslie wind turbine wake model

The Ainslie wind turbine wake model[9] is used to determine the velocity deficit in a far wake. The model assumes a fully turbulent and axi-symmetric flow. Tangential velocities are neglected, as well as pressure gradients outside of the flow. The model is valid from a distance of two wind turbine rotor diameters onwards. The model is based on the Navier-Stokes equations using a thin layer approach for non-viscous flow. The axial and radial velocities in the wake are determined through an implicit finite-difference scheme and a forward finite difference method is used for the axial velocity component. The constants used in the formulation of Ainslie are validated with wind tunnel data. The original Ainslie model is extended with an atmospheric turbulence model of Lange[10] and Tao Hun[11]. The Ainslie model assumes that the velocities are determined by the speed at the centre line of the wake, with a Gaussian distribution of the axial velocity components over the diameter. The speed decrease on the centre line is dependent on wind speed, the wind turbine thrust and the atmospheric turbulence intensity. The results of the simplified model compare well with the results of Computational Fluid Dynamics (CFD).

2.2. Wind Turbine properties

Data related to the thrust coefficient Ct, as a function of wind speed, was provided for a typical 8 MW wind turbine (Table 1). For low wind speeds the Ct value is high, gradually decreasing for higher wind speeds. The maximum value for the Ct of the 8 MW turbine is 0.92 at the 'cut in' speed, the lowest operational wind speed for the turbine. A Ct value of 0.88 is the value for thrust for the theoretical maximum value for the generated power. For higher values of power produced by the wind turbine the Ct value will only marginally increase so it is assumed that our calculation method is also valid for wind turbines with a higher power output.

2.3. Computations

Using the Ainslie model the wake centre line speeds are determined for different parameters. In addition it can be determined at which distance from the wind turbine in the downstream wake a speed difference of 6, 10.5 and 15 kts is present. The Ainslie model augmented by Tao Hun's turbulence intensity model, computes the local speeds in a wake, depending on the wind speed, thrust and turbulence intensity. The dependency on the turbulence intensity, the wind turbine shaft height and the rotor diameter of the turbine, will also be considered in the following paragraphs. The critical condition is mainly determined by the value of the thrust coefficient Ct in combination with the undisturbed wind speed U_0 and not by the power of the turbine.

For a set of wind speeds U_0 the velocities in the wake are determined. These wind speeds are based on the operating conditions of the wind turbine and on the input of the helicopter operators.

- Cut-In speed: 4 m/s (7.8 kts), the wind speed at which the wind turbine rotor starts to rotate.
- Rated speed: 12.5 m/s (24.3 kts), the wind speed at which the wind turbine energy production reaches its optimum. With increasing wind speed the energy production will be controlled to remain at a more or less constant value.
- Cut-out speed: 25 m/s (48.6 kts), the wind speed above which the power output of the wind turbine is controlled to limit the mechanical loads on the turbine.

Presented at 44th European Rotorcraft Forum, Delft, The Netherlands, 19-20 September, 2018

- Highest considered wind speed of 70 kts.

The computed velocity deficit and crosswind criterion for downstream distances are indicated in figure 1 to 4, for combinations of the following wind speed and thrust coefficients: 4 m/s and a Ct of 0.92, of 12.5 m/s and a Ct of 0.45 and a high wind speed combination of 25 m/s and a Ct of 0.05. For a wind speed of 70 kts (36 m/s) the Ct value is not known from the supplied wind turbine data, but is estimated from the trend of the Ct with the wind speed and set at 0.05. As a starting condition for the turbulence intensity a value of 6% is assumed, which is considered a representative value for offshore wind conditions. Figure 1 to figure 4 present the speed decrease in the wake for the speed criteria mentioned above, normalised by U_0.

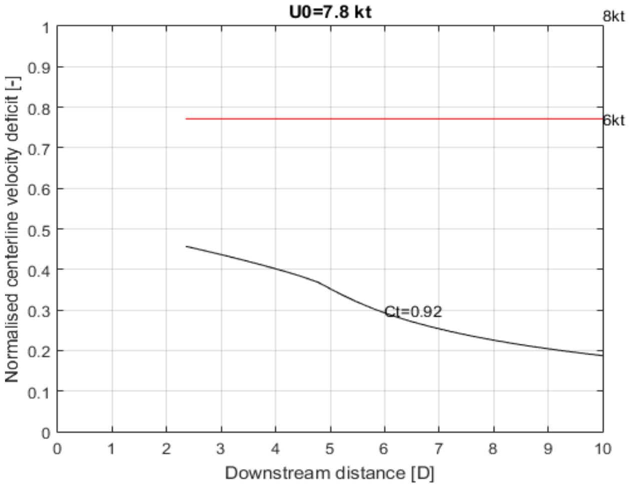

Figure 1 Normalized velocity deficit for U_0=4m/s and C_t=0.92.

For both the lowest as well as for the highest undisturbed wind speeds the velocity deficit in the entire wake remains below the imposed limit of 6 kts (Figures 1, 3 and 4). For medium wind speed over a distance up to about 4.2 wind turbine rotor diameters, a velocity deficit higher than the 6 kts is found in the wake (Figure 2).

In addition to the characteristic wind speeds and thrust coefficient combinations, the local speed in the wake is determined for other combinations of U_0 and Ct to identify critical conditions. One critical condition is found for a wind speed of 11 m/s (21.4 kts) and a Ct of 0.67 (Figure 5). The associated safe distance is approximately 5.5 wind turbine rotor diameters.

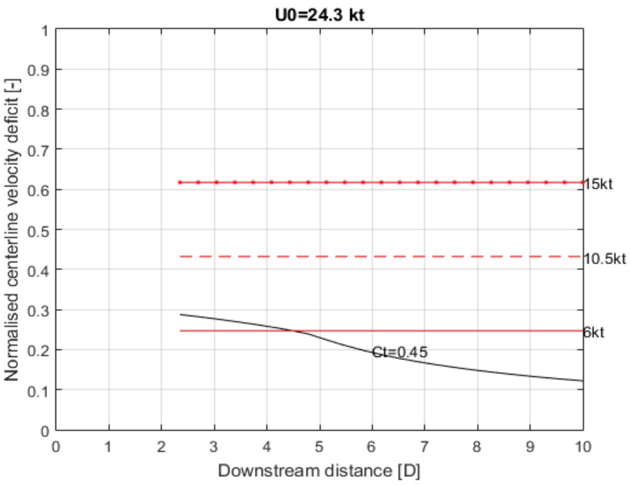

Figure 2 Normalized velocity deficit for U_0=12.5m/s and C_t=0.45.

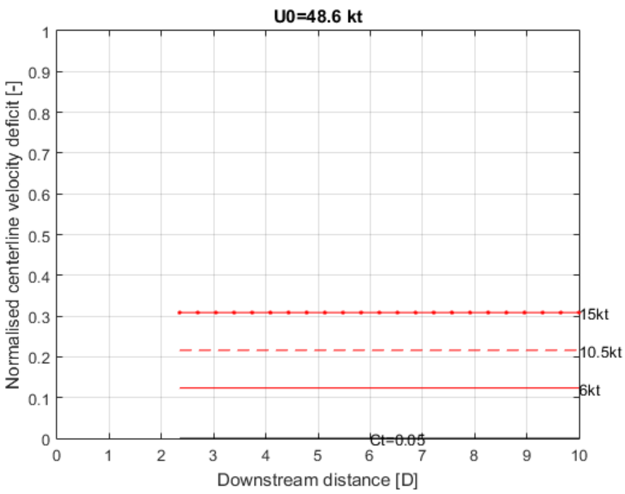

Figure 3 Normalized velocity deficit for U_0=25m/s and C_t=0.05.

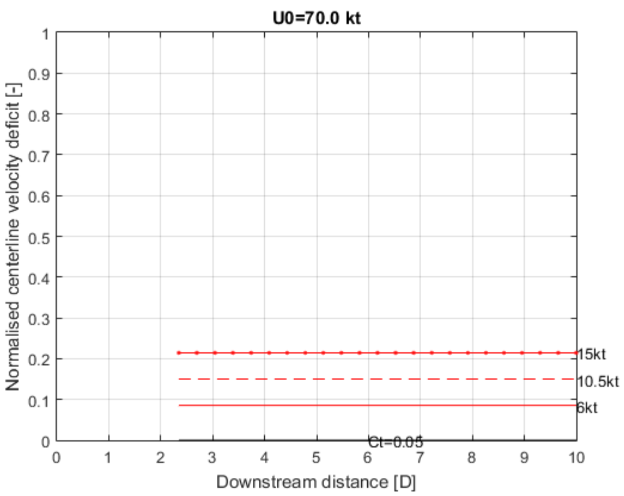

Figure 4 Normalized velocity deficit for U_0=36m/s and C_t=0.05.

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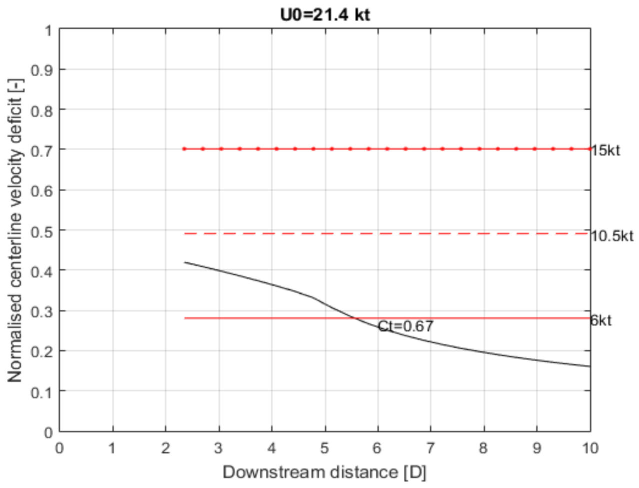

Figure 5 Normalized velocity deficient for U_0=11m/s and C_t=0.67.

An overview of the advised safe-distance, based on the maximum velocity deficit at hub height is presented in Table 1. It is arranged for different wind speeds and the presumed 6 kts crosswind criteria. The distance is expressed in wind turbine rotor diameters. The green boxes indicate a safety distance less than the model can reliably calculate.

Wind speed		Criterium		
[m/s]	[kts]	6 kts	10.5 kts	15 kts
4	7.8	2	2	2
5	18.9	2	2	2
6	11.7	2	2	2
7	13.6	3	2	2
8	15.6	5	2	2
9	17.5	5	2	2
10	19.4	6	2	2
11	21.4	6	2	2
12	23.3	5	2	2
13	25.3	3	2	2
14	27.2	2	2	2
16	31.1	2	2	2

Table 1. The safe distance, expressed as wind turbine rotor diameter, for different wind speeds and the crosswind criteria for a single wind turbine.

At wind speeds of 11.7 to 25.3 kts a velocity deficit of more than 6 kts is found at distances of 2 to 6 wind turbine rotor diameters. They are shown in red. For other wind speed conditions the velocity deficit in the wake remains under 6 kts. When applying the crosswind criteria of 10.5 and 15 kts there are no restrictions found.

2.4. Influence of the turbulence intensity

The Ainslie model proposed turbulence intensity I_0 of 10%. A low turbulence intensity value leads to a higher velocity deficit. The sensitivity for the turbulence intensity on the safe distance is examined. An analysis is done for turbulence intensities from 4 to 16%, where 4% represents a layered, low-turbulent flow and a value of 16% is considered as highly turbulent. A value of 6%, representative for offshore atmospheric conditions, was used in the former analyses. Figure 6 presents the influence for a range of turbulence intensity for the critical condition of a wind speed of 11 m/s and a Ct value of 0.67 that was found earlier.

For the critical condition with a low I_0 value of 4% the velocity deficit is calculated. For this relatively low turbulence intensity a safe distance of at least 6 wind turbine rotor diameters is found for the 6 kts criterion.

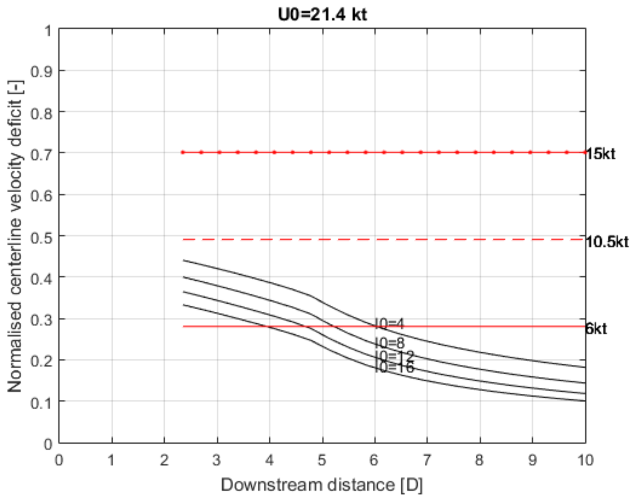

Figure 6 Normalised velocity deficit with different turbulence intensity values I0 = 4 (top), 8, 12 and 16 (bottom), U_0 = 11 m/s and C_t = 0.67.

2.5. Wind turbine rotor shaft height and rotor diameter

The influence of the height of the wind turbine rotor shaft is determined for 70, 110 and 150 m. Figure 7 shows that the influence of the height on the speed decrease in the wake is not large. The general trend is that the velocity deficit in the wake decreases with increasing axle height of the wind turbine.

The rotor diameter of the wind turbine, assuming a constant Ct, has no influence on the velocity deficit in the wake. This is due to the assumed similarity and scaling rule for the wind speed distribution over the wake diameter in the Ainslie model.

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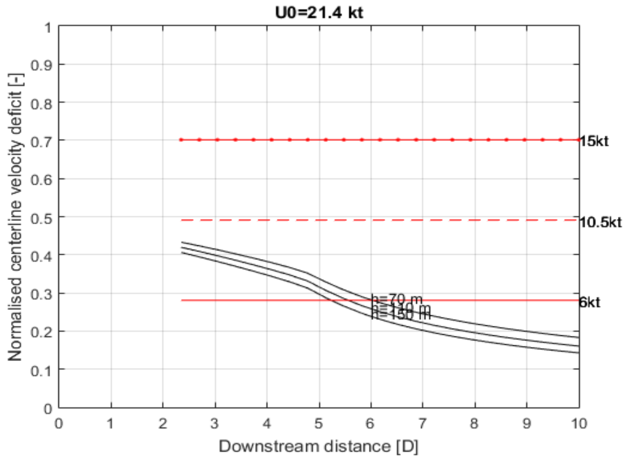

Figure 7 Normalised velocity deficit for U_0 =11m/s and C_t =0.67, for axis height of 70m (top), 110 and 150m (bottom)

2.6. Influence of the wind farm

An indication for the development of a wake for multiple turbines in a wind farm with the turbines mutually affecting each other's wake is provided in [12]. Through turbulence exchange the turbulence intensity in the wake will increase causing the velocity jump over the wind turbine downstream to be lower than the previous wind turbine. The velocity deficit however will cumulatively increase over the subsequent wind turbines. The power output of the second turbine is less than that of the first and the wake velocities will eventually reach a balance in subsequent turbine wakes. In[13] an empirical estimation method is presented that contains a multiplier that predicts an increase in the velocity deficit of up to three times as high as a single wind turbine. As a result, caution is advised when applying the safe distance guideline for a wind farm. In[13] an example is presented of a 3.6 MW wind turbine, where a velocity deficit of 7 kts is found at a distance of 0.5 NM (927 m) and a wind speed of 8.5 m/s. This means that for a 3 MW wind turbine with a diameter of 110 m, a safe distance of over eight wind turbine rotor diameter is to be expected, more than from the analyses for a single wind turbine. For the latter example of a wind farm, a simple probability analysis can be made assuming that the eight rotor diameters safe-distance that was found represents a 'worst case'. For this purpose, a benchmark velocity field of a wind farm is used, originating from a flow calculation by the Rheinisch-Westfälisches Elektrizitätswerk (RWE)[14]. The benchmark configuration consists of a wind turbine with a diameter of 117 m, an axis height of 91.5 m for a wind speed at axis height of 10 m/s. It was found that the wake velocity deficit at six rotor diameters from a wind farm is only about 1 kts higher when compared to the value of 5.2 kts for a single wind turbine (Figure 8). At a distance of eight rotor diameters from the wind farm a wake velocity of about 5 kts is found, which is lower than the speed on the six rotor diameters safe distance for a single wind turbine (Figure 9). This makes it plausible that the 8 rotor diameter safe distance is a 'worst case'. Future, larger wind turbines have a higher axle height that, based on Figure 7, leads to a closer distance to the wind turbine at which the same velocity deficit is found.

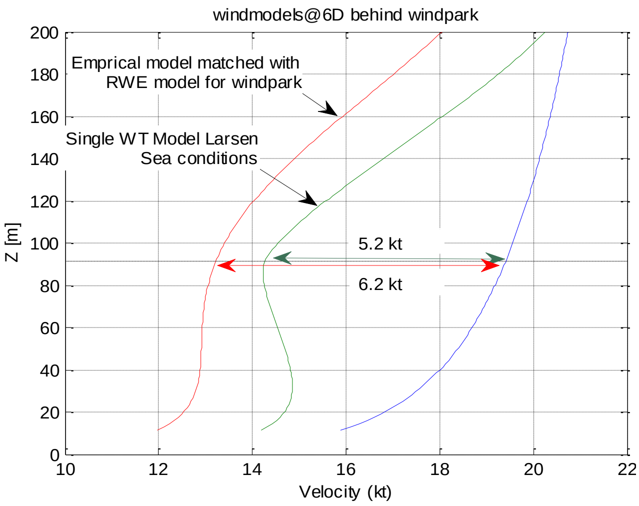

Figure 8 Velocity profile at 6 wind turbine diameters behind a wind farm.

3. CONCLUSIONS

The existing criterion of 6 kts lateral gust speed for fixed wing aircraft is used as a criterion for determining the safe distance for helicopters in close vicinity to a single wind turbine and wind turbine park. The use of this criterion implies a conservative approach since helicopters are generally less sensitive to lateral gusts, than fixed wing aircraft. Further research will indicate whether the fixed wind criterion can be adapted and tailored to helicopters.

The local wind speeds in the centre line of the wake for a single wind turbine, are calculated for representative values of the undisturbed wind speed and the thrust coefficient of an 8 MW wind turbine. For a critical combination of the two parameters a velocity deficit of up to 6 kts is found, at almost six wind turbine rotor diameters in the wake. On this basis, a safe distance with respect to a single wind turbine, of six wind turbine diameters is advised, that guarantees that a gust beyond this distance, for all wind conditions, will not exceed 6 kts. This safe distance guideline can support directives or regulations relating to helicopters operations near single wind turbines.

Considering the 10.5 and 15 kts criteria originating from ICAO advisory documents, there are no

Presented at 44th European Rotorcraft Forum, Delft, The Netherlands, 19-20 September, 2018

restrictions found with respect to the distance to a wind turbine, apart from a distance of less than 2D, where the theoretical model for calculation of the velocity deficit is not valid.

The effect of multiple wind turbines in a wind farm on the velocity deficit have been analysed on the basis of findings in open literature. According to an empirical estimation model, consecutive wakes can triple the velocity deficit values. The recommended six wind turbine rotor diameters should therefore be taken with caution for wind farms as it applies to a single wind turbine. In a wind farm wake there may still be a speed difference up to 7 kts at more than eight wind turbine rotor diameters. On the grounds of a more detailed analysis it is concluded that the safe distance of eight rotor diameters for a wind farm can be regarded as a 'worst case' scenario.

The present research is limited to the influence of a horizontal, lateral gust on the helicopter in the wake of a wind turbine. The turbulence in a wind turbine wake is complex and is subject of current investigations. It is expected that the chaotic changes in magnitude and direction of wind speed components in the flow, has significant effects on the helicopter handling and workload of the pilot Current results can serve as a basis for further studies that look at helicopter behaviour in a more detailed wake, for instance the presence of the tip vortex tube and the wake turbulence further downstream.

Finally, the reduction in wind speed will increase the required power of the helicopter, especially in the low speed flight envelope of the helicopter. This increased power requirement will have to be met by the engine and gearbox performance characteristics and will also affect pilot workload.

References

1. CAA CAP 764, “Policy and Guidelines on Wind Turbines”, Sixth Edition, February 2016
2. Wang, White, Barakos, “Wind Turbine Wake Encounter Study”, Version 1.0., University of Liverpool, March 27, 2015.
3. B. Sanderse, “Aerodynamics of wind turbine wakes”, Literature review, ECN-E--09-016, CWI.
4. Nieuwpoort A.M.H., Gooden J.H.M., de Prins J.L., “Wind criteria due to obstacles at and around airports”, NLR-TP-2010-312, July 2010.
5. LEANWIND, “Logistic Efficiencies and Naval architecture for Wind Installations with Novel Developments”, Summary description of LEANWIND 8 MW reference turbine, University College Cork, 21 April 2015.
6. Flight Safety Foundation, “Approach-and-Landing Accident Reduction Task Force, FSF ALAR Briefing Note 8.7 – Crosswind Landings”, FSF 2000.
7. Federal Aviation Administration, Advisory Circular AC 150/5300-13A Airport Design, Date 2/26/201
8. Padfield G.D., Helicopter Flight Dynamics, “The Theory and Application of Flying Qualities and Simulation Modelling”, Blackwell Science Ltd., 1996.
9. Ainslie J.F, “Calculating the flowfield in the wake of wind turbines”, Journal of Wind Engineering and Industrial Aerodynamics, 1988.
10. Lange, Waldl, Barthelmie, Gil Guerrero, Heinemann, “Modelling of Offshore Wind Turbine Wakes with the Wind Farm Program FLaP”, Article in Wind Energy, January 2003.
11. Tao Hun, “The Assessment of dynamic wake effects on loading, dynamic wake modelling and comparison of methods of wake loading assessment”, TU-Delft, November 2011.
12. T.E. Mulinazzi and Z.C. Zheng, “Wind Farm Turbulence Impacts on General Aviation Airports in Kansas”. Technical Report K-TRAN KU-13-6, Kansas State University, January 2014.
13. J.A. Post, U.G. Dees, “FOSA voor ARA and Departure Q01 Helm-A na realisatie Helmveld Windmolenpark”, NLR-CR-2012-146 (in Dutch), August 2012.
14. Private communication with RWE (Rheinisch Westfälisches Elektrizitätswerk).

Presented at 44th European Rotorcraft Forum, Delft, The Netherlands, 19-20 September, 2018