Hybrid Deep Learning-Based Networks for Deterministic and Probabilistic Wind Nowcasting within a Wake Vortex Warning System for Vertiport Operations

Sooseok Lee[1,2,3*], Frank Holzäpfel [1], Anton Stephan[1], Dieter Moormann[3]
[1] *Institut für Physik der Atmosphäre, DLR*
[2] *Technologien für Kleinflugzeuge, DLR*
[3] *Institute of Flight System Dynamics, RWTH Aachen University*
**Corresponding author: sooseok.lee@dlr.de*

The development of Urban Air Mobility (UAM) and vertiport operations introduced one of the significant concerns: the potential impact of wake vortex generated by large aircraft during landing or take-off. These can pose risks to electric Vertical Take-Off and Landing (eVTOL) aircraft operated at vertiports near the runways of major airports. Given their relatively low mass and limited momentum compared to larger aircraft, eVTOL vehicles are more vulnerable to such disturbances due to the limited time and altitude available for recovery during encounters. Since the trajectory of wake vortices is highly influenced by wind strength and direction, it becomes an important factor to accurately predict wind patterns. To address this issue, the Flight Safety of Small Aircraft under Adverse Meteorological Conditions (SMART-MET) project is currently developing a Wake Vortex Warning System for Vertiports (WVWS-V) including three main components: (1) wind nowcasting using a statistical persistence method [1] and various machine learning techniques, (2) wake vortex prediction using the P2P model [2], and (3) encounter assessment based on wake-induced perturbation criteria. In the project, wind nowcasting fundamentally contributes to precisely predicting transport and decay of wake vortices.

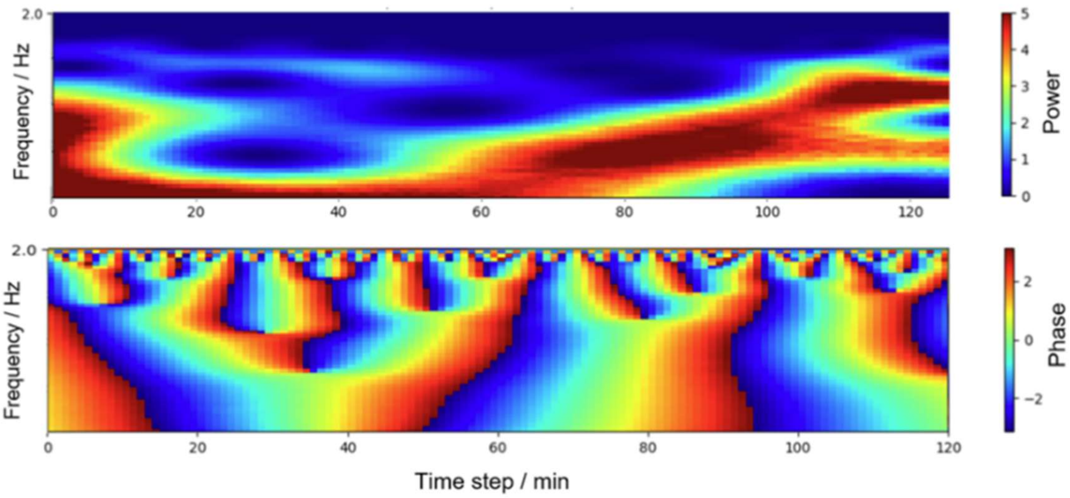

Figure 1: Time–frequency analysis of the v-component wind speed over a 3-hour period on 3 January 2022, using Complex-Wavelet Transform. The upper image shows the wavelet power spectrum, where high-power regions (in red) indicate localized dominant fluctuation activity in both time and frequency. The lower panel presents the corresponding phase information. The phase in the CWT reveals that there are discrete transitions and discontinuous patterns.

In particular, the wind prediction model is carried out using two approaches: deterministic and probabilistic nowcasting. In the deterministic wind nowcasting, the primary objective is to select the superior model by comparing the performance of various machine learning models and a statistical persistence model [1]. In terms of deterministic prediction, a hybrid model is proposed in the study, combining continuous wavelet transform for capturing dynamic patterns, Two-Dimensional Convolutional Neural Network (2D-CNN), and Long Short-Term Memory (LSTM). Figure 1 reveals how much information can be obtained from univariate profiles by using the hybrid model. The proposed model is an ensemble model that improves the ability to capture the ramp events, addressing the shortcomings of existing single-time series models when using only the LSTM or GRU models that overlook outliers in order to prioritize the minimization of overall error and thus fail to properly capture periodically non-stationary patterns [3][4].

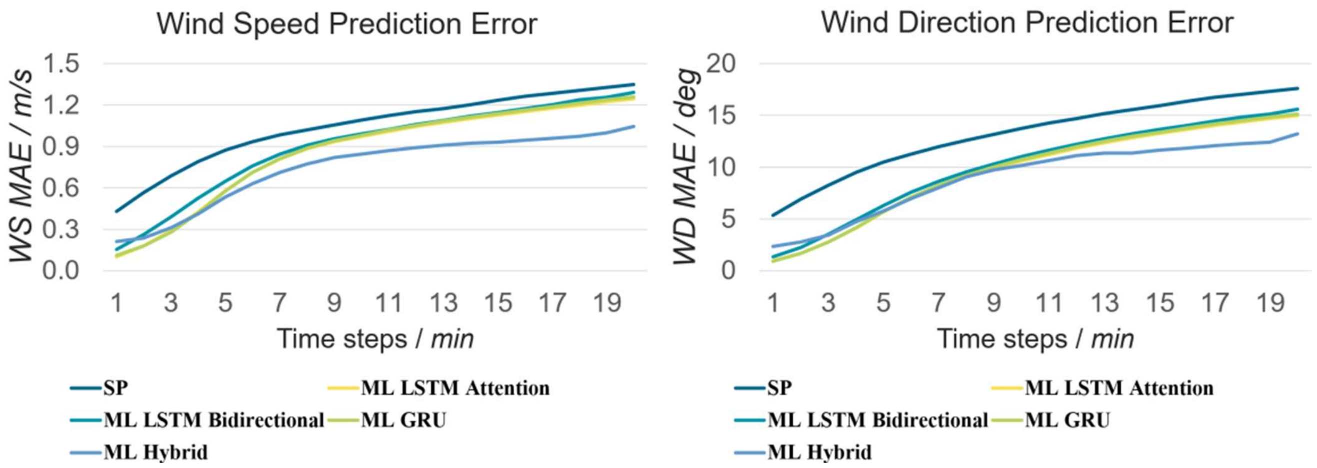

Figure 2: Mean Absolute Error (MAE) comparison of deterministic nowcasting models. Statistical Persistence (SP) Model and Machine Learning (ML) models manifest that error increasing across time steps in Wind Direction (WD) and Wind Speed (WS) prediction. The hybrid model outperforms other SP and ML models and LSTM-Attention displayed the best performance among single-ML models. In case of the hybrid model, the initial time step predictions lack superior performance by the model's complexity that tends to neglect the high dependency on the immediately preceding trends.

For probabilistic wind forecasting, a major challenge arises from the observation that the empirical distribution of the wind component variance deviates from a Gaussian distribution. In order to form the same distribution as the empirical variance in a formula, the Mixture Density Network [5] is utilized with superposed multivariate Gaussian distributions over wind components where u and v are used as elements of the covariance matrix in the MDN training, representing their empirical distribution more accurately than conventional models with narrower prediction ranges of wind speed and direction compared to the baseline model.

Comparative evaluations with the Statistical Persistence (SP) baseline and other Machine Learning (ML) architectures demonstrate that the proposed models achieve superior performance in both deterministic and probabilistic aspects. As shown in Figure 2, the deterministic prediction Mean Absolute Error (MAE) of the overall wind speed and wind direction for a 20-minute time step was 0.36 m/s and 4.78 degrees better than the SP model. In addition, The average prediction width of the 95% confidence interval for the probabilistic nowcasting over a 20-minute time step is 47.18 degrees of wind direction and 3.57 m/s of wind speed in the SP model, while the ML-based model had a width of 30.90 degrees and a wind speed of 2.4 m/s. While single-Recurrent Neural Network (RNN)-based models exhibited limited enhancement in the performance, the proposed model achieved substantial improvements particularly in intervals of ramp events, as well as in general patterns. In probabilistic predictions, machine learning-based models have narrower prediction widths under the condition that satisfies the given confidence interval, reflecting that the model has lower levels of uncertainty.

Furthermore, this study also shows how predicted wind is used in wake vortex prediction within WVWS-V. The trajectory and lifetime of wake vortices are indicated according to the predicted wind, and the wake vortex hazard area is formed based on the center and circulation of each pair of wake vortices. In the integrated modules, the study suggests how the predicted wind conditions can lead to the intrusion of wake vortices into the flight paths of small aircraft, resulting in practical solutions for the aviation safety of eVTOLs near runways of major airports.

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Biography
Sooseok

After earning a master's degree in space engineering from Technische Universität Berlin, Sooseok has specialized in satellite attitude control, satellite image data processing, fluid dynamics, and machine learning in both research and industry. Currently, Sooseok is conducting research as a doctoral researcher in the wake vortex research group at the Institute of Atmospheric Physics, DLR, while pursuing a PhD at RWTH Aachen University.