AI based Wake Vortex Prediction System for Vertiports

Anton Stephan[1], Sooseok Lee[2], Frank Holzäpfel[3]
[1] German Aerospace Center (DLR), Oberpfaffenhofen, 82234, Germany, Anton.Stephan@dlr.de;
[2] German Aerospace Center (DLR), Würselen, 52146, Germany, Sooseok.Lee@dlr.de;
[3] German Aerospace Center (DLR), Oberpfaffenhofen, 82234, Germany, Frank.Holzaepfel@dlr.de

Introduction

The development of Urban Air Mobility (UAM) with the connected vertiport operations has brought about new challenges in predicting environmental hazards. One significant concern is related to wake vortices generated by large aircraft during landing or take-off, which can impact electrical Vertical Take-Off and Landing (eVTOL) aircraft like air taxis operating at low altitudes near vertiports located adjacent to the runways of major airports, see Fig. 1. Given their relatively low mass and limited momentum compared to larger aircraft, eVTOL vehicles are more vulnerable to such disturbances [1], which is aggravated by the little time and altitude available for recovery during encounters. For eVTOL operations in ground proximity wind speed and direction are the main environmental parameters controlling vortex transport and decay. This study presents a calibrated probabilistic wake vortex prediction framework for a Wake Vortex Warning System for Vertiports, using the Probabilistic Two-Phase (P2P) wake vortex model as a physics core [2]. Additionally, a probabilistic AI based wind prediction is implemented.

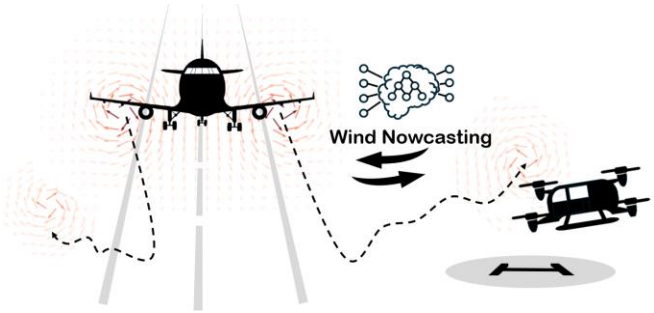

Figure 1: Wake vortex trajectory and hazard tube generated by crosswind=-5.10 m/s, headwind=3.27m/s

Wake Vortex Prediction

A time series-aware calibration model learns a multivariate quantile-normalized score while uncertainty from temporal non-stationarity between training and testing conditions is handled via cross validation-based conformal prediction. Multiple AI based calibration approaches are compared, covering distributional baselines and regression-based methods with data collected during a measurement campaign at Vienna airport, merged with the prediction of a physical probabilistic model (P2P). The proposed Echo State Enhanced Transformer achieves the best performance between target coverage and interval width while maintaining balanced uncertainty control for port and starboard vortices.

Windprediction

The probabilistic wind nowcasting framework provides a deterministic wind prediction together with the eigenvalues and eigenvectors of the wind distribution, which are used to construct the probabilistic wind field using advanced AI techniques and mathematical methods, like complex Continuous Wavelet Transform (CWT), Convolutional Neural Networks (CNN), multivariate-Mixture Density Networks (MDN) [3]. Using this information, the largest attainable displacements of the wake vortices within one time horizon are selected and processed producing corresponding elliptical hazard areas, see Fig. 1, providing the most extreme boundary surfaces. This extreme scenario selection is intended to approximate a conservative worst-case envelope by the wake vortex transport along the lateral and axial directions within the 95% confidence area.

Wake Vortex Warning System for Vertiports

Combing the two presented parts enables real-time three-dimensional simulation and prediction, as illustrated in Fig. 2. The ellipse generated for each vortex pair at each cross section represents a local hazard area, and connecting these ellipses along the integrated trajectories yields a non-uniform elliptical hazard tube in 3D space. If an air-taxi flight path lies in the resulting hazard region during the corresponding time interval, the system triggers a warning mechanism.

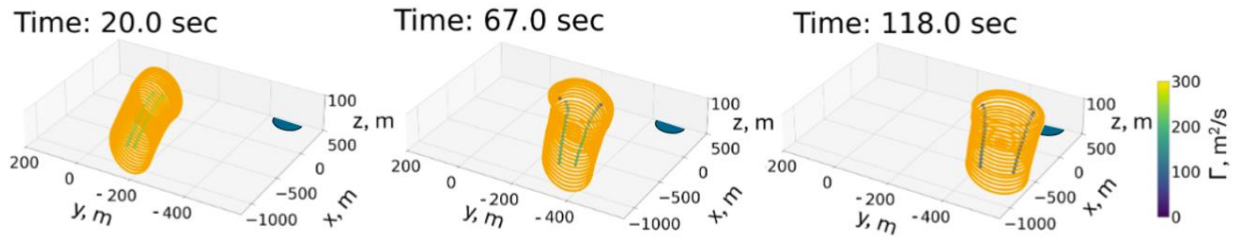

Figure 2: Wake vortex trajectory and hazard tube generated by crosswind=-5.10 m/s, headwind=3.27m/s. Vertiport location in blue.

Conclusion & Implications

A Wake Vortex Warning System for Vertiports was developed including an AI based probabilistic wind prediction and a calibration of a wake vortex prediction model with real measurements. Multiple AI approaches were chosen leading to a best suited solution with optimal confidence areas. This system enables a safe operation of eVTOL aircraft in airport proximity.

[1] Thompson, E.L., Taye, A.G., Guo, W., Wei, P., Quinones-Grueiro, M., Ahmed, I. et al. A survey of eVTOL aircraft and AAM711 operation hazards. In: AIAA Aviation 2022 Forum, 2022.
[2]Holzäpfel, F., and Robins, R. E., “Probabilistic Two-Phase Aircraft Wake-Vortex Model: Application and Assessment,” Journal of Aircraft, Vol. 41, No. 5, 2004, pp. 1117–1126. https://doi.org/10.2514/1.2280
[3] Lee, S., Holzäpfel, F., Stephan, A., and Moormann, D., “Hybrid Deep Learning-Based Networks for Deterministic and Probabilistic Wind Nowcasting Within a Wake Vortex Warning System for Vertiport Operations,” Meteorological Applications, Vol. 33, No. 2, 2026, p. e70173. https://doi.org/10.1002/met.70173.

Biography

Anton Stephan

Dr. Anton Stephan is a research scientist at the Institute of Atmospheric Physics (DLR), specializing in aircraft-weather-interactions. His work focuses on aircraft and UAM safety with regard to turbulence, employing modeling, numerical simulations and experimental methods. Stephan collaborates internationally in different projects and mentors early-career researchers.