Effect of wind turbine wake turbulence on offshore helicopter operations in and around wind farms

HFDM analysis and consultation with helicopter operators

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By:
Theo de Jong (PL)
Joost van der Ploeg
Jeroen Timmers
Adrian Young
Ramon Veneman
Rick Rosenkrantz

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Summary

In this study, Helicopter Flight Data Monitoring (HFDM) data from HeliService has been used to determine the effect of wind turbine wake turbulence on helicopters to gain more insight in the minimum safe distances for helicopter operations when operating in and near offshore wind farms. A better understanding of the effects of wind turbine wake turbulence on helicopters could reduce the uncertainty in the current recommended distances and could help in defining adequate wind turbine-stop-procedures.

The HFDM data contains information of flights, operated by HeliService, to wind farms Gemini, Bard Offshore 1 and Global Tech 1. These flights concern helicopter operations outside and inside wind farms and outside and inside the wind turbine wake turbulence zones behind the wind turbines.

A dataset of 440 flights over a time frame of one and a halve years has been used, with specific wind data for each flight and specific data for every wind turbine. Additionally, for wind farm Gemini, status information for each wind turbine was provided by Outsmart Operations Control Centre.

Data analysis

The analysis of individual tracks showed no apparent difference in acceleration data between segments of flights inside and outside the wake turbulence zone or inside and outside the wind farms.

The analysis of the dataset for wind farm Gemini (119 flights) with the most accurate data showed that the minimum and maximum normal-, lateral- and longitudinal accelerations are generally similar inside and outside the wake turbulence zone and inside and outside the wind farm. The analysis of the complete dataset (440 flights) for all wind farms showed similar results to the results for only Gemini wind farm and is further supporting the conclusions based on the larger dataset.

Operational acceleration limits specifically for turbulence do not exist. The observed values of the minimum and maximum normal accelerations are all relatively low (0.65 g to 1.4 g) and well within the design limits[1] (-1.0 g to 3.5 g), even well within the design limits which have an extremely remote probability of being exceeded (-0.5 g to +2.0 g). The minimum and maximum lateral and longitudinal accelerations are approximately -0.2 g and +0.2 g, which are also relatively low and well within acceptable ranges.

In the dataset the minimum and maximum accelerations are seen in <u>and</u> outside wind farms in a similar way. Therefore, the effect of wind turbine wake turbulence on offshore helicopters does not seem limiting to operations (with respect to accelerations).

Operational experts

The findings and conclusions of this study have been shared with three helicopter operators in the Netherlands; HeliService, CHC and NHV. These operators are of the opinion that the conclusions from the data analysis reflect their daily experience of operations in the North Sea.

The data analysis shows no apparent difference between acceleration data inside and outside the wake turbulence zone or inside and outside the wind farm. So, no effect of wind farms on measured acceleration is seen. HeliService supports this observation based on their experience with operations in these wind farms.

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[1] Limit manoeuvring load factor from EASA Certification Specification CS.29

Combined with the fact that there are no unexpected turbulence reports for flights within wind farms, helicopter operations in wind farms are considered safe by operators HeliService, CHC and NHV.

The conclusion for normal operations[2] is that a 'stop procedure' is not necessary.

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[2] Helicopter hoist operations for example, are not considered as normal operations. During hoist operations, the specific wind turbine will of course be stopped.

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1   Introduction

1.1   Background

The emergence of wind farms in the North Sea has the potential to affect offshore flight operations with helicopters to and from oil and gas platforms as well as service platforms for the wind energy sector. Where wind farms are developed near oil and gas or service platforms, the accessibility of the platform can be limited. In addition to accessibility, wake turbulence caused by wind turbines can be a potential hazard to helicopter flight operations.

To avoid these negative consequences, it is proposed to have wind turbines cease their operations when helicopters are operating in the vicinity. This minimises the expected wake turbulence effect of the wind turbines on the helicopters. There is however no conclusive data to determine the precise distance from a wind turbine that a helicopter can safely pass behind a rotating wind turbine and not be affected by its wake turbulence. To date, the issue is therefore mitigated in the Netherlands by "stop procedure zones" (zones around wind turbines where a wind turbine-stop-procedure is applicable), which experts consider large enough to provide an adequate safety margin.

This conservative approach is currently used in studies and designs for infrastructure and airspace projects in the North Sea. Depending on the exact wind turbine-stop-procedures in effect, such zones could impact helicopter accessibility, limit the size of planned wind farms, or have a negative impact on the business case for the wind farm. With a growing number of wind farms in the North Sea, this impact increases.

A better understanding of the effects of wind turbine wake turbulence on helicopters could reduce the uncertainty in the current recommended distances and could help in defining adequate wind turbine-stop-procedures.

1.2   Question and scope

To70 has been asked by the Ministry of EZK[3]/RVO[4] to perform a study on wind turbine wake turbulence effects on helicopters to give more insight in the minimum safe distances for helicopter operations when operating in or around wind farms, taking into account the actual effects of wind turbine wake turbulence, and taking into account different circumstances and conditions.

The scope of the study is limited to:
* the analysis of the effects of wind turbine wake turbulence on the AW169 offshore helicopter, meaning that no general conclusions can be drawn, since effects might be related to helicopter type[5].
* the analysis of accelerations on the helicopter, since these parameters are available in this HFDM dataset. Attitude information such as, pitch-, roll-, and yaw information is not present in the dataset

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[3] EZK: Ministry of Economic Affairs and Climate Policy

[4] RVO: Netherlands Enterprise Agency

[5] However, the AW169 type has been chosen because of it being a good representation of helicopters that fly in the North Sea area. Also, lighter helicopters (probably more sensitive to turbulence) are not foreseen in these offshore helicopter operations.

and can therefore not be analysed. Also, pilot input is not part of this HFDM dataset, so this data analysis will not incorporate possible effects on pilot behaviour or workload.

- the analysis of helicopter flights in three wind farms; Gemini, Bard Offshore 1 and Global Tech I. The wind turbines in these wind farms are all similar in size (approx. 150 m tip height and rotor diameter from 116 m to 130 m), meaning that the conclusions from this data analysis will not be directly scalable to other wind turbine sizes[6].

Assumptions:

- The source of the wind data used in this study is a weather station based in wind farm Gemini. It is assumed that wind conditions are the same at neighbouring wind farms Bard Offshore 1 and Global Tech I. Since wind farm Gemini has the focus in this study and conditions do not vary greatly, this is estimated to be acceptable.
- Accelerations encountered by the helicopter are assumed to be a measure of the effect of wind turbine turbulence on helicopters.

1.3 Approach

In the Netherlands, additional[7] safety margins[8] near wind farms are currently used, which are mainly based on theoretical studies. In practice, helicopter operators operating in and around offshore wind farms have stated that their aircraft are not adversely affected by the wind turbine wake turbulence. To70 has received data from aircraft's sensors that has been collected as part of HeliService's HFDM programme, collected during actual flight operations in and around wind farms. This way, the effect of wind turbine wake turbulence on helicopters can be determined quantitatively.

The approach consists of the following steps:

- Preparation: gathering of the data required to start data analysis:
    - o HeliService HFDM-data;
    - o Wind data;
    - o Wind farm and wind turbine details;
    - o Collection of information on the current regulations.
- Quantitative Analysis
    - o Analysis of the available flights in and around offshore wind farms.
- Consultation with helicopter operators
    - o Based on the current regulations, the outcomes of the quantitative analysis and expert judgement, the findings are consulted with helicopter operators and an estimate of the effect of wake turbulence on other types of helicopters is provided.

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[6] Although helicopter operator CHC operating in the vicinity of the offshore wind farm Hornsea, with wind turbines of 190 m tip height (154 m rotor diameter), confirms the findings.

[7] Additional safety margins: distance of eight times the rotor diameter (8xRD).

[8] For existing operational procedures, see EASA regulations: *Standardised Rules of the Air* and *Air Operations*
https://www.easa.europa.eu/regulation-groups/sera-standardised-european-rules-air,
https://www.easa.europa.eu/document-library/general-publications/easy-access-rules-air-operations

This study is performed in a workgroup consisting of the Ministry of EZK, RVO and the Ministry of IenW[9]. The approach of the study has been presented to and discussed with ILT[10] in a meeting on January 9th, 2020. Helicopter operators HeliService, CHC, and NHV have been consulted in a workshop on January 14th, 2020.

1.4   Document structure

In chapter 2 an overview of the current regulations and practices on wind turbine wake turbulence is given. Chapters 3 and 4 describe the data necessary for the data analysis and the way the data is combined to be able to start the quantitative data analysis in chapter 5. The approach and preliminary results have been discussed with offshore helicopter operators, which is summarised in chapter 6 (a detailed summary of the expert session can be found in Appendix F). Finally, chapter 7 presents the conclusions and recommendations of the study.

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[9] IenW: Ministry of Infrastructure and Water Management

[10] ILT, Inspectie Leefomgeving en Transport is the Human Environment and Transport Inspectorate

2 Current regulations and practices on wake turbulence safety zone for helicopter operations

In this chapter a collection of information on the current regulation and practices on the safety zone for helicopter operations regarding wake turbulence effects is presented.

Commencing at a high level, the issue of wind energy and aviation is being addressed by aviation regulators. Four prime issues are of interest:

- Wind turbines as obstacles under ICAO Annex 14 and PANS-OPS;
- Wind turbine lighting;
- Interference with radar by wind turbines, and
- The effects of wind turbine turbulence on aviation.

While there is much regulatory material available for the first three issues, there is, at present, little regulatory material published by aviation authorities regarding the effects of wind turbine turbulence on aircraft, fixed-wing or rotary, large or small.

This study has reviewed material produced by:

- International aviation organisations (ICAO and EASA);
- A number of national aviation authorities in States that are active in wind energy (Australia, Canada, Germany, Netherlands, Sweden, United Kingdom and United States of America);
- Research institutes and other sources.

2.1 International aviation organisations

ICAO

In 2017, ICAO produced a guidance document on renewable energy and its applicability to aviation, Renewable Energy for Aviation: Practical Applications to Achieve Carbon Reductions and Cost Savings [11]. The document refers to sources of renewable energy and not to challenges posed by these sources. No publicly available ICAO material is known that addresses the effects of wind turbine turbulence on aircraft.

EASA

In the European context, EASA produces aviation requirements and advisory material across a wide range of aviation topics. EASA has published regulatory material on wind turbines as obstacles needing to be lit, but not as a source of wind turbine turbulence for aircraft.

2.2 National aviation authorities

A review of the regulations in the States listed above shows that individual States have promulgated more material than the international organisations have. Most of the material that has been identified is classified as being guidance material; in EASA-terms, acceptable means of compliance. This implies that the material is not binding, but in lieu of other means, the State will make use of the guidance material

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[11] https://www.icao.int/environmental-protection/Documents/ICAO_UNDP_GEF_RenewableEnergyGuidance.pdf

published. In general, there is more material published on the lighting of obstacles than there is on the effects of wind turbine turbulence on aircraft. The sources described below are provided as representative examples of the material available.

Australia

The protection of airports from obstacles, including wind turbines, in Australia is delegated by federal government to the regional governments of the states and territories. The civil aviation authority, CASA, published guidance material on the lighting of wind farms in an Advisory Circular, AC 139-18 in 2005. This document has since been withdrawn.

The only relevant and valid document produced by CASA is related to the National Airports Safeguarding Framework[12]. Guideline D[13] to this framework entitled Managing the Risk to Aviation Safety of Wind Turbine Installation (wind farms) / Wind monitoring Towers addresses the issues in the withdrawn AC as well as obstacle issues and, in brief, turbulence. The guideline states that wind turbine turbulence may be "noticeable" up to 16 rotor diameters from the turbine. The document continues, "At this time, the effect of this level of turbulence on aircraft in the vicinity is not known with certainty".

Canada

A Transport Canada regulation, TP 1247 - Land Use in the Vicinity of Aerodromes[14], includes a section of regulations addressing the issue of wind energy and aviation. Annex 14, PANS-OPS, radar interference and lighting are all addressed. The effects of wind turbine turbulence on aircraft are not addressed.

Germany

No guidance material for the effects of wind turbine turbulence on aircraft was found in an on-line search for data.

Netherlands

The Netherlands does produce guidance material for a range of issues regarding the effects of wind energy on aviation. The two most detailed documents are produced by the civil aviation authority (ILT *Luchtvaart*) and are both acceptable means of compliance (In Dutch, *Informatieblad*) relating to the lighting of wind turbines on land[15] and offshore[16]. This material is referenced by a webpage[17] produced by

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[12] https://www.infrastructure.gov.au/aviation/environmental/airport_safeguarding/nasf/index.aspx
[13]

https://www.infrastructure.gov.au/aviation/environmental/airport_safeguarding/nasf/files/5.1.4_Guideline_E.doc

[14] https://www.tc.gc.ca/eng/civilaviation/publications/tp1247-menu-1418.htm

[15] https://www.rijksoverheid.nl/documenten/publicaties/2016/11/15/aanduiding-van-windturbines-en-windparken-op-het-nederlandse-vasteland

[16] https://www.rijksoverheid.nl/documenten/publicaties/2016/11/15/aanduiding-offshore-windturbines-en-offshore-windparken

[17] https://www.rvo.nl/onderwerpen/duurzaam-ondernemen/duurzame-energie-opwekken/windenergie-op-land/milieu-en-omgeving/vliegveiligheid-obstakelverlichting

the Ministry of EZK. The same ministry manages a webpage[18] detailing safety considerations for wind turbines including aviation issues, but not that relating to turbulence. Further guidance, on protecting radar signals from interference is provided on another webpage[19] managed by the Ministry of Economic Affairs. This includes references to national requirements.

Considering material that addresses the potential effect of wind turbine turbulence on aircraft, the Dutch authorities rely on research on the effects of wind turbine turbulence on offshore helicopters[20] and for the effects on operations near general aviation aerodromes[21]. In the former report, Netherland Aerospace Centre (NLR) notes that the modelling of turbulence downwind of a wind turbine wake is complex. The report sets out a recommended 6 kts gust limit due to wind turbine turbulence causing a sudden lateral speed change. This document has been adopted by Dutch authorities as guidance for determining the safe distance for helicopters from a wind farm. This limit is recognised by NLR as being conservative as helicopters are generally less sensitive to crosswind disturbances than fixed wing aircraft and the 6 kts gust limit was set for such aircraft and not helicopters. Following modelling, a 6 kts gust may be found at almost six wind turbine rotor diameters (6xRD) downwind of a turbine. National guidance has used both the figure of 6xRD and one of 8xRD – representing the worst-case situation – in decisions made to date. Application of the results from the above two sources has resulted in different values being applied at different locations. In the *Luchthavenbesluit helilandingsplaats* Eemshaven, a margin of 5xRD is applied as a safety buffer. In offshore projects, using the above-mentioned report, margins of 6xRD (for a single wind turbine) or 8xRD (for a wind farm) have been adopted.

In summary, it is assumed that all low-level aviation operations offshore will avoid wind turbines that are operating by a margin equal to at least 6xRD or 8xRD. On land, this assumption is amended so that the closest point of passage past a turning turbine, at low level, will be 5xRD.

Sweden
The Swedish aviation authority, Transport Styrelsen, publishes no material on the effects of wind turbine turbulence on aircraft. The Swedish Environmental Code, *Miljöbalken[22]*, allows for interested parties to object to proposed wind farms. Research material, found in the public domain, suggests that objections from the military authorities have been received in the past. These objections were related to radar interference and not to the effects of wind turbine turbulence on military aircraft[23].

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[18] https://www.windenergie.nl/leefomgeving/veiligheidsnormen-windturbine

[19] https://www.rvo.nl/onderwerpen/duurzaam-ondernemen/duurzame-energie-opwekken/windenergie-op-land/milieu-en-omgeving/radar

[20] Offshore windturbine zog en veilige helikopteroperaties - bepaling veilige afstand helikopters t.o.v. een windturbine park (Report NLR-CR-2016-266), NLR, 2016 - translated in 2019 to: Determining a safe-distance guideline for helicopters near a wind turbine and wind park, NLR-TP-2019-083, NLR, 2019

[21] https://www.nlr.org/wp-content/uploads/2018/01/NLR-Paper-Wind-turbines-near-aerodromes.pdf

[22] https://www.riksdagen.se/sv/dokument-lagar/dokument/svensk-forfattningssamling/miljobalk-1998808_sfs-1998-808

[23] The permission process for large onshore wind turbines in Sweden, Lotta Nilbecker, 2014, Master's thesis Lunds universitet

United Kingdom

The protection of aerodromes from hazards such as obstacles is known in the United Kingdom as safeguarding. In England and Wales this is addressed in the Town and Country Planning (General Development Procedure)[24]. Separate, but similar provisions apply in Scotland[25] and Northern Ireland. A number of wind energy related policy- and guidance documents are produced by the UK CAA[26]. One of these guidance documents takes into consideration all the applicable material for safely locating wind turbines close to airports; CAP 764, CAA Policy and Guidelines on Wind Turbines[27].

CAP 764 refers to the same studies that are mentioned by CASA in Australia; turbulence is measurable at 16xRD downwind of the wind turbine[28] but that wake effects, on small turbines (diameter less than 30 m) exist up to 5xRD. The University of Liverpool and CAA UK have worked together on the issue of wind turbine turbulence and aviation[29]. Their work is not conclusive and work on larger turbines is being considered.

The guidance document notes that up to 2015, no safety reports had been received by the CAA related to wind turbine turbulence. The document mentions, but does not quantify or describe, anecdotal reports of such events.

United States of America

The aviation authority in the US, FAA, publishes several Advisory Circulars[30] that include the issue of wind energy and aviation. It also issues internal policy documents in the form of FAA Orders[31]. As in other States, this is primarily related to obstacle evaluation at airports (FAA AC 150/5300-13), lighting (FAA AC 70/7460-1) and the impact of turbines on radar and other signals (FAA Order JO 7400.2L Appendix 12). The effects of wind turbine turbulence on aircraft are not addressed.

2.3 Research institutes and other sources

Many institutions have performed work on the effects of turbulence from wind turbines. Most of this work has been in relation to maximising the efficiency of wind farms. The following addresses work that has examined a link between wind turbine turbulence and its effect on aviation.

NASA, USA

A search of NASA's Aviation Safety Reporting System (ASRS) for pilot reports regarding turbulence caused by passage behind wind turbines found two reports. The metadata from the two reports suggests that the

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[24] https://www.legislation.gov.uk/uksi/1995/419/contents/made

[25] https://www.gov.scot/publications/planning-circular-2-2003-scottish-planning-series-town-country-planning/

[26] http://www.caa.co.uk/Safety-Initiatives-and-Resources/Safety-projects/Windfarms/Windfarms/

[27] https://publicapps.caa.co.uk/docs/33/CAP764%20Issue6%20FINAL%20Feb.pdf

[28] Wind Turbine Wake Analysis, L.J. Vermeer, J.N. Sorenson, A Crespo, Progress in Aerospace Sciences, 39 (2003) 467-510

[29] https://www.liverpool.ac.uk/flight-science/cfd/wake-encounter-aircraft/

[30] https://www.faa.gov/regulations_policies/advisory_circulars/

[31] https://www.faa.gov/regulations_policies/orders_notices/

same pilot of a small fixed-wing aircraft (Cessna 172) made both reports regarding the same wind turbine. In context, the ASRS receives over 2000 reports per week from pilots in the US.

NLR, Netherlands
See also text for Netherlands above.

TU Delft, Netherlands
Work at TU Delft by Varriale *et al* in a 2018 paper entitled "Flight Load Assessment for Light Aircraft Landing Trajectories in Windy Atmosphere and Near Wind Farms[32]" concluded that wake turbulence in small fixed-wing aircraft is noticeable up to twenty rotor diameters from the wind turbine. Maximum loads were recorded at between one and three rotor diameters in low wind conditions and between one and seven rotor diameters in high wind conditions. None of the maximum loads were considered hazardous[33] to small fixed-wing aircraft. It is noted that this work is rare as the research attempts to present wind turbine wake in terms of the standard V-n diagram used in aircraft design. Varriale *et al* are supported in their position by Tomaszewski *et al*[34] who concluded that the roll hazard generated by downwind turbine turbulence are sufficiently weak to allow "a pilot to quickly correct against wake turbulence induced roll instead of allowing roll to escalate".

University of Kansas, USA
On-line research found multiple references to work performed in School of Engineering at the University of Kansas. Zhongquan and Huixuan[35] developed a hazard index based on expected roll inputs and found that hazardous conditions – for general aviation aircraft – exists, for a 100 m blade diameter, up to nearly 2 km downwind of the turbine. As with other models Zhongquan & Huixuan found that the strength of the wake initially increased with distance and then, after reaching a peak, decreases.
The distance at which the strength of the turbulence reaches its peak differs and its potential impact on aircraft also differs. Varriale *et al* conclude that the distance at which the turbulence is noted varies with wind strength; at 1xRD to 3xRD downwind when the wind speed is low, and from 1xRD to 7xRD with a high wind speed. This is consistent with Sanderse[36] and others who found that turbulence increases downwind before decaying.

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[32] Flight Load Assessment for Light Aircraft Landing Trajectories in Windy Atmosphere and Near Wind Farms, C Varriale et al, TU Delft, 2018

[33] Hazardous in terms of structural load or stall speeds

[34] Do wind turbines pose roll hazards to light aircraft?, J Tomaszewski, J Lundquist, M Churchfield, P Moriarty, Wind Energy Science, 2018

[35] Classification of Wind Farm Turbulence and Its Effects on General Aviation Aircraft and Airports (Report K-TRAN: KU-16-3), C Zhongquan and W Huixuan, The University of Kansas, 2018

[36] Aerodynamics of wind turbine wakes Literature review (Report ECN-e--09-016), B Sanderse, ECN, 2016
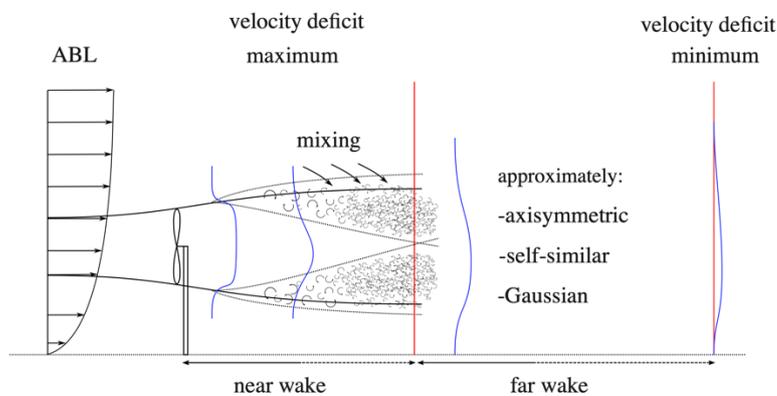
Figure 2-1: Velocity profile in the wake of a wind turbine (Source: Sanderse[36])

The model produced by Sanderse shows some variance to that proposed by Vermeer *et al*[37] and applied by NLR[38] in their work on the effect of wind turbine turbulence on aircraft.

2.4   Summary current regulations and practices for the Netherlands

The overview of the current regulations and practices shows that no regulations exist, only guidelines. The Dutch authorities rely on theoretical research by the NLR. Their report has been used for determining the safe distance from offshore wind farms. The worst case of 8 times the rotor diameter has been adopted in offshore projects in the Netherlands. This limit is recognised to be conservative, as helicopters are generally less sensitive to gusts than fixed wing aircraft (as modelled in NLR study) because of higher wing loading compared to fixed wing aircraft and the use of a gust limit of a fixed wing aircraft.

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[37] Wind turbine wake aerodynamics, L Vermeer, N Sørensen, A Crespoc, Progress in Aerospace Sciences, 2003

[38] Wind Turbines near Airports Problems and solutions for wind turbine siting in the vicinity of airports (Report NLR-TR-2016-240), P van der Geest, 2016

3 Data

In contrast to current Dutch guidance based on theory, in Germany helicopter operators operate daily in and around wind farms at distances closer to wind turbines than currently in Dutch guidance (8xRD). Helicopter sensor data of these flights can be used to analyse the actual effects of wind turbine turbulence on helicopters.

In this chapter, the data which is required to perform this study is introduced and described. Section 3.1 presents the Helicopter Flight Data Monitoring (HFDM) dataset. Section 3.2 describes the wind farm and wind turbine information, followed by the wind data in Section 3.3.

3.1 Helicopter Flight Data Monitoring (HFDM) dataset

For this specific request To70 has collaborated with HeliService International GmbH (hereafter HeliService). HeliService is a commercial air operator based in Germany that is specialised in offshore helicopter operations and has provided HFDM data.

HFDM is a systematic method of accessing, analysing and acting upon information obtained from flight data to identify and address operational risks before they can lead to incidents and accidents. HFDM data contains recorded flight data parameters from onboard sensors.

In comparison to turbulence reports filed by pilots, HFDM flight data is objective and can be used to determine if limitations have been exceeded (airframe and other limitations).

For events monitored, HFDM uses event sets. In Table 3-1 HFDM event sets related to turbulence are shown with an overview of parameters required.

Table 3-1: HFDM event sets related to turbulence[39]

HFDM Event set (selection)		
Flight Attitude & controls		
Event Title/Description	Parameters required	Comments
Manoeuvre g-loading (+ve & -ve) or turbulence	Normal, lateral and longitudinal accelerations (Weight-on-wheel (WOW), Radio altitude)	To identify excessive g-loading of rotor disc both positive and negative. WOW required to determine air/ground, Radio altitude required if height limit is required.
Pilot workload / Turbulence	Collective and /or cyclic and/or Pedal position and change rate. (Lat & Long)	To detect high workload and/or turbulence encountered during take-off and landing phases. Lat & Long for specific landing sites. A specific and complicated algorithm for this event is required.

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[39] Helicopter Flight Data Monitoring, Industry best practices, Global HFDM Steering Group, 01-04-2012 version 1.1.

The dataset for this study consisted of 440 flights of the AW169 helicopter (See Figure 3-1). This medium sized helicopter has a maximum take-off weight of 4800 kg. It must be noted that sensitivity to turbulence differs per aircraft type, weight, airspeed, altitude, configuration, wing surface area, etc.

Figure 3-1: Leonardo AW169 helicopter[40]

The 440 flights in the dataset all have operations inside wind farms Gemini, Bard Offshore 1, or Global Tech I and were carried out in the period from April 2018 until July 2019. The 440 flights make a quantitative analysis possible. In Figure 3-2 a picture of the Gemini wind farm is shown.

Figure 3-2: Gemini wind farm[41]

In the HFDM data for the AW169 obtained from HeliService, the parameters used in this study are shown in Table 3-2. The complete list of available parameters in this HFDM data can be found in Appendix A, Table A-1.

Table 3-2: HFDM data parameters used

Parameter	Nr.	Description	Units
Time (secs)	0	Time of data point since start	Seconds
Normal acceleration	1	Acceleration perpendicular to the flight path, upwards	G
Lateral Acceleration	2	Acceleration perpendicular to the flight path, sideways	G
Longitudinal Acceleration	3	Acceleration along the flight path	G
Latitude (Fine)	4	North-South coordinate	Decimals, Degrees, Minutes
Longitude (Fine)	5	East-West coordinate	Decimals, Degrees, Minutes
Pressure Altitude ADU1	6	Altitude based on pressure (not calibrated)	Feet
Radio Altitude RADALT1	7	Altitude measured below helicopter	Feet

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[40] Source picture: HeliService International GmbH

[41] Source picture: www.geminiwindpark.nl/downloads.html

Parameter	Nr.	Description	Units
Track	9	Heading with respect to real North	Degrees
Date_Year	10	Year of data point	Years
Date_Month	11	Month of data point	Months
Date_Day	12	Day of data point	Days
Time_Hours	13	Hour of data point	Hours (Universal time)
Time_Minutes	14	Minute of data point	Minutes
Time_Seconds	15	Second of data point	Seconds
WOW1	23	Weight-on-wheels	Ground/Air

From these parameters, the accelerations can be used as a measure of the effect of wind turbine wake turbulence on helicopters as mentioned in Table 3-1. In the event of turbulence or manoeuvre g-loading, recorded accelerations can identify excessive values.

Because there are no set limits for g-load except for the limits given by the manufacturer of the airframe, these design limits are used as a first reference. The limit manoeuvring load factor for transport helicopters states (EASA Certification Specification CS-29.337[42]):

The rotorcraft must be designed for:

1. (a) A limit manoeuvring load factor ranging from a positive limit of 3.5 to a negative limit of -1.0; or
2. (b) Any positive limit manoeuvring load factor not less than 2.0 and any negative limit manoeuvring load factor of not less than -0.5 for which:
    1. (1) The probability of being exceeded is shown by analysis and flight tests to be extremely remote; and
    2. (2) The selected values are appropriate to each weight condition between the design maximum and design minimum weights.

The latter range of -0.5 g to +2.0 g with an extremely remote probability of being exceeded has a safety margin. With a lack of better upper and lower limits specifically for turbulence, these values will be used as reference criteria in the analysis in Chapter 5.

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[42] Source for the limit manoeuvring load factor is EASA CS 29.337:

https://www.easa.europa.eu/sites/default/files/dfu/CS-29%20Initial%20issue.pdf

3.2 Wind farm and wind turbine data

The HDFM data contains flights to three wind farms north of the Netherlands (See Figure 3-3).

Figure 3-3: Wind farms Gemini (I-Buitengaats & II-ZeeEnergie), Bard Offshore 1 and Global Tech I

The average height of the wind turbines in the three windfarms is 150 m, with the average hub height (centre of rotor) at 90 m. The rotor diameter varies from 116 m for wind turbines in Global Tech I to 130 m for wind turbines in Gemini. The cut-in speed[43] is approximately 4 m/s for the three types of wind turbines. The cut-out speed[44] is 25 m/s for Gemini and Global Tech I and 30 m/s for Bard Offshore1. Relevant information of these wind farms has been summarised in Table 3-3 below.

Table 3-3: Wind farm and wind turbine information[45]

	Wind farms		
	Gemini I / II	Global Tech I	Bard Offshore 1
Number of wind turbines	150 (75 / 75)	80	80
Wind turbine manufacturer	Siemens	Areva	Bard
Wind turbine model	SWT-4.0-130	M5000-116	VM
Wind turbine power	4000 kW	5000 kW	5000 kW
Wind turbine height	153.5 m (504 ft)	148 m (486 ft)	151 m (495ft)
Hub height	88.5 m (290 ft)	90 m (295 ft)	90 m (295 ft)
Rotor diameter (RD)	130 m (427 ft)	116 m (381 ft)	122 m (400 ft)
Cut-in windspeed	5 m/s (9.7 kts)	4 m/s (7.8 kts)	3 m/s (5.8 m/s)
Cut-out windspeed	25 m/s (48.6 kts)	25 m/s (48.6 kts)	30 m/s (58.3 kts)

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[43] Cut-in speed: the speed at which the turbine first starts to rotate and generates power

[44] Cut-out speed: the speed at which the turbine is forced to a standstill to prevent risk of damage to the rotor at excessive speeds.

[45] Source of information: geminiwindpark.nl and www.thewindpower.net

The coordinates of individual wind turbines in wind farms Gemini I/II, Global Tech I, Bard Offshore I are listed in Appendix B.

Helicopter operations in wind farm Gemini are mainly towards the platforms in the middle of the wind farm. During these helicopter operations generally the wind turbines remain active. Only during hoisting operations, is the specific wind turbine being hoisted to, actively turned off.
The Offshore High Voltage Stations (OHVS) in the centre of these wind farms (See Figure 3-4) transform the power supplied by the wind turbines in order to export power to the onshore grid. These transformer stations also have heliports, so crews can be replaced by helicopter operators. The HFDM dataset shows flights to and from these stations in the centre of the wind farms. The height of these transformer stations is such that they are above the lowest part of the wind turbine rotors[46], meaning they are potentially in the wake turbulence of the wind turbines depending on the wind direction.

Figure 3-4: Offshore High Voltage Station (OHVS) with helipad in centre of Gemini wind farm[47]

Wind turbine status information of individual wind turbines in wind farm Gemini has been requested and received from Outsmart (Operations Control Centre). The status information has been included in the data so that it is certain when a turbine is turned on or off for the periods a helicopter is flying by. This data is used to filter the track & acceleration data for only those segments where the wind turbines are in operation (so filter-out all non-operative turbines). This will improve the quality of the results.

3.3 Wind data

The wind data has been obtained from Koninklijk Nederlands Meteorologisch Instituut (KNMI)[48], with a measuring station in the centre of wind farm Gemini Buitengaats (station BG-OHVS2). The wind data is assumed to be approximately the same for all wind farms since they are all in close proximity of each other. See Appendix C for the relevant properties of the wind data.
The variables used are:

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[46] The minimum rotortip height is 23.5 m for Gemini, 32 m for Global Tech 1, and 29 m for Bard Offshore 1

[47] Source of pictures: www.geminiwindpark.nl/downloads.html
[48] Retrieved from KNMI: https://www.knmi.nl/nederlandnu/klimatologie/uurgegevens_Noordzee, station 214, Buitengaats/BG-OHVS2

- Hourly average wind speed
- Hourly average wind direction
- Maximum wind speed for every hour

In the time frames of the HFDM dataset, the hourly average wind speed conditions were as follows:

- 75% of flights: 0 - 10 m/s (20 kts)
- 25% of flights: 10 - 17 m/s (33 kts)

Figure 3-5 shows the occurrence of the average wind speed for the flights in the dataset.
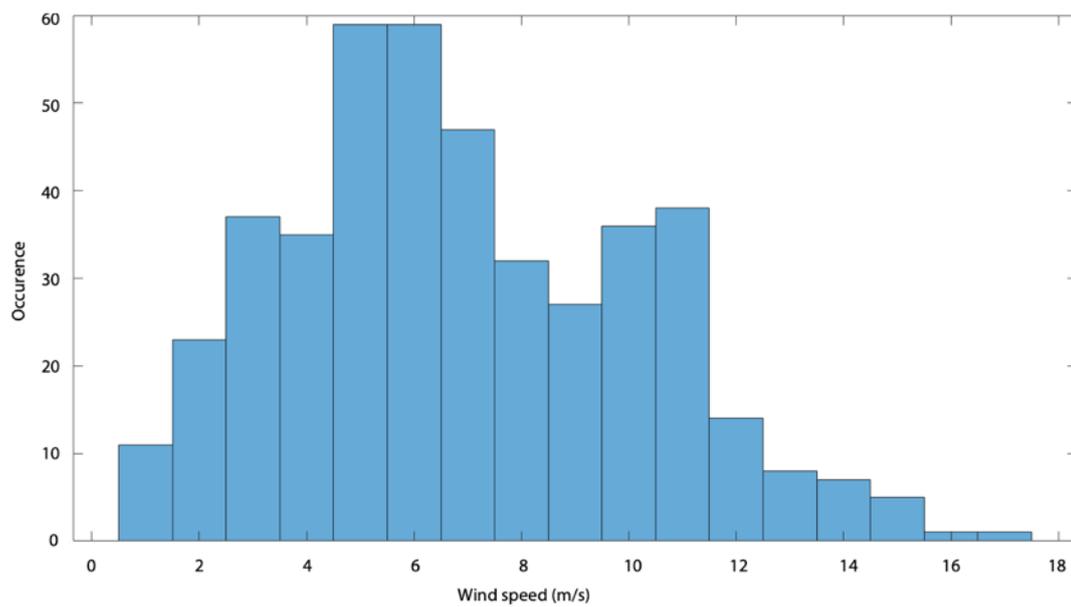
Figure 3-5: Histogram of average wind speed

3.4 The available data visualised

Figure 3-6 shows the 440 tracks of the HFDM dataset, together with the location of the wind farms and the source of the wind data.
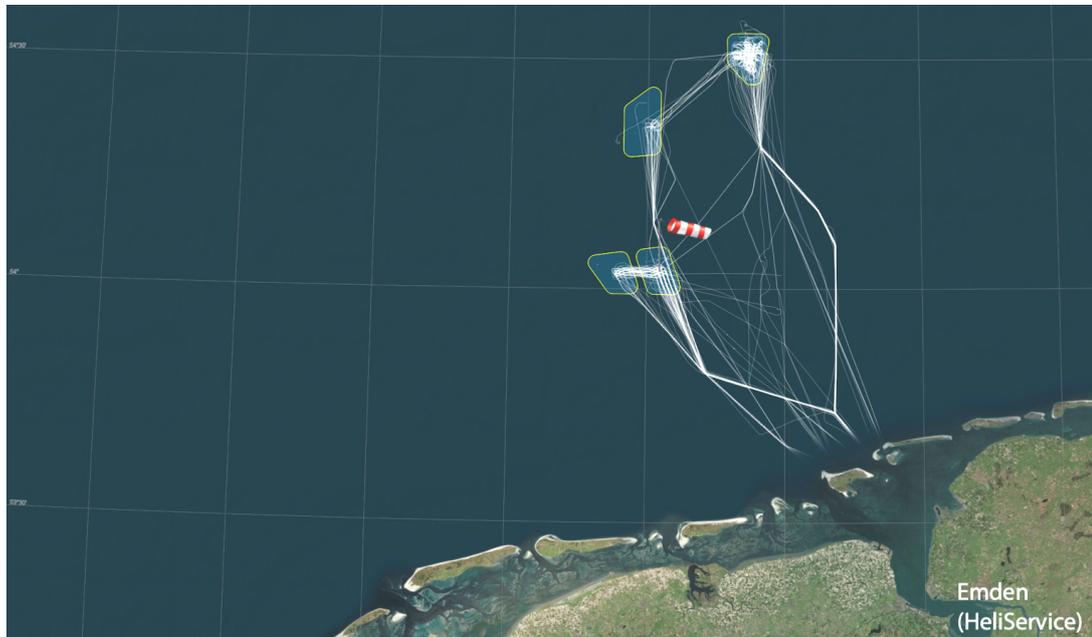
Figure 3-6: Dataset with 440 tracks shown with location of wind farms and source of wind data

In Figure 3-7, the source of the wind data is shown in the centre of wind farm Gemini Buitengaats. With the individual locations and height of wind turbines known, the situation including transformer platform are modelled in 3D, which can aid in the understanding of the problem and verification of the calculations described in Chapter 4. The wind farm outlined area shows the buffer based on the NLR report for offshore wind turbine wake turbulence. With 8xRD for wind turbines in Gemini, the distance is approximately 1000 m.
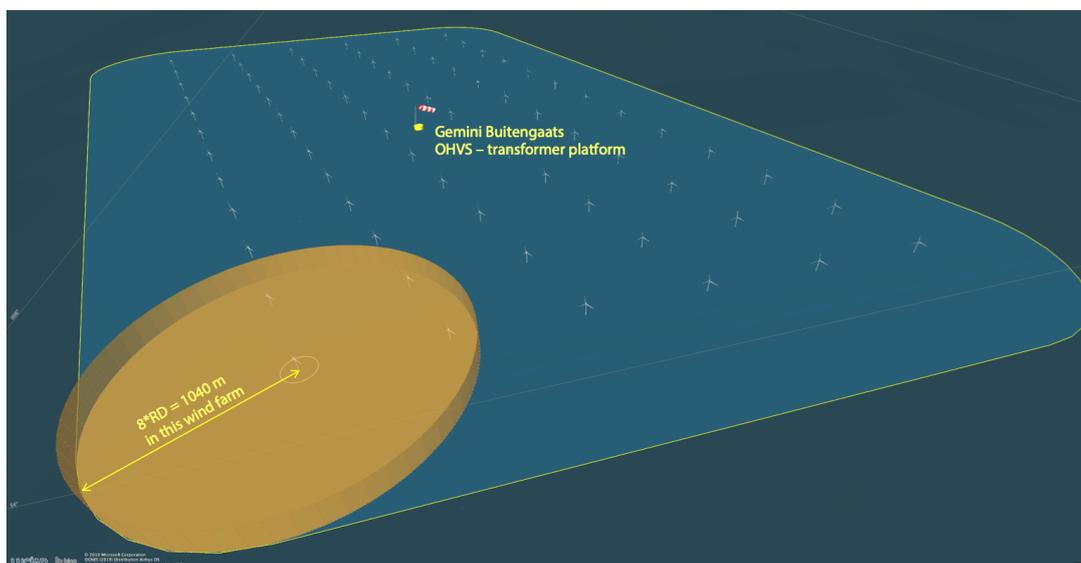
Figure 3-7: Wind data source in centre of Gemini Buitengaats

4   Methodology data processing

4.1   Data processing steps to combine HFDM data with wind turbine and wind data

The steps to combine the available data are shown in the flow chart below (Figure 4-1). The helicopter track data combined with the wind turbine location data can be used to determine when the helicopter is within a wind farm. To determine when the helicopter is within the wind turbine wake turbulence zone of the turning wind turbine, the wind direction data is required. Additionally, for wind farm Gemini, wind turbine status data is available and will be used to provide more reliable data when determining when the helicopter might experience wind turbine wake turbulence. Visualisation of the results is used for verification (See Section 4.2), after which the analysis can start (See Chapter 5). This section will explain the steps in more detail.
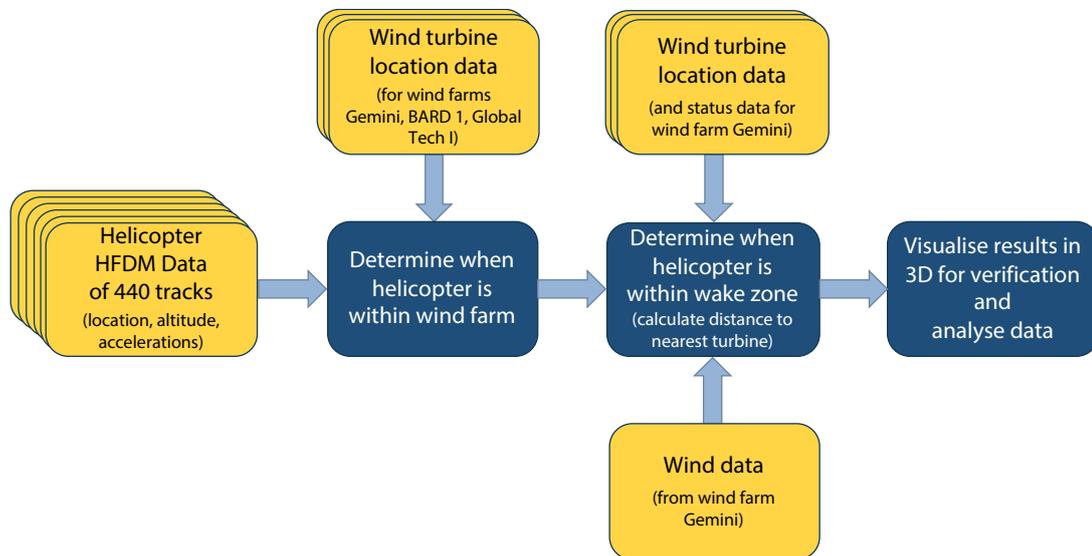
Figure 4-1: Flow diagram with data processing steps

The steps below are done for each flight individually, which are all related to the pre-processing of the data received.

- The HFDM parameters used in this analysis (See Table 3-2) are not logged at the same frequency. The normal acceleration is logged at 12.5 Hz (0.08 s time interval), which is the highest frequency in the dataset. In order to smoothen the analysis process, the other data is interpolated such that all parameters have the same time steps.
- Only the relevant parts of the dataset are considered, therefore only the airborne part of tracks are considered. This is done by removing all datapoints with variable 'Weight-on-wheels (WOW)' is true.
- There are some rare datapoints where all parameters are zero. These datapoints are removed because these are considered as an error.
- In the data of a number of tracks, a peak is observed at certain specific repetitive times, throughout the entire flight. The source is unknown, but because of the periodicity it is not possible that these are induced by external factors such as turbulence and therefore are considered as data errors. HeliService confirmed that these periodical peaks are likely to be evidence of bad data within the set. These datapoints have been removed.

- Coordinates are transformed from the Degree-Minute-Second format to decimal degrees.
- For each flight (flight track duration between 15-80 minutes), the wind direction and wind speed have been determined, where a single value is taken (wind data is only available as once per hour). The weather data is taken from the KNMI.

With the pre-processing complete, some additional steps are taken to determine when the helicopter is within one of the wind farms. For this, within a wind farm is defined as being within 1000 m from a wind turbine (See Figure 3-7). This corresponds to the 8xRD that was found in the NLR study.

In order to determine whether a helicopter is flying in- or outside the wake turbulence of a wind turbine, an area is defined where wind turbine wake influence is likely present. Figure 4-2 shows how this area has been modelled in this analysis.
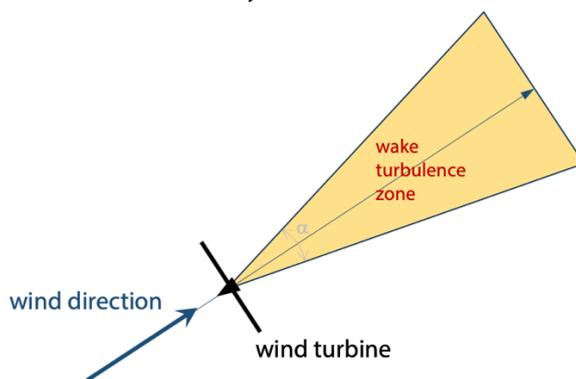
Figure 4-2: Simplified model of wake turbulence zone

The angle of this area has been determined from Figure 4-3 where the propagation of wind turbine wake for different models can be seen. Calculating the angle for the experimental data in Figure 4-3 at 2xRD downstream, results in an angle of 33.4 degrees.
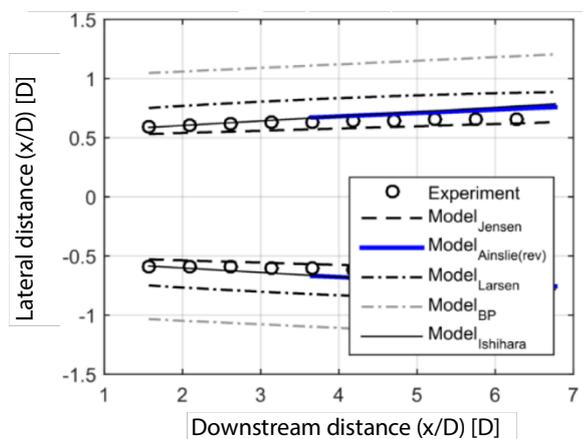
Figure 4-3: Downstream wake propagation using different models[49]

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[49] Kim, Hyungyu & Kim, Kwansoo & Bottasso, Carlo & Campagnolo, Filippo & Paek, Insu. (2018). Wind Turbine Wake Characterization for Improvement of the Ainslie Eddy Viscosity Wake Model. Energies. 11. 2823. 10.3390/en11102823.

For the length of the wake turbulence zone, again eight times the rotor diameter from the NLR study has been taken. For the height of the wind turbine wake turbulence zone, it is assumed that wind turbine wake turbulence does not propagate upwards, although a margin of 25 meters above the tip height is incorporated.

Figure 4-4 shows the schematic to determine whether the helicopter is in a wind turbine wake turbulence zone. With this zone defined, the segment of the track where the helicopter is in the wake turbulence zone is calculated and shown in red.
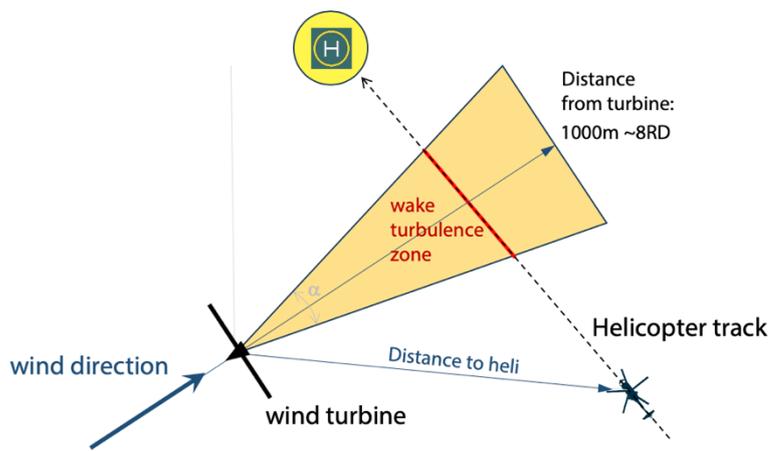
Figure 4-4: Schematic to determine whether helicopter is in wake turbulence zone

The next chapter presents a visual verification of the data and the wake turbulence zone calculation.

4.2   Visual verification of data and wake turbulence zone calculation

Individual tracks have been visualised in 2D and 3D to get a good understanding of the data and for verification of the wake turbulence zone calculation. In the rest of this document, a specific individual flight from Emden to Gemini (ZeeEnergie and Buitengaats) has been chosen for demonstration purposes. In Figure 4-5 the track of this flight is shown.
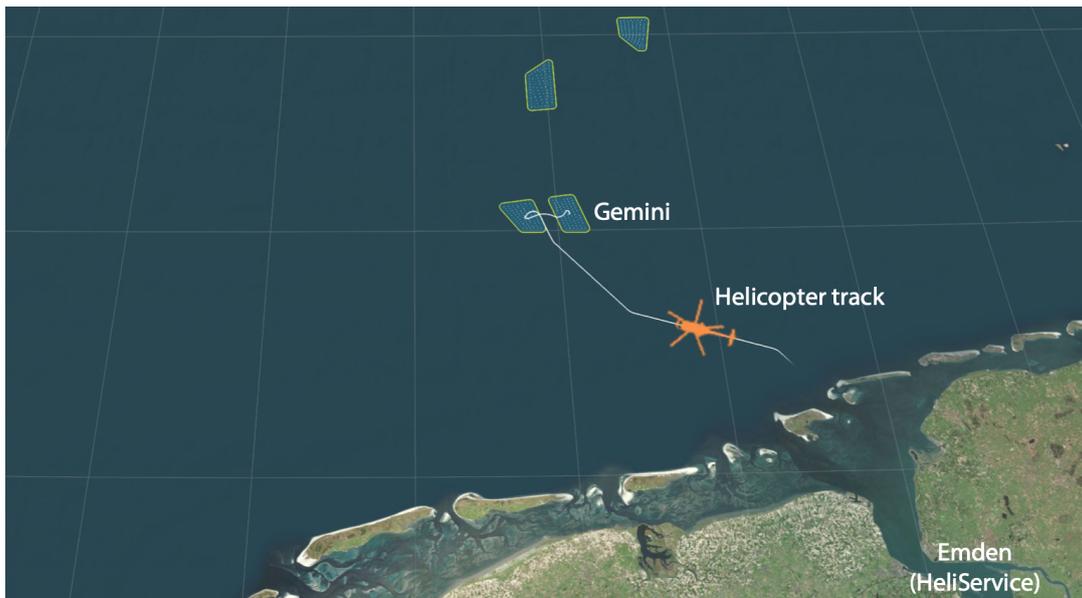
Figure 4-5: Example track from Emden to Gemini wind farm

It is a flight during which both parts of Gemini wind farm (ZeeEnergie and Buitengaats) have been flown in at an altitude below the maximum height of the wind turbines (height of rotor hub plus radius of rotor), therefore potentially in the wake zone of relevant wind turbines, depending on the wind direction and distance from these wind turbines (See Figure 4-6).
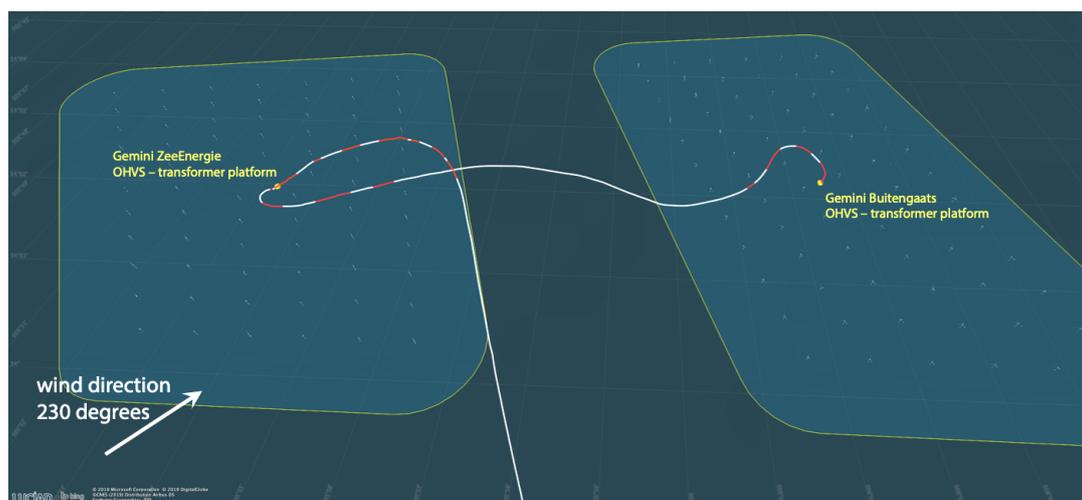
Figure 4-6: Individual flight in Gemini wind farm with segments of track in possible wake zone (red)

The helicopter flies through wind farm Gemini-ZeeEnergie towards its transformer platform, after which it flies through Gemini-Buitengaats landing at the transformer platform, under conditions of relatively high

average wind speed (15 m/s, approximately 29 kts) and with a wind direction of 230 degrees. Based on this wind direction and the helicopter being within the distance of 8xRD from the wind turbine, the segments of the track are calculated where the helicopter is in the influence of wind turbine wake turbulence (wake turbulence zone). These segments are shown in red in Figure 4-6 and are calculated for all 440 tracks and corresponding wind conditions. The wake zone calculation is visualised in Figure 4-7. With wind from 230 degrees, the 3D visualised volumes correspond with calculated segments of the helicopter track in the wake zone.
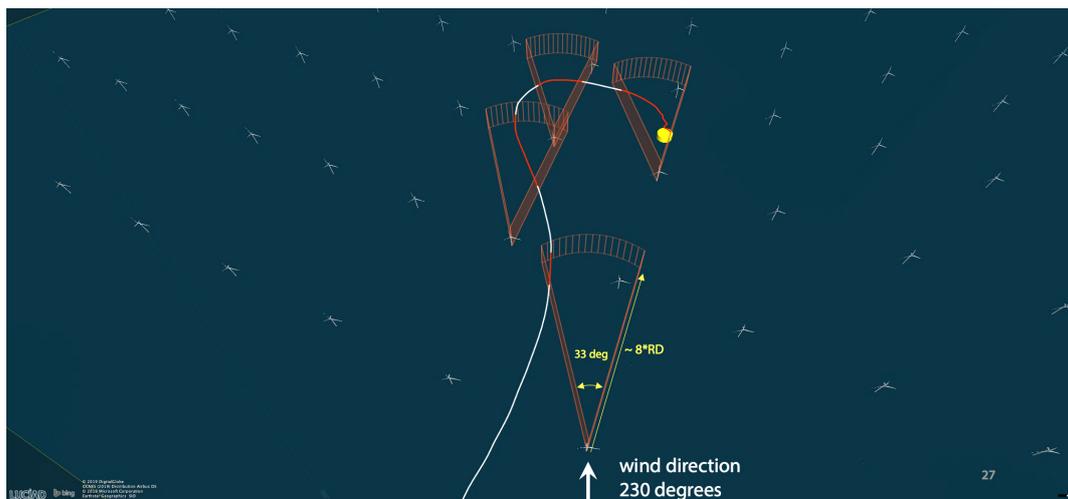
Figure 4-7: Visual verification of wake zone calculation (top-view)

Figure 4-7 is presented in a different perspective in Figure 4-8.
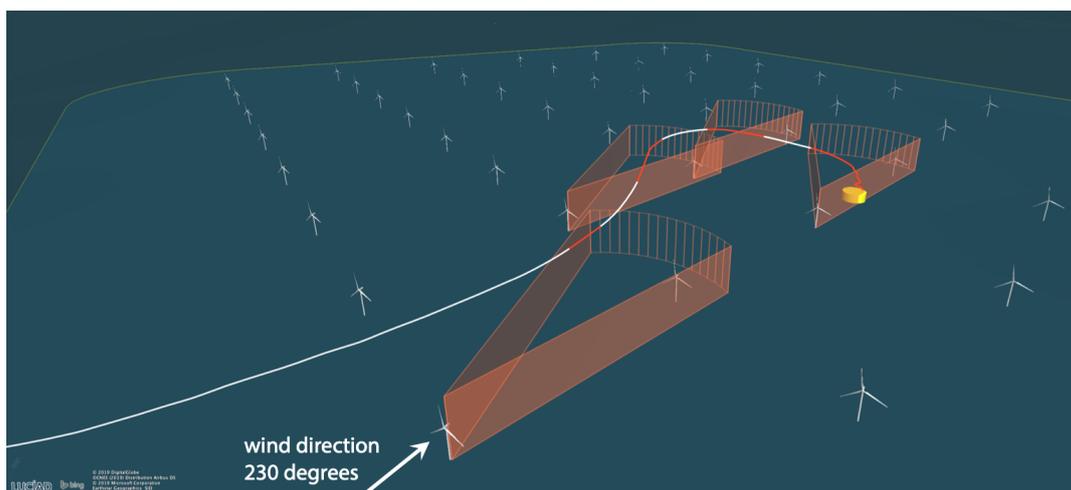
Figure 4-8: Visual verification of wake zone calculation (3D-view)

5 Quantitative data analysis

The goal of the data analysis is to determine the effect of wind turbine wake turbulence on helicopters. This will be determined by analysing the accelerations recorded by the helicopter HFDM data of 440 flights during helicopter operations in and around offshore wind farms.

As a first step towards quantitative data analysis, individual tracks have been analysed, of which the example track from the previous chapter will be used in Section 5.1. The complete dataset of 440 tracks is analysed in Section 5.2.

5.1 Analysis of individual track

For the individual track, first the normal acceleration is plotted over time (See Figure 5-1). The reason why during the first minutes and last minutes no data is seen, is because only the airborne part is plotted, since only in-flight data is relevant (HFDM parameter Weight-on-wheels is used for this).

The duration of the flight is approximately 50 minutes from Emden to Gemini Buitengaats. The first part of the flight is outside the wind farm, followed by the part where the helicopter operates within the wind farm at the level of the wind turbines.
The parts in red show the segments of the track in the wake zone. No apparent difference is seen between segments in- and outside the wake zone and in- and outside the wind farm.
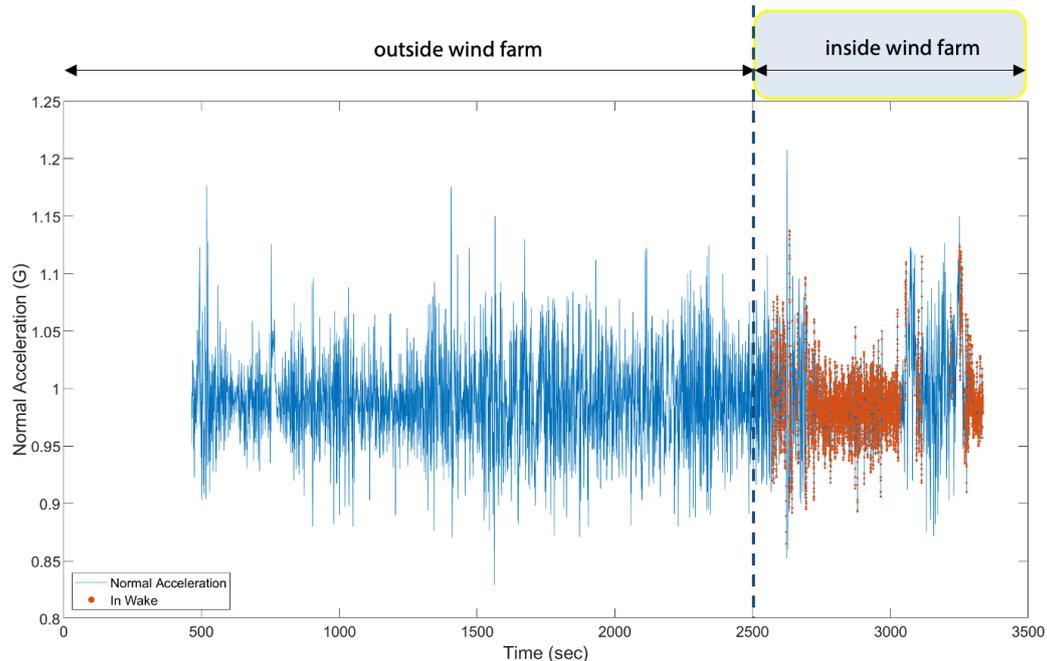
Figure 5-1: Normal acceleration (g) over time with segments of track in wake zone in red

The minimum and maximum normal accelerations measured during this entire flight, are in the order of 0.8 g and 1.2 g. These are low values compared to the -0.5 g and +2.0 g design limits with margin (See Section 3.1). In Figure 5-2 the 0.85 to 1.15 g band has been shown to clarify the range of accelerations.
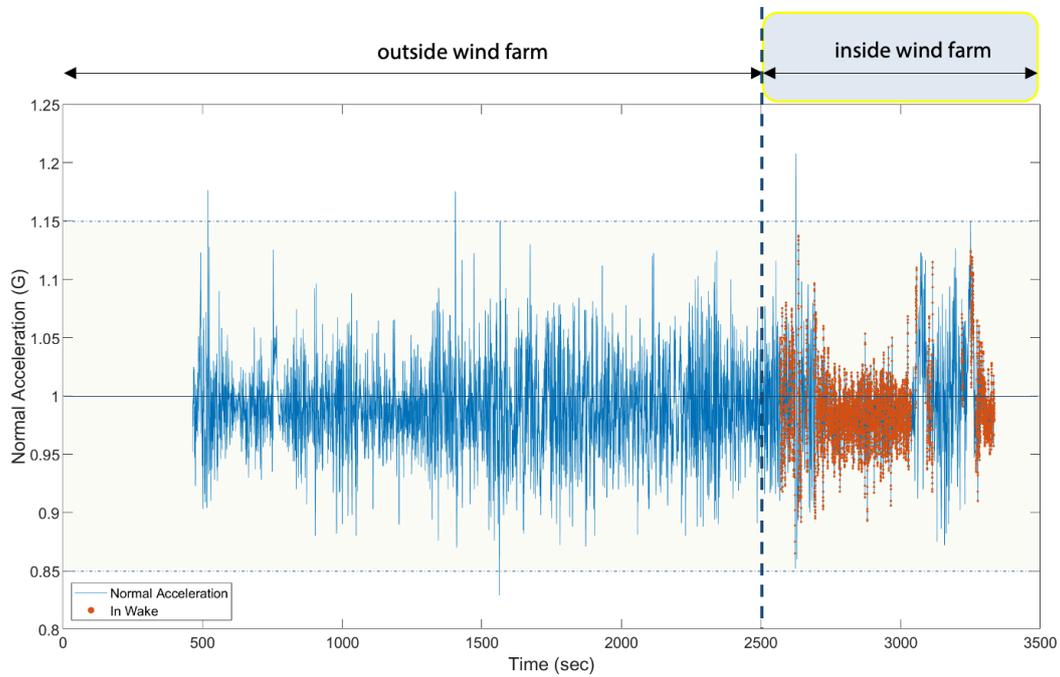
Figure 5-2: Normal acceleration (g) over time with 0.85 g to 1.15 g band

For the lateral acceleration over time (See Figure 5-3), the minimum and maximum acceleration is -0.09 g and + 0.08 g. It must be noted that the high frequency spikes are more relevant, because the low frequency changes in acceleration are most likely the result of manoeuvring (turns etc.) and the different phases of flight (resulting in a different helicopter attitude affecting the measured acceleration). For the spikes no apparent difference between segments in- and outside wake or in- and outside wind farm is seen.
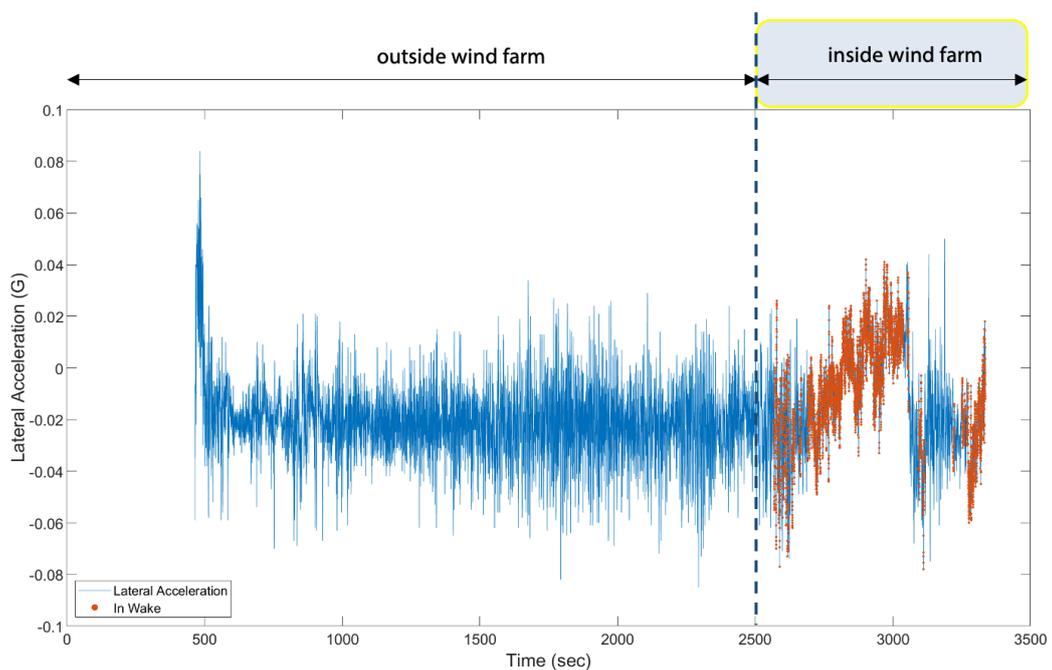
Figure 5-3: Lateral acceleration (g) over time with segments of track in wake zone in red

For the longitudinal acceleration over time (See Figure 5-4), the minimum and maximum are -0.11 and +0.17 g. Again, the low frequency changes in acceleration are most likely due to manoeuvres and the different phases of flight (resulting in a different helicopter attitude affecting the measured acceleration), with the high frequency spikes on top. Again, for the spikes no apparent difference between segments in- and outside wake or in- and outside wind farm is seen.
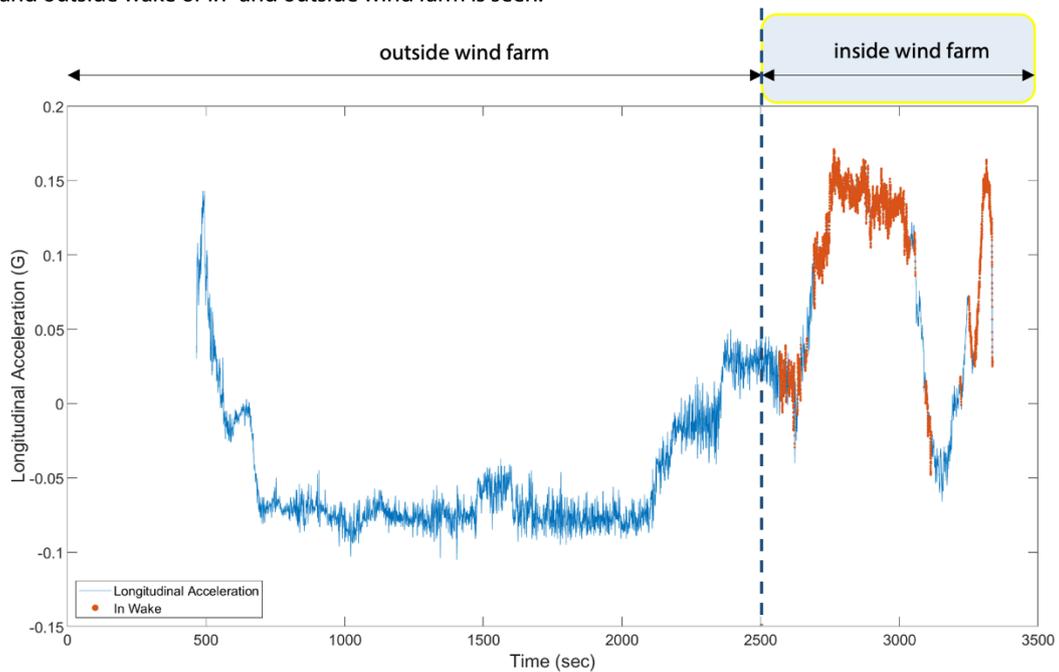
Figure 5-4: Longitudinal acceleration (g) over time with segments of track in wake zone in red

The overview of the accelerations combined with the parameters used to calculate the wake zone is shown in Figure 5-5.
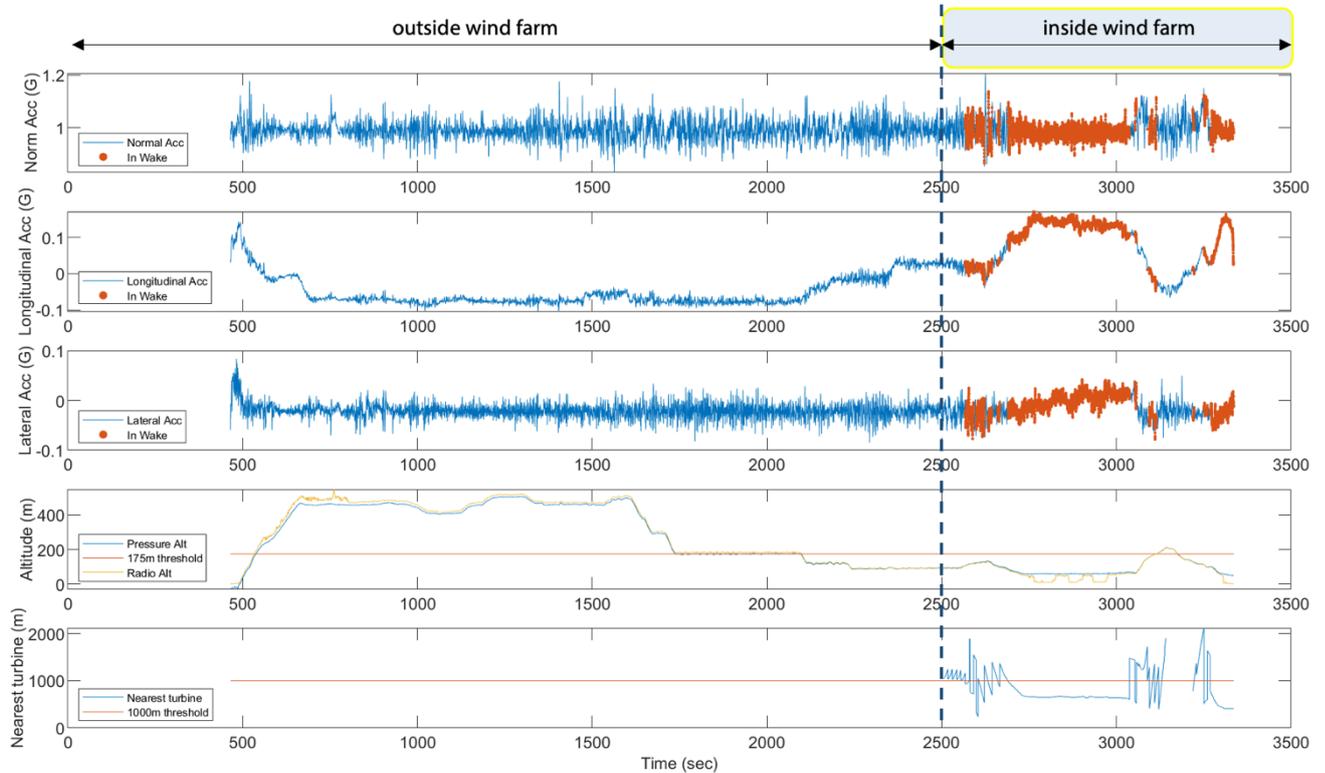
Figure 5-5: Accelerations (g) and threshold parameters for wake zone calculation over time

The lower two subfigures show the threshold parameters which are used for the wake zone calculation. When the helicopter is within a certain distance of the wind turbine, below a certain altitude, and the position of the helicopter is behind the wind turbine in the wake zone, then the segments of the track are marked red in the accelerations.

Multiple tracks have been analysed in a similar way as this individual track. The general observation is that no apparent difference is seen between segments in- and outside the wake zone, or in- and outside the wind farm.

5.2   Analysis of dataset

In this section the dataset of multiple flights will be used for the quantitative analyses.

To be able to analyse for noticeable differences in accelerations, different categories have been made (See Figure 5-6).

| Inside and outside wake zone | Inside and outside wind farm |
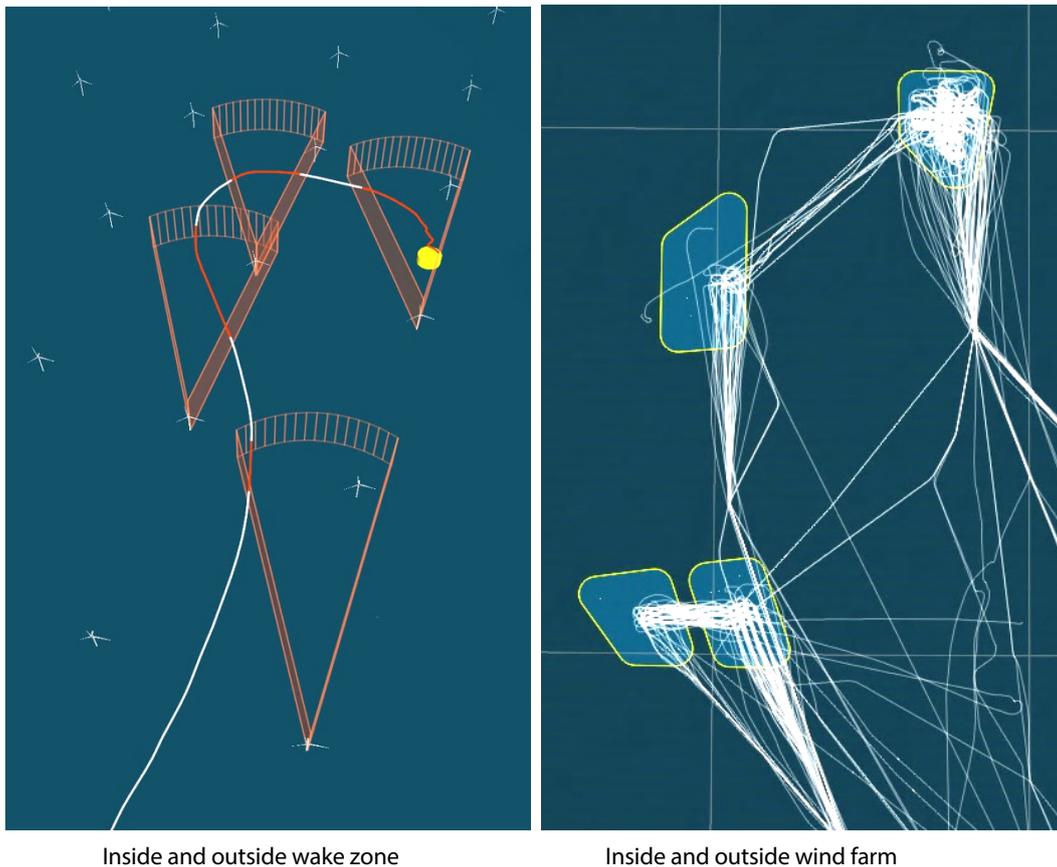
Figure 5-6: Different categories for analysis of dataset

To take into account different conditions, the analysis has been performed for two sets of average wind speed:
- [0-10 m/s] and [10-17 m/s] (33 kts)

The analysis has been done for flights in wind farm Gemini (119 flights) and for all wind farms (440 flights). The reason behind this is that for Gemini more accurate data is available (more reliable results);
- Status of individual wind turbines is known, therefore the presence of turning wind turbine wake is known;
- Source of the wind data is local, meaning more accurate wind data compared to the other wind farms;
- Mode of helicopter operations within the wind farm is in line with the scenario of helicopters flying in the wake zone of turning wind turbines to the service station in the centre of the wind farm.

Still, the analysis for all wind farms is interesting because of the larger dataset.

Of these categories, the data is presented in histograms of accelerations. The proposed reference criteria for the values of accelerations are -0.5 g and +2.0 g (See Section 3.1). These values are not expected to be reached, based on the individually selected tracks analysed, of which one is shown in the previous section.

5.2.1 Results for Gemini wind farm

Inside-outside wake zone

For wind farm Gemini the histograms of accelerations inside and outside the wake zone are shown in Figure 5-7. Generally, the histograms show results in line with the individually analysed tracks.

The data has been further categorised in low average wind speed in blue (0-10 m/s) and high average wind speed in red (10-17 m/s). For the normal accelerations it seems that with higher average wind speed the acceleration values are a bit more spread indicating more positive and negative g's are measured under these conditions.
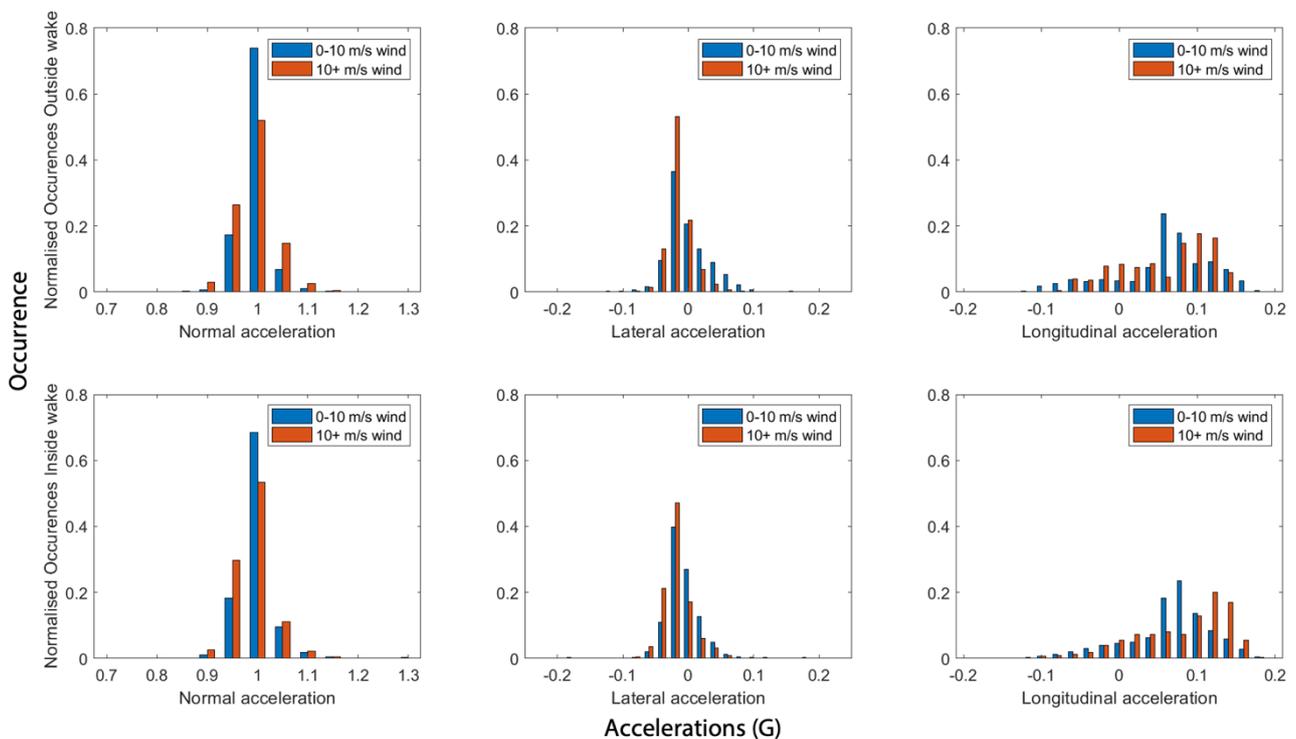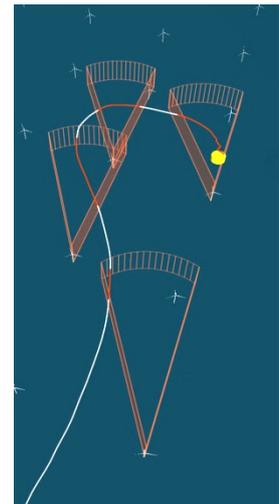
Figure 5-7: Histograms of accelerations inside/outside wake zone of wind farm (Gemini)

To more precisely analyse the minimum and maximum values of accelerations, these values are shown in a separate set of histograms (See Figure 5-8).
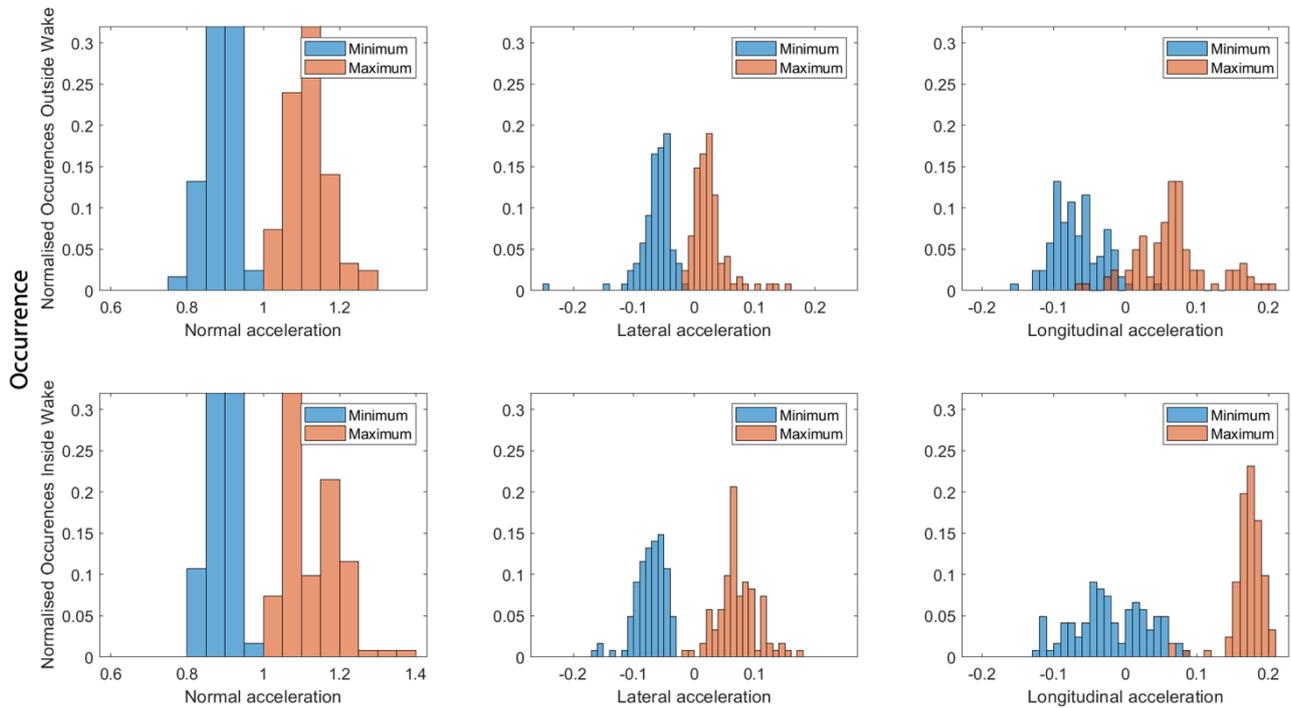
Figure 5-8: Histograms of min/max accelerations inside/outside wake zone of wind farm (Gemini)

The minimum normal acceleration for both inside and outside the wake zone is approximately 0.8 g. The maximum normal accelerations measured inside the wake zone are 1.4 g compared to 1.3 g outside the wake zone. These are all relatively low values compared to the -0.5 g and +2.0 g design limits with margin. The lateral and longitudinal accelerations generally al remain within -0.2 g and +0.2 g inside and outside the wake.

Inside-outside wind farm

In Figure 5-9 the histograms of accelerations inside and outside wind farms are shown for wind farm Gemini. Again, the histograms show results in line with the individually analysed tracks.

Generally, the accelerations are relatively low and similar for both inside and outside the wind farm, except for the lateral accelerations within the wind farm. The slightly larger lateral accelerations within the wind farm can be explained due to the manoeuvring (turns) within the wind farm and is not caused by high frequency spikes. To more precisely analyse the minimum and maximum values of accelerations, these values are shown in a separate set of histograms (See Figure 5-10).
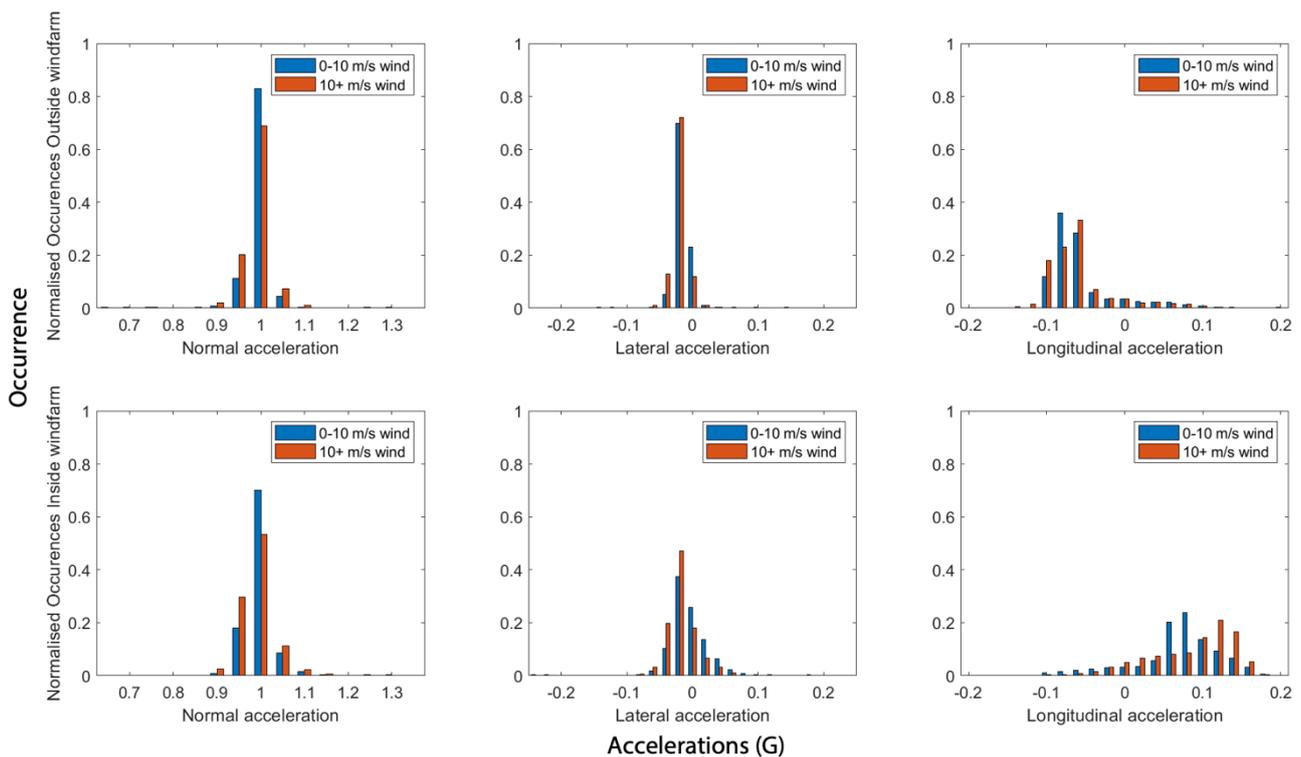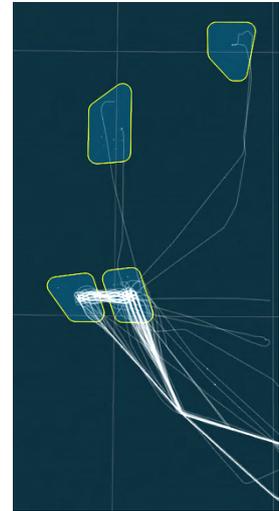
Figure 5-9: Histograms of accelerations inside/outside wind farm (Gemini)
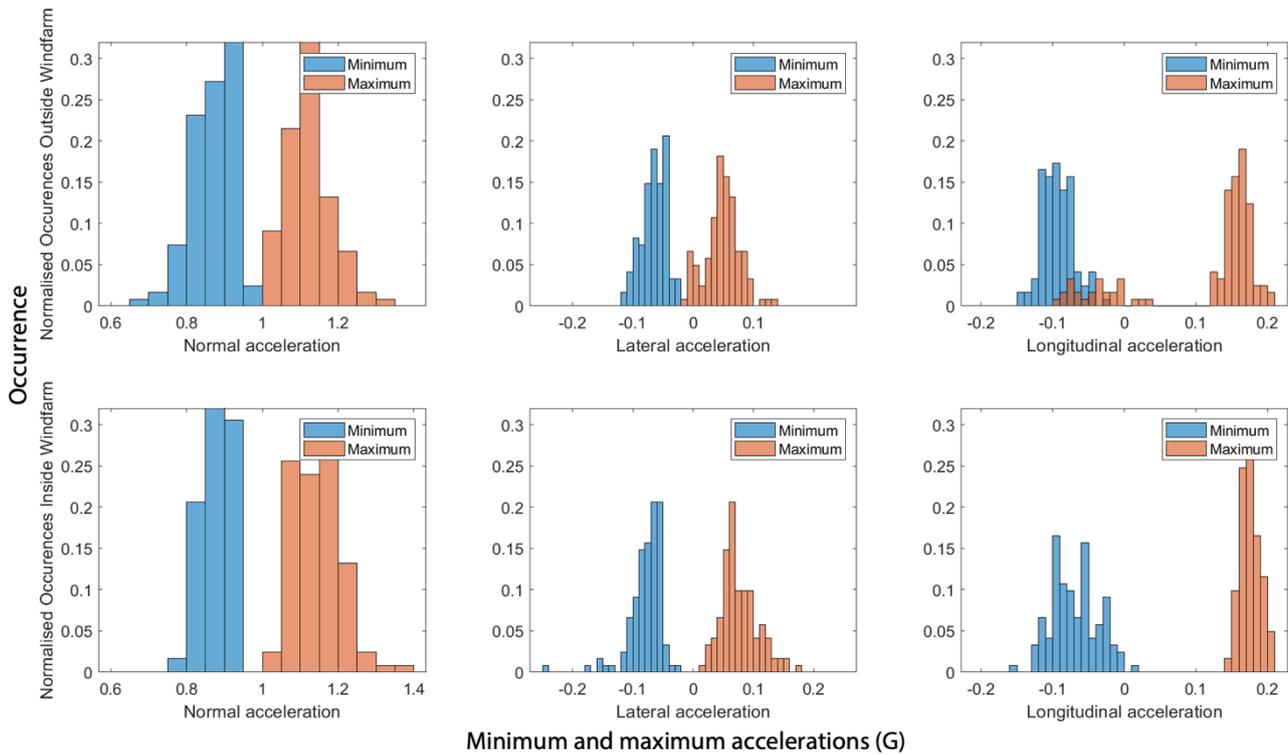
Figure 5-10: Histograms of min/max accelerations inside/outside wind farm (Gemini)

The minimum and maximum normal acceleration inside the wind farm is comparable to outside the windfarm with slightly larger negative accelerations (0.65 g compared to 0.75 g) seen outside the wind farm. As mentioned, the lateral accelerations are higher within the wind farm compared to outside the wind farm but remain relatively small. The longitudinal accelerations inside and outside the wind farm are comparable with respect to minimum and maximum values (-0.15 g to 0.2 g).

5.2.2   Results for all wind farms

Inside-outside wake zone

For all wind farms (Gemini, Global Tech I and Bard Offshore 1) the histograms of accelerations inside and outside the wake zone are shown in Figure 5-11. Generally, the histograms show results in line with the individually analysed tracks.

The accelerations are relatively low and similar for both inside and outside the wake zone.

To more precisely analyse the minimum and maximum values of accelerations, these values are shown in a separate set of histograms (See Figure 5-12).
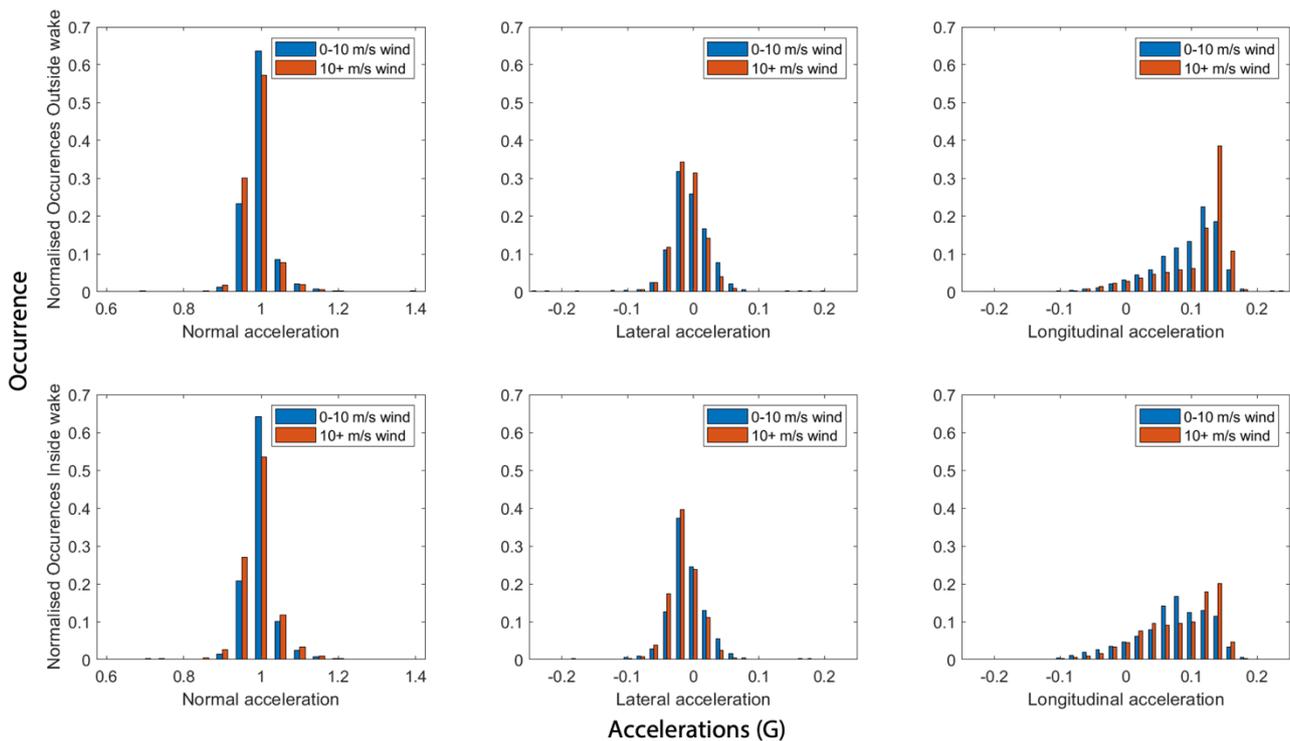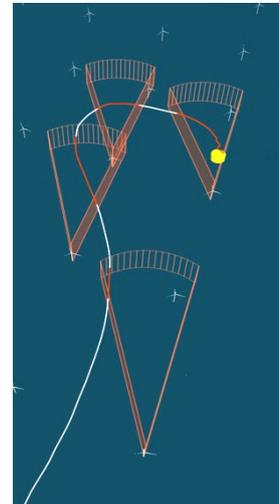
Figure 5-11: Histograms of accelerations inside/outside wake zone (all wind farms)
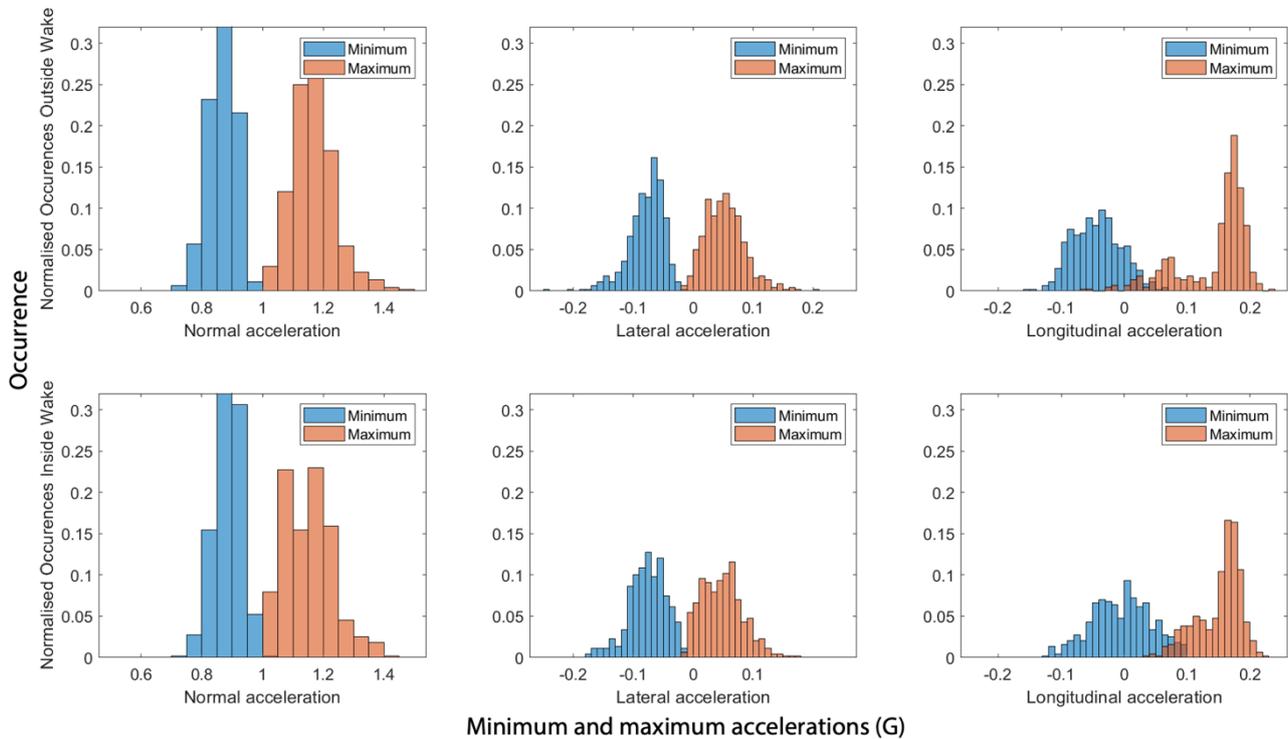
Figure 5-12: Histograms of min/max accelerations inside/outside wake zone (all wind farms)

The minimum and maximum normal accelerations are similar inside and outside the wake zone (0.7 g to 1.45 g). The minimum and maximum lateral and longitudinal accelerations also are similar inside and outside the wake zone, both -0.2 g to 0.2 g.

Inside-outside wind farms

In Figure 5-13 the histograms of accelerations inside and outside wind farms are shown for all wind farms (Gemini, Global Tech I, and Bard Offshore 1). Again, the histograms show results in line with the individually analysed tracks.

Generally, the accelerations are relatively low and similar for both inside and outside the wind farms, except for the lateral accelerations within the wind farms. Since the Gemini data is part of this complete dataset, the slightly larger lateral accelerations within the wind farms can be explained due to the manoeuvring (turns) within the wind farms and is not caused by high frequency spikes.

To more precisely analyse the minimum and maximum values of accelerations, these values are shown in a separate set of histograms (See Figure 5-14).
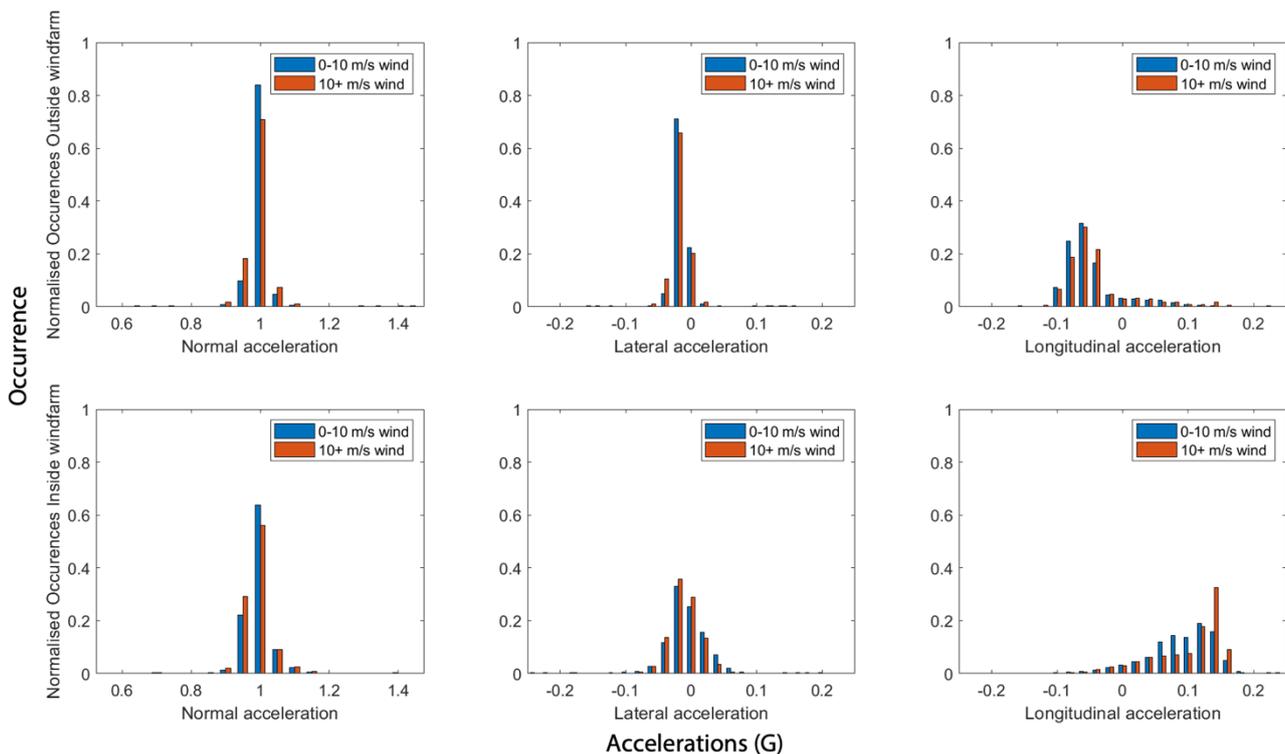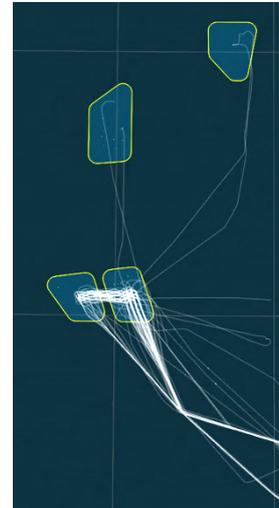
Figure 5-13: Histograms of accelerations inside/outside wind farms (all wind farms)
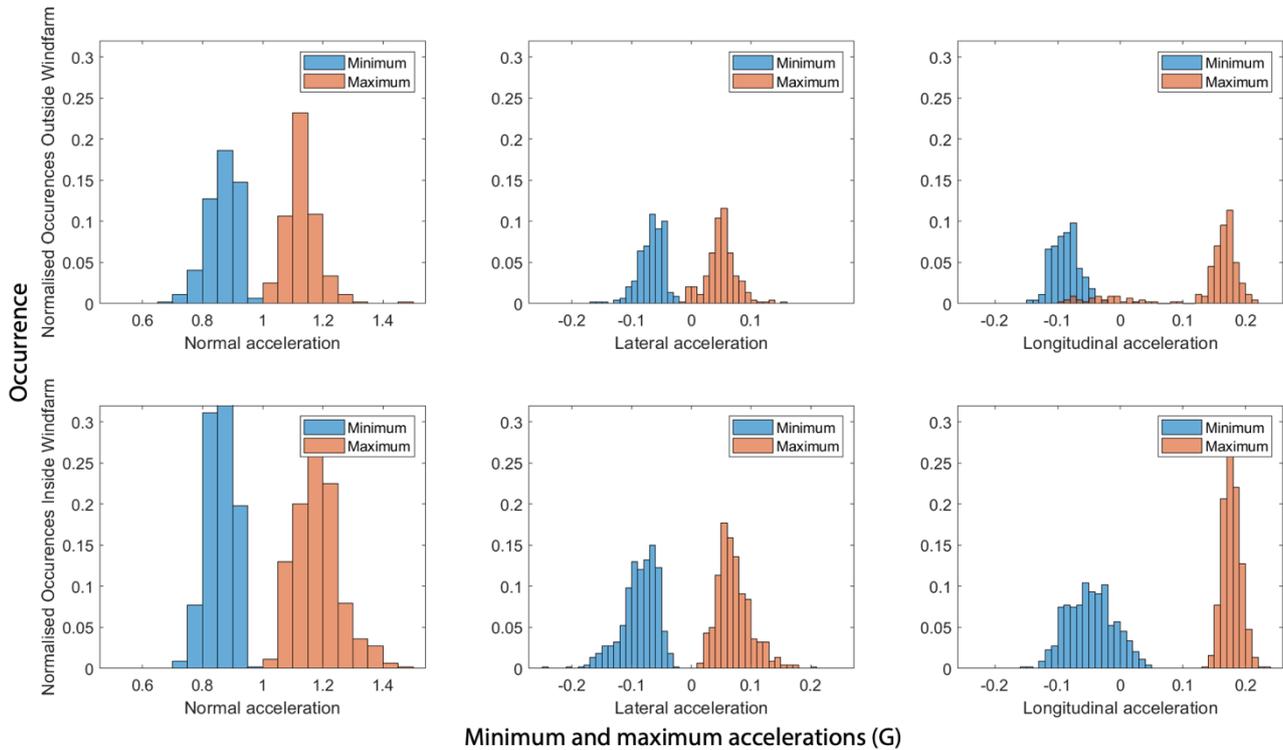
Figure 5-14: Histograms of min/max accelerations inside/outside wind farms (all wind farms)

The minimum and maximum normal acceleration inside and outside the wind farms is similar to the results for Gemini wind farm (See previous section). The minimum and maximum normal accelerations are approximately 0.65 g and 1.4 g and the minimum and maximum lateral and longitudinal accelerations are approximately -0.2 g and +0.2 g. These values are all within acceptable ranges.

5.3   Conclusions quantitative analysis

The analysis of individual tracks showed no apparent difference in acceleration data between segments of flight inside and outside the wake zone or inside and outside the wind farms.

Gemini wind farm

The analysis of the dataset for wind farm Gemini (119 flights) with the most accurate data showed that the minimum and maximum accelerations are generally similar inside and outside the wake zone and inside and outside the wind farm.

Wind farms Gemini, Global Tech I and Bard Offshore 1

The analysis of the complete dataset (440 flights) for all wind farms showed similar results to the results for Gemini wind farm and is further supporting the conclusions based on the larger dataset.

The values of the minimum and maximum normal accelerations are all relatively low (0.65 g to 1.4 g) and well within the design limits (-1.0 g to 3.5 g), even well within the design limits with margin, which have an extremely remote probability of being exceeded (-0.5 g to +2.0 g). The minimum and maximum lateral and longitudinal accelerations are approximately -0.2 g and +0.2 g, which are also relatively low and well within acceptable ranges.

Because the minimum and maximum accelerations are seen in and outside wake zones and in <u>and</u> outside wind farms in a similar way, the effect of wind turbine wake turbulence on helicopters does not seem limiting to operations (with respect to accelerations).

6   Consultation of the findings

The approach and preliminary results of the data analysis have been presented and discussed with the aviation authority (ILT) on 09-01-2020. The attendees at this meeting are listed in Appendix D.
To confirm and supplement the findings based on actual helicopter flight data, helicopter operators with practical experience are consulted on 14-01-2020. The attendees at this expert session are listed in Appendix E.
The information gathered during this meeting supports the conclusion that wind turbines cause no notable differences for helicopters when comparing the accelerations between flying in- and outside the wind farms. The discussion from the expert session is summarised per topic in Appendix F. The joint conclusions are presented below.

Joint conclusions helicopter operators
The opinions from different operators with daily experience is in line with the conclusions from the data analysis.
The data analysis shows no apparent difference between acceleration data inside the wind farm and outside the wind farm. So, no significant effect of wind farms on measured acceleration is seen.
HeliService supports this observation based on their experience with operations in these wind farms. Combined with the fact that there are no unexpected turbulence reports, helicopter operations in wind farms are considered safe by operators HeliService, CHC and NHV.
It is agreed that to define the exact minimal safe operating distance from a wind turbine, an instrumented helicopter is required and by setting up a test plan, different scenarios could be evaluated. The expectation of the group is that results of that experiment would be in line with the current study but would provide more detail.

The general consensus is that all large objects cause wake turbulence due to them disturbing the wind flow. It is even stated that objects other than wind turbines, such as ships and platforms, cause more wake turbulence than wind turbines (whether they are turning or not). Unexpected turbulence is reported when occurring unexpectedly, wind turbine turbulence could be handled the same. Coming closer to wind turbines for hoisting operations, more turbulence can be encountered from the static object, but this is also the case when flying near large ships or platforms, which is already done often. The conclusion for normal operations[50] therefore is that a 'stop procedure' is not necessary.

A combination of the theory, data analysis and experience of operational experts could be convincing enough of safe operations in and around wind farms.

Estimate of the effect of wake turbulence on other types of helicopters
The helicopter type used in the study is stated to be a good representation of helicopters that fly in the North Sea area. Smaller/lighter helicopters are not foreseen to be used in offshore helicopter operations, a.o. due to their limited range in combination with the long distance to offshore wind farms.

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[50] Helicopter hoist operations for example, are not considered as normal operations. During hoist operations, the specific wind turbine will of course be stopped.

On the other hand, the size of the helicopters is limited because of the size of the rotor disc conflicting with the turbine rotor during hoist operations. Therefore, the size/weight of a helicopter comparable to an AW139 is mentioned as one of the largest helicopters to be expected in wind farm operations. This larger and heavier helicopter in comparison to the AW169, of which the data is used in this study, is probably less sensitive to turbulence.

7 Conclusions and recommendations

7.1 Conclusions

To70 has been asked to perform a study on wind turbine wake turbulence effects on helicopters, to give more insight in the minimum safe distances for helicopter operations when operating in or around wind farms, taking into account the actual effects of wind turbine wake turbulence, and taking into account different circumstances and conditions.

> The data analysis shows no apparent difference between acceleration data inside and outside the wake turbulence zone or inside and outside the wind farm. Therefore, the effect of wind turbine wake turbulence on offshore helicopters does not seem limiting to operations. HeliService supports this conclusion based on their experience with operations in these wind farms.

Combined with the fact that there are no unexpected turbulence reports for flights within wind farms, helicopter operations in wind farms are considered safe by operators HeliService, CHC and NHV. The operators indicated that the current mitigation 'stop procedure' is thus not seen as necessary.

7.2 Recommendations

Additional research can further improve insight in the minimum safe distances for helicopter operations in and near offshore wind farms, if this is deemed necessary by authorities or other stakeholders.

Although the helicopter operators expect wind turbine wake turbulence not to be an issue and the 'stop procedure' not to be necessary, additional research is possible to further strengthen the conclusion for:

- Different helicopter types and weight (e.g. AW139).
- Larger wind turbines (more than 150 m) with larger rotor diameters (more than 130 m) and/or wind turbines with more power (more than 5000 kW) and/or onshore wind turbines.

Also, apart from the data analysis based on accelerations, pilot workload (input) and change in helicopter attitude during wind turbine wake turbulence can be researched.

Appendix A   HFDM data parameters

In the HFDM data for the AW169 obtained from HeliService, the following parameters were available, see Table A-1 below.

Table A-1: HFDM data parameters available

Parameter	Nr.	Description	Units
Time (secs)	0	Time of data point since start	Seconds
Normal acceleration	1	Acceleration perpendicular to the flight path, upwards	G
Lateral Acceleration	2	Acceleration perpendicular to the flight path, sideways	G
Longitudinal Acceleration	3	Acceleration along the flight path	G
Latitude (Fine)	4	North-South coordinate	Decimals, Degrees, Minutes
Longitude (Fine)	5	East-West coordinate	Decimals, Degrees, Minutes
Pressure Altitude ADU1	6	Altitude based on pressure (not calibrated)	Feet
Radio Altitude RADALT1	7	Altitude measured below helicopter	Feet
Magnetic Heading AHRS1	8	Heading with respect to magnetic North	Degrees
Track	9	Heading with respect to real North	Degrees
Date_Year	10	Year of data point	Years
Date_Month	11	Month of data point	Months
Date_Day	12	Day of data point	Days
Time_Hours	13	Hour of data point	Hours (Universal time)
Time_Minutes	14	Minute of data point	Minutes
Time_Seconds	15	Second of data point	Seconds
NG1	16	Engine 1 setting	Percentage
NG2	17	Engine 2 setting	Percentage
NR1	18	Rotor speed	Percentage
TQ1	19	Torque 1	Percentage
TQ2	20	Torque 2	Percentage
Ground Dist to Touchdown	21	Altitude above ground	True/False
Landing Gear Position	22	Indication of landing gear up or down	True/False
WOW1	23	Weight-on-wheels	Ground/Air

Appendix B Coordinates of wind turbines in wind farms

In this appendix the coordinates of wind turbine in wind farms Gemini I/II, Global Tech I and Bard Offshore I are listed in Tables B-1, B-2 and B-3.

Table B-1: Coordinates of wind turbines in wind farm Gemini I – Buitengaats

Turbine	UTM X	UTM Y	Name	Object ID	Lat	Lon
Q1	697864,53	5991937,28	Buitengaats / Gemini I	67	54,037667	6,021712
Q2	696889,01	5992174,72	Buitengaats / Gemini I	68	54,040171	6,006990
Q3	696638,27	5992821,19	Buitengaats / Gemini I	69	54,046069	6,003585
Q4	696387,22	5993467,31	Buitengaats / Gemini I	70	54,051964	6,000175
Q5	696135,64	5994113,13	Buitengaats / Gemini I	71	54,057856	5,996755
Q6	695885,19	5994758,92	Buitengaats / Gemini I	72	54,063748	5,993351
Q7	695634,06	5995405,22	Buitengaats / Gemini I	73	54,069644	5,989936
R1	698585,82	5992354,77	Buitengaats / Gemini I	74	54,041137	6,032983
R2	697632,36	5992538,02	Buitengaats / Gemini I	75	54,043148	6,018562
R3	697398,5	5993138,95	Buitengaats / Gemini I	76	54,048631	6,015387
R4	697164,89	5993740,83	Buitengaats / Gemini I	77	54,054122	6,012215
R5	696931,57	5994341,99	Buitengaats / Gemini I	78	54,059607	6,009046
R6	696697,55	5994944,41	Buitengaats / Gemini I	79	54,065103	6,005866
R7	696464,12	5995544,96	Buitengaats / Gemini I	80	54,070583	6,002694
S1	698327,87	5993020,58	Buitengaats / Gemini I	81	54,047212	6,029484
S2	698070,13	5993686,43	Buitengaats / Gemini I	82	54,053287	6,025988
S3	697811,99	5994352,83	Buitengaats / Gemini I	83	54,059367	6,022485
S4	697553,71	5995018,58	Buitengaats / Gemini I	84	54,065442	6,018978
S5	698371,82	5995206,255	Buitengaats / Gemini I	85	54,066812	6,031584
S6	698612,51	5994586,85	Buitengaats / Gemini I	86	54,061160	6,034851
S7	698851,33	5993966,87	Buitengaats / Gemini I	87	54,055503	6,038088
S8	699091,81	5993346,33	Buitengaats / Gemini I	88	54,049841	6,041349
T1	699331,77	5992726,93	Buitengaats / Gemini I	89	54,044189	6,044602
T2	700023,89	5993221,96	Buitengaats / Gemini I	90	54,048364	6,055483
T3	699758,69	5993907,9	Buitengaats / Gemini I	91	54,054623	6,051890
T4	699493,8	5994593,96	Buitengaats / Gemini I	92	54,060883	6,048301
T5	699227,58	5995281,26	Buitengaats / Gemini I	93	54,067155	6,044691
T6	698962,68	5995966,94	Buitengaats / Gemini I	94	54,073411	6,041099
T7	698132,97	5995827	Buitengaats / Gemini I	130	54,072475	6,028345
U1	699571,99	5992107,23	Buitengaats / Gemini I	131	54,038535	6,047858
U2	700289,11	5992536,34	Buitengaats / Gemini I	132	54,042108	6,059076
U3	701025,84	5992916,19	Buitengaats / Gemini I	133	54,045230	6,070562
U4	700778,49	5993553,95	Buitengaats / Gemini I	134	54,051051	6,067212

Turbine	UTM X	UTM Y	Name	Object ID	Lat	Lon
U5	700533,22	5994191,92	Buitengaats / Gemini I	135	54,056872	6,063892
U6	700286,86	5994830,97	Buitengaats / Gemini I	136	54,062703	6,060556
U7	700039,92	5995468,9	Buitengaats / Gemini I	137	54,068524	6,057210
U8	699794,47	5996107,44	Buitengaats / Gemini I	138	54,074351	6,053885
V1	700555,98	5991846,27	Buitengaats / Gemini I	139	54,035811	6,062690
V2	701271,7	5992278,12	Buitengaats / Gemini I	140	54,039408	6,073888
V3	701520,04	5991636,14	Buitengaats / Gemini I	141	54,033549	6,077249
V4	701765,99	5990997,77	Buitengaats / Gemini I	142	54,027724	6,080575
V5	702012,71	5990360,25	Buitengaats / Gemini I	143	54,021906	6,083912
V7	702505,22	5989082,68	Buitengaats / Gemini I	144	54,010247	6,090568
V8	702752,25	5988445,08	Buitengaats / Gemini I	145	54,004428	6,093907
W1	699812,79	5991485,03	Buitengaats / Gemini I	146	54,032857	6,051121
W2	700821,22	5991159,71	Buitengaats / Gemini I	147	54,029546	6,066280
W3	701085,85	5990473,76	Buitengaats / Gemini I	148	54,023286	6,069860
W4	701351,51	5989788,31	Buitengaats / Gemini I	149	54,017031	6,073456
W5	701616,97	5989100,58	Buitengaats / Gemini I	150	54,010755	6,077045
W6	701882,19	5988414,73	Buitengaats / Gemini I	151	54,004496	6,080632
W7	701012,5	5988385,17	Buitengaats / Gemini I	152	54,004570	6,067362
X1	700053,22	5990865,17	Buitengaats / Gemini I	153	54,027201	6,054378
X2	700291,65	5990245,14	Buitengaats / Gemini I	154	54,021543	6,057604
X3	700531,89	5989624,72	Buitengaats / Gemini I	155	54,015882	6,060857
X4	700772,1	5989004,99	Buitengaats / Gemini I	156	54,010226	6,064108
X5	699878,09	5989020,9	Buitengaats / Gemini I	157	54,010716	6,050496
X6	699619,61	5989688,54	Buitengaats / Gemini I	158	54,016808	6,046996
X7	699362,18	5990353,57	Buitengaats / Gemini I	159	54,022876	6,043508
Y1	699104,22	5991019,58	Buitengaats / Gemini I	160	54,028953	6,040013
Y2	698332,96	5990730,63	Buitengaats / Gemini I	161	54,026657	6,028066
Y3	698566,29	5990129,43	Buitengaats / Gemini I	162	54,021171	6,031231
Y4	698800,5	5989528,15	Buitengaats / Gemini I	163	54,015684	6,034407
Y5	699032,87	5988927,16	Buitengaats / Gemini I	164	54,010201	6,037555
Y7	700135,81	5988355,33	Buitengaats / Gemini I	165	54,004642	6,053985
Z1	698846,34	5991686,22	Buitengaats / Gemini I	166	54,035036	6,036518
Z2	698098,77	5991332,68	Buitengaats / Gemini I	167	54,032150	6,024889
Z3	697141,25	5991526,12	Buitengaats / Gemini I	168	54,034253	6,010416
Z4	697391,67	5990879,75	Buitengaats / Gemini I	169	54,028356	6,013814
Z5	697642,85	5990234,53	Buitengaats / Gemini I	170	54,022469	6,017224
Z6	697895,29	5989587,78	Buitengaats / Gemini I	171	54,016567	6,020651
Z7	698145,71	5988942,59	Buitengaats / Gemini I	172	54,010681	6,024047

Turbine	UTM X	UTM Y	Name	Object ID	Lat	Lon
Z8	698397,4	5988296,02	Buitengaats / Gemini I	173	54,004781	6,027460
R8	697294,32	5995684,13	Buitengaats / Gemini I	283	54,071515	6,015453
V6	702259,23	5989721,19	Buitengaats / Gemini I	284	54,016074	6,087244
Y6	699265,82	5988325,01	Buitengaats / Gemini I	285	54,004707	6,040711

Source: Overheid[51]

Table B-2: Coordinates of wind turbines in wind farm Gemini II – ZeeEnergie

Turbine	UTM X	UTM Y	Name	Object ID	Lat	Lon
B3	686943,97	5992713,09	ZeeEnergie / Gemini II	1	54,048704	5,855650
B4	686608,22	5993235,9	ZeeEnergie / Gemini II	2	54,053518	5,850850
B5	686271,7	5993758,91	ZeeEnergie / Gemini II	3	54,058335	5,846037
B6	685681,74	5993019,14	ZeeEnergie / Gemini II	4	54,051907	5,836582
B7	686082,72	5992459,91	ZeeEnergie / Gemini II	5	54,046742	5,842357
B8	686482,79	5991899,93	ZeeEnergie / Gemini II	6	54,041571	5,848115
C1	688804,01	5991254,09	ZeeEnergie / Gemini II	7	54,034929	5,883116
C2	688496,25	5991790,55	ZeeEnergie / Gemini II	8	54,039858	5,878756
C3	688187,26	5992327,81	ZeeEnergie / Gemini II	9	54,044793	5,874377
C4	687878,89	5992865,54	ZeeEnergie / Gemini II	10	54,049732	5,870006
C5	687570,82	5993402,31	ZeeEnergie / Gemini II	11	54,054663	5,865638
C6	687262,03	5993938,89	ZeeEnergie / Gemini II	12	54,059592	5,861258
C7	688260,34	5994121,17	ZeeEnergie / Gemini II	13	54,060865	5,876604
D1	689379,94	5991914,74	ZeeEnergie / Gemini II	14	54,040649	5,892310
D2	689100,09	5992466,81	ZeeEnergie / Gemini II	15	54,045707	5,888386
D3	688820,67	5993018,06	ZeeEnergie / Gemini II	16	54,050758	5,884467
D4	688540,05	5993569,06	ZeeEnergie / Gemini II	17	54,055806	5,880529
D5	689251,2	5994301,11	ZeeEnergie / Gemini II	18	54,062117	5,891835
D6	689528,04	5993679,33	ZeeEnergie / Gemini II	19	54,056434	5,895671
D7	689804,98	5993056,73	ZeeEnergie / Gemini II	20	54,050743	5,899507
D8	690083,33	5992434,01	ZeeEnergie / Gemini II	21	54,045051	5,903363
E1	689661,08	5991364,12	ZeeEnergie / Gemini II	22	54,035603	5,896254
E3	691362,26	5991581,61	ZeeEnergie / Gemini II	23	54,036927	5,922332
E4	691137,84	5992161,77	ZeeEnergie / Gemini II	24	54,042218	5,919275
E5	690913,67	5992741,68	ZeeEnergie / Gemini II	25	54,047506	5,916221
E6	690689,94	5993321,83	ZeeEnergie / Gemini II	26	54,052796	5,913173
E7	690464,81	5993900,54	ZeeEnergie / Gemini II	27	54,058074	5,910102

Turbine	UTM X	UTM Y	Name	Object ID	Lat	Lon
E8	690241,14	5994480,95	ZeeEnergie / Gemini II	28	54,063367	5,907053
F1	690553,21	5991179,98	ZeeEnergie / Gemini II	29	54,033621	5,909743
F2	691588,06	5990998,88	ZeeEnergie / Gemini II	30	54,031612	5,925408
F3	691812,26	5990419,86	ZeeEnergie / Gemini II	31	54,026332	5,928461
F4	692036,09	5989839,83	ZeeEnergie / Gemini II	33	54,021042	5,931507
F5	692260,23	5989260,05	ZeeEnergie / Gemini II	34	54,015755	5,934557
F6	692484,36	5988679,69	ZeeEnergie / Gemini II	35	54,010462	5,937606
F7	692709,22	5988099,85	ZeeEnergie / Gemini II	36	54,005173	5,940665
G1	689609,64	5990772,14	ZeeEnergie / Gemini II	37	54,030308	5,895100
G2	690753,06	5990547,75	ZeeEnergie / Gemini II	38	54,027872	5,912393
G3	691037,07	5989929,12	ZeeEnergie / Gemini II	39	54,022214	5,916334
G4	691319,85	5989310,12	ZeeEnergie / Gemini II	40	54,016553	5,920255
G5	691604,71	5988690,53	ZeeEnergie / Gemini II	41	54,010886	5,924207
G6	691887,05	5988071,73	ZeeEnergie / Gemini II	42	54,005227	5,928119
G7	691065,22	5988043,97	ZeeEnergie / Gemini II	43	54,005282	5,915579
H1	689901,13	5990226,25	ZeeEnergie / Gemini II	44	54,025301	5,899203
H2	690191,76	5989681,26	ZeeEnergie / Gemini II	45	54,020302	5,903293
H3	690483,01	5989135,03	ZeeEnergie / Gemini II	46	54,015291	5,907391
H4	690774,12	5988588,01	ZeeEnergie / Gemini II	47	54,010273	5,911485
H5	689922,88	5988543,86	ZeeEnergie / Gemini II	48	54,010191	5,898484
H6	689596,85	5989073,47	ZeeEnergie / Gemini II	49	54,015065	5,893846
J1	688946,88	5990129,94	ZeeEnergie / Gemini II	50	54,024786	5,884596
J2	687847,49	5990238,26	ZeeEnergie / Gemini II	51	54,026160	5,867902
J3	688243,1	5989675,45	ZeeEnergie / Gemini II	52	54,020964	5,873585
J4	688637,32	5989113,32	ZeeEnergie / Gemini II	53	54,015774	5,879245
J5	689032,32	5988549,46	ZeeEnergie / Gemini II	54	54,010568	5,884916
J6	689425,72	5987986,7	ZeeEnergie / Gemini II	55	54,005372	5,890561
J7	690248,41	5988015,68	ZeeEnergie / Gemini II	56	54,005330	5,903115
K1	688622,06	5990659,17	ZeeEnergie / Gemini II	57	54,029656	5,879972
K2	687367,84	5990792,38	ZeeEnergie / Gemini II	58	54,031308	5,860931
K3	686447,11	5990679,22	ZeeEnergie / Gemini II	59	54,030626	5,846822
K4	686869,68	5990146,36	ZeeEnergie / Gemini II	60	54,025690	5,852937
K5	687290,78	5989615,69	ZeeEnergie / Gemini II	61	54,020774	5,859030
K6	687731,81	5989059,12	ZeeEnergie / Gemini II	62	54,015617	5,865410
K7	688173,16	5988503,07	ZeeEnergie / Gemini II	63	54,010465	5,871793
K8	688604,28	5987958,62	ZeeEnergie / Gemini II	64	54,005421	5,878026
A6	684722	5992855,1	ZeeEnergie / Gemini II	280	54,050779	5,821840
E2	690360,25	5991811,64	ZeeEnergie / Gemini II	281	54,039362	5,907196

Turbine	UTM X	UTM Y	Name	Object ID	Lat	Lon
H7	689272,33	5989601,03	ZeeEnergie / Gemini II	282	54,019919	5,889228
A1	687952,87	5991144,98	ZeeEnergie / Gemini II	286	54,034261	5,870069
A2	686883,54	5991341,2	ZeeEnergie / Gemini II	287	54,036411	5,853884
A3	686015,92	5991223,2	ZeeEnergie / Gemini II	288	54,035665	5,840580
A4	685584,99	5991766,78	ZeeEnergie / Gemini II	289	54,040700	5,834340
A5	685153,79	5992310,52	ZeeEnergie / Gemini II	290	54,045736	5,828095
A7	684291,13	5993398,3	ZeeEnergie / Gemini II	291	54,055810	5,815597
A8	685282,27	5993579,01	ZeeEnergie / Gemini II	292	54,057077	5,830830
B1	687617,36	5991668,17	ZeeEnergie / Gemini II	293	54,039079	5,865276
B2	687281,23	5992190	ZeeEnergie / Gemini II	294	54,043886	5,860472

Source: Overheid[52]

Table B-3: Coordinates of wind turbines in wind farms Global Tech I and Bard Offshore 1

Global Tech I			Bard Offshore 1		
Turbine	Lat	Lon	Turbine	Lat	Lon
1	54,498056	6,373056	1	54,414444	6,018333
2	54,485833	6,367222	2	54,406667	6,018333
3	54,479722	6,362778	3	54,399167	6,018333
4	54,473611	6,357778	4	54,391389	6,018056
5	54,485833	6,381111	5	54,383889	6,018056
6	54,479722	6,377222	6	54,376111	6,018333
7	54,473611	6,372500	7	54,368611	6,018333
8	54,467778	6,379722	8	54,360833	6,018333
9	54,491944	6,370278	9	54,421944	6,018333
10	54,498056	6,400556	10	54,416667	6,006389
11	54,467778	6,367222	11	54,406389	6,006111
12	54,461667	6,376944	12	54,398611	6,001667
13	54,504167	6,373889	13	54,390278	6,005000
14	54,498056	6,386389	14	54,382222	6,008333
15	54,491944	6,383889	15	54,371111	6,005000
16	54,491944	6,398333	16	54,363056	6,008333
17	54,485833	6,394722	17	54,411944	5,995278
18	54,479722	6,391667	18	54,406944	5,984167
19	54,473611	6,387222	19	54,402778	5,993056
20	54,467778	6,392222	20	54,397500	5,981944

[52] Retrieved from Open data van de overheid:
https://data.overheid.nl/dataset/48488-posities-van-turbines-zoals-deze-zijn-vastgelegd-in-de-vergunningen#panel-4-downloadable-files
https://geoservices.rijkswaterstaat.nl/apps/geoserver/windenergiegebieden/ows?service=WFS&version=1.1.0&request=GetFeature&typeName=turbines_en_ohvs&outputFormat=csv

Global Tech I			Bard Offshore 1		
Turbine	Lat	Lon	Turbine	Lat	Lon
21	54,461667	6,390000	21	54,389167	5,985278
22	54,504167	6,387778	22	54,381111	5,988611
23	54,510278	6,389444	23	54,372778	5,991944
24	54,510278	6,375000	24	54,364722	5,995278
25	54,516389	6,376389	25	54,401944	5,973056
26	54,516389	6,347222	26	54,397222	5,961944
27	54,510278	6,346667	27	54,388056	5,968889
28	54,516389	6,332778	28	54,380000	5,972222
29	54,510278	6,332500	29	54,371667	5,975278
30	54,504167	6,332222	30	54,363611	5,978611
31	54,498056	6,320000	31	54,356389	5,998333
32	54,504167	6,318333	32	54,355278	5,981944
33	54,510278	6,318333	33	54,392222	5,950833
34	54,510278	6,360833	34	54,379167	5,952778
35	54,504167	6,360000	35	54,387222	5,939722
36	54,498056	6,359722	36	54,379167	5,939444
37	54,491944	6,356667	37	54,371667	5,939444
38	54,485833	6,353056	38	54,371111	5,956111
39	54,522500	6,377222	39	54,362778	5,959722
40	54,528611	6,379444	40	54,354722	5,965833
41	54,516389	6,390833	41	54,363889	5,939444
42	54,522500	6,391944	42	54,356389	5,939444
43	54,528611	6,394722	43	54,355556	5,952222
44	54,534722	6,394722	44	54,349444	5,939444
45	54,540833	6,401944	45	54,345278	5,949444
46	54,504167	6,401667	46	54,341111	5,939444
47	54,510278	6,403611	47	54,337222	5,952778
48	54,516389	6,405278	48	54,333333	5,939444
49	54,522500	6,406667	49	54,347222	5,985278
50	54,528611	6,410000	50	54,346389	5,968889
51	54,534722	6,410000	51	54,328889	5,955833
52	54,540833	6,415833	52	54,325833	5,939444
53	54,504167	6,346111	53	54,338333	5,972222
54	54,498056	6,346389	54	54,330000	5,975556
55	54,498056	6,333333	55	54,320556	5,959167
56	54,491944	6,329444	56	54,318056	5,939444
57	54,491944	6,343056	57	54,338889	5,988333

Global Tech I				Bard Offshore 1		
Turbine	Lat	Lon		Turbine	Lat	Lon
58	54,485833	6,338889		58	54,330833	5,991667
59	54,479722	6,348611		59	54,321667	5,978611
60	54,522500	6,332778		60	54,312500	5,962500
61	54,522500	6,318056		61	54,310556	5,939444
62	54,516389	6,318333		62	54,304167	5,965556
63	54,528611	6,318333		63	54,303611	5,952500
64	54,534722	6,318056		64	54,302778	5,939444
65	54,540833	6,318056		65	54,348333	6,004722
66	54,540833	6,332222		66	54,322500	5,995000
67	54,534722	6,333333		67	54,313611	5,981944
68	54,528611	6,333611		68	54,305000	5,978611
69	54,516389	6,361667		69	54,340000	6,004722
70	54,522500	6,362500		70	54,331667	6,004722
71	54,528611	6,364167		71	54,314444	5,998333
72	54,534722	6,364167		72	54,305556	5,991667
73	54,540833	6,360000		73	54,353333	6,018333
74	54,540833	6,373889		74	54,345556	6,018056
75	54,540833	6,388056		75	54,338056	6,018056
76	54,534722	6,379444		76	54,330278	6,018333
77	54,522500	6,347778		77	54,322778	6,018333
78	54,528611	6,348889		78	54,315000	6,018056
79	54,534722	6,348611		79	54,306944	6,017778
80	54,540833	6,346111		80	54,306389	6,004722

Source: AIP Germany (2019)[53]

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[53] AIP Germany. (2019). Retrieved from AIP Germany - ENR 5.4 Nordsee-8 – Global Tech I, ENR 5.4 Nordsee-20 – Bard Offshore 1: https://secais.dfs.de/pilotservice/home.jsp

Appendix C   Wind data

The wind data has been retrieved from the Royal Netherlands Meteorological Institute (KNMI)[54]. The hourly data from the North Sea station #214 Buitengaats (BG-OHVS2) has been used.

Part of the header of the datafile is presented below. This shows the relevant properties of the wind data.

BRON/SOURCE:

KONINKLIJK NEDERLANDS METEOROLOGISCH INSTITUUT (KNMI)/ROYAL NETHERLANDS METEOROLOGICAL INSTITUTE (KNMI)

YYYYMMDD = date (YYYY=year, MM=month, DD=day)

HH   = time (HH hour, UT. 12 UT=13 MET, 14 MEZT. Hourly division 05 runs from 04.00 UT to 5.00 UT

DD   = Mean wind direction (in degrees) during the 10-minute period preceding the time of observation

                (360=north, 90=east, 180=south, 270=west, 0=calm 990=variable)

FH   = Hourly mean wind speed (in 0.1 m/s)

FF   = Mean wind speed (in 0.1 m/s) during the 10-minute period preceding the time of observation

FX   = Maximum wind gust (in 0.1 m/s) during the hourly division

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[54] Retrieved from KNMI: https://www.knmi.nl/nederlandnu/klimatologie/uurgegevens_Noordzee, station 214, Buitengaats/BG-OHVS2

Appendix D   Attendees session with workgroup and ILT on 09-01-2020

Attendees at session to discuss the approach and preliminary results with ILT (Civil Aviation Authority) on the 9th of January 2020.

Name	Organisation	Role
Theo de Jong	To70	Coordinator, input analysis expertise *Project lead*
Joost van der Ploeg	To70	Input analysis expertise *Coding and technical analysis*
Jeroen Timmers	To70	Additional To70 expertise *Helicopter project experience*
Matté Brijder	RVO	Workgroup member / Client *Wind farm site decisions*
Camiel van der Hout	EZK	Workgroup member / Client *Wind farm site decisions*
Jan Hazes	IenW/MinDef	Workgroup member *Military aviation authority, senior policy advisor ATM issues*
Thomas Collette	RWS	Workgroup member *Contractor lot decisions, experienced with offshore oil and gas projects*
Dennis Verheul	ILT	Inspector (Civil Aviation Authority) *Experienced helicopter pilot*

Appendix E   Attendees expert session on 14-01-2020

Attendees at expert session on the 14th January 2020 where the approach and preliminary results of the study is presented followed by a discussion with helicopter operators.

Name	Organisation	Role
Theo de Jong	To70	Expert session coordinator *Project lead*
Joost van der Ploeg	To70	Expert session secretary *Coding and technical analysis*
Jeroen Timmers	To70	Additional To70 expertise *Helicopter project experience*
Camiel van der Hout	EZK/RVO	Workgroup member/ Client *Wind farm site decisions*
Raoul Syrier	RWS	Workgroup member *Team-member drafting site decision for wind parks*
Jan Hazes	IenW/MinDef	Workgroup member *Military aviation authority, senior policy advisor ATM issues*
Felix van Laak	HeliService International	Helicopter operator representative *Deputy Flight operations manager, involved in project from beginning as provider of data, runs HFDM program at HeliService*
Jacob Bart	CHC	Helicopter operator representative *Technical pilot AW139*
Roger van Schijndel	CHC	Helicopter operator representative *Manager flight ops, flown AW169 around wind farms*
Derk Rus	NHV	Helicopter operator representative *SAR captain NHV Den Helder, AS365*
Max van Nugteren	NHV	Helicopter operator representative *First officer*

Appendix F   Expert session on 14-01-2020

On 14-01-2020, a meeting was held between To70, Ministerie van EZK, RVO, Ministerie van IenW, Rijkswaterstaat, CHC, NHV and HeliService, to discuss the findings of research performed by To70 about the effects of wind turbine wake turbulence on helicopter operations. This meeting served the goal of supplementing the findings, based on actual helicopter flight data (HFDM), with practical experience from helicopter operators.

HFDM data
HeliService confirms our conclusions that wind turbines cause no notable difference for helicopters when comparing the accelerations between flying in- and outside the wake of wind turbines. Although the study is limited to the data available, the HFDM is chosen and limited to one airframe to have a comparable amount of data. HeliService thinks HFDM is the best data available because it is a constant recording and objective. The difficult part is setting the limits what to expect and accept (there are no set limits for g-load except for the limits given by the manufacturer of the airframe).

CHC mentioned a report of an occurrence of extreme turbulence (clear air turbulence) and tried to find that turbulence in HFDM data but was not able to find it in their data, therefore arguing whether HFDM data would be sufficient for an analysis on turbulence. For example, a sample frequency of 1 or 2 Hz of the flight controls makes it very difficult to detect turbulence.
To draw scientific conclusions from an analysis like this, it is suggested to perform a test flight with better equipment and a test program could be set up with specific testing scenarios with various distances to turbines and various wind speeds.

Monitoring and reports of turbulence
All helicopter operators mentioned that occurrences of turbulence are reported.

HeliService monitors turbulence at their HFDM department and gets reports of turbulence. There are reports of turbulence outside wind farms (unexpected turbulence). Since HeliService is flying inside wind farms, they are accustomed to a certain level of turbulence, but none have yet been reported which limit operations.
HeliService crews are prepared that there might be some turbulence in wind farms (as well as close to any object, such as ships or platforms). But most of the wind farms have designed corridors where if you stay in the middle of the corridor (away from the turbulence as far as possible), it does not hamper the operation at all.

CHC mentions that with experiences in the Hornsea wind farm in the UK, with wind turbines of 190 m high[55] (154 m rotor diameter [56]), no issues are reported (AW169).

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[55] https://orstedcdn.azureedge.net/-/media/WWW/Docs/Corp/UK/Hornseaprojectone/180928_Hornsea-1--2-October-Newsletter_AW2-
web.ashx?la=en&rev=866fca57cbf84bd39ad47d3e489a52b1&hash=E8B7F2159377E0F518912A4B8A0FEBB9

[56] https://www.thewindpower.net/windfarm_en_16665_hornsea-project-one-njord.php

German CAA about the HeliService operations in wind farms

HeliService states that there has not been any issue about wind turbine turbulence. The HFDM program has been audited by the German CAA (who look at flights, random selection of flights, inspectors who fly along on flights) and the conclusion was that there is no need for further studies.

Generally, the operator of a platform has much higher standards than necessary within aviation safety because of the risk to passengers.

Most customers of HeliService have own limits, for example wind speed limitations for landing or hoist operation, which are more restrictive than the aircraft limitations.

Wind turbine / object influence on helicopter operations

HeliService experiences turbulence from wind turbines that are rotating similar to turbulence from wind turbines that are stationary; stationary turbines produce turbulence as well, since they are objects that cause vortices in laminar wind layers. This will result in a disturbance in the wind flow but not as circular and does not affect the operations.

HeliService even argues that stationary turbines could cause more turbulence than rotating blades, whereas NHV refers to research stating blades rotating at optimal speed causes maximum turbulence. Nevertheless, platforms and large ships are more limiting to operations than wind turbines. All operators agree with this statement, saying more turbulence is felt when near a large ship than when near a wind turbine.

HeliService mentions that the study presented, focused mainly on the scenario of flights that end up with landing on the platform in the middle of a wind farm (in the wake of turning wind turbines at Gemini). HeliService operates differently at Global Tech I, where mainly hoist operations are carried out. During hoist operations at a stationary turbine, HeliService flies in the wind farm at the level of the turbine nacelles (hub) at 300 to 400 feet without landing. During these kinds of flights, the helicopter is very much exposed to wind turbine turbulence (from the object), flying at a constant level in the wake turbulence zone. These turbulences however do not hamper the operation since the effect on the aircraft is relatively low.

Safety - limitations

CHC mentions that limitations with respect to turbulence are based on day-to-day operations, where pilots report issues with turbulence during take-off and landing. In the operational way, it is possible to see if limitations are needed to perform safe operations. Because HeliService has a lot of operational experience of flying in wind farms and hoisting near wind turbines, their knowledge on limitations is seen as very useful for this study. HeliService mentions that the only limiting factor in wind farms is due to some platforms generating turbulence, via the vortex created on the deck.

HeliService monitors turbulence based on feedback from crews and mentions that this type of operations requires practicality and safety first, but comfortability is not a requirement and all people on board know that. It is stressed that none of HeliService flight crew ever doubt about the safety of operations near wind turbines. In offshore operations a certain amount of movement of the aircraft is normal.

Workload

Obstacles

The workload and situational awareness in wind farms is different due to the fact that because of the close proximity of obstacles, pilots fly hands-on. The workload/situational awareness is increased due to the phase of flight (approach/departure), and the possible wind turbine turbulence does not affect workload.

Automatic Flight Control System (AFCS)

All offshore helicopters flying in the North Sea have AFCS controlling the pitch/yaw rates, which help mitigate turbulence. It is a comfort and workload reducing system for the pilot and also active when flying manual (flight director disengaged, but autopilot on).

Wind turbine stop-procedures in the wind farm site decision

Where the 'stop procedure' is for helicopter operations going to offshore gas platforms, HeliService agrees that a 'stop procedure (2 rotations per minute actually)' is unnecessary, because of their experiences in wind farms with rotating wind turbines. Additionally, the hoisting operations are performed without problems next to stationary turbines, which cause turbulence as well. And in the whole, turbines are less limiting than other large objects.

The wind farms are at a distance of a minimum 2.5 NM (based on IFR procedures) from oil and gas platforms, so there is no reason for a 'stop procedure' for normal operations.

Search and Rescue (SAR) has the requirement that a wind turbine must be able to be stopped to get a mechanic off for example. For these hoisting operations the rotor disc diameter could limit a SAR helicopter when hoisting to a turbine.

A 'stop procedure' is not seen as necessary by NHV for SAR operations. For vessels operating in the wind farm, it is preferable to have the ship outside the wind farm during a rescue operation. The main issue is the turbulence close to a ship, where a lot of turbulence can be expected depending on the size of the ship and wind speed and direction.

Operations in wind farm

The wind farms have pre-set corridors which usually only apply during night operations for obstacle clearance. During day operations any corridor is used, with the final phase of landing into the wind and deviating from a corridor.

HeliService also argued that there is no need to fly over a windfarm when intending to land there. Before flying into a windfarm, visual reference to the wind turbines, landing platform or construction vessels inside the windfarm must be established.

All operators agree that rotating blades do not cause difficulties in determining distance to wind turbines, saying the bright yellow foundation is the most visible.

Customer limitations are that only one helicopter is present at a time per wind farm.

Helicopter type

AW169 helicopter type

The conclusions are for one type of aircraft, the AW169 with a maximum mass of 4.8 tons. This type of aircraft was chosen because the most consistent data was available for this type. The operators state that the AW169 is a relatively good representation of helicopters that fly in the North Sea area. The most common helicopter is probably the AW139 which has a maximum mass of 7 tons. So, if the smaller aircraft can handle the turbulence, the helicopter operators state that a larger helicopter can handle the turbulence as well. All operators agree that larger and heavier helicopters are probably less prone to turbulence.

The future use of helicopters to/from offshore wind farms

It is not foreseen that smaller/lighter helicopters than the AW169 or the smaller EC145/H145 will be used in operations to and in offshore wind farms, because of the range required of the helicopters due to the distance to the offshore wind farms. Another reason is that customers are moving away from single pilot operations. Multi pilot operations for smaller helicopters leads to limited payloads, therefore the AW169 and the EC145/H145 are the smallest helicopters which are expected in offshore wind farm operations. A larger distance to an offshore wind farm requires a helicopter with a greater range which are typically larger helicopters. But the size of the helicopters is limited because of the size of the rotor disc conflicting with the turbine rotor during hoist operations. Because of this the AW139 is mentioned as one of the largest helicopters to be expected in wind farm operations.

Onshore wind turbines

Operators doubt that for example an extrapolation to onshore wind turbines can be made, although they mention large cities cause more disturbance/turbulence than onshore wind turbines. Here as well, a test flight with special equipment could help in the analysis.