Development of Method for Turbulence Simulation using Onboard LIDAR Data Assimilation

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Air turbulence is one of the major causes of airborne accidents. The Japan Transport Safety Board reported that 46% of accidents in the last ten years were caused by turbulence. In particular, clear air turbulence (CAT) is a serious issue because it occurs without a warning sign, such as a thunderstorm.

As a practical action against turbulence risk, Airbus and Tamarack developed a wing tip device to alleviate gust wind-induced wing load variation. ATLAS™ Active Winglet from Tamarack Aerospace has a control surface that automatically moves to generate a force opposite to that of the detected wing load. This device can reduce the wing load concurrently with a turbulence encounter. The Japan Aerospace Exploration Agency (JAXA) has also engaged in a program to reduce the risk of accidents by detecting turbulence using the Doppler light detection and ranging (LIDAR) Systems, developed by Mitsubishi Electric.

However, airborne LIDAR measurements are insufficient for a precise estimation of turbulence in terms of spatial resolution. Although computational fluid dynamics (CFD) can solve this problem, its initial and boundary conditions for meteorological phenomena, including CAT, are usually unknown. Consequently, there is a lack of precise turbulence-structure reproduction techniques.

Data assimilation (DA) is a powerful tool for CAT prediction that estimates the optimal initial condition for an N-S solver by integrating airborne observations and output from the simulation. DA modifies the output of an N-S solver on the basis of observed data, and variables around the observed points are bound by the governing equation of the fluid. This implies that DA can facilitate CFD reproducing a flow field close to the airborne wind observation, and the modified flow fields are physically consistent. In our study, a square root filter (SRF) was employed for the DA process.

In the DA experiments, we assumed that the vortices generated by the shear layer instability were the CAT. Air turbulence was simulated in a non-terrain domain with an in-house compressible Navier-Stokes solver. We placed a wind shear layer on the initial flow field and induced Kelvin-Helmholtz (K–H) instability. In the prognostic chart of significant weather, provided by the Japan Meteorological Agency, the region with a high possibility of CAT existence often emerges along with the jet stream at high altitude. Additionally, it is known that CAT is mainly caused by strong wind shear due to meteorological phenomena, such as jet streams and low-pressure areas.

In this study, roll vortices that simulate CAT were estimated using the DA and a pseudo wind observation. Wind observation was conducted in the LIDAR configuration, in which forward winds were observed in a straight line from an aircraft. We validated the performance of the DA by the identical twin experiment; the true state and the wind observation were generated numerically.

As a result of the identical twin experiment in the 3D flow configuration, observation of horizontal and vertical wind elements that could compose the K-H vortex were critical in capturing the roll vortices.

Observation of only the horizontal wind did not improve the estimation. Additionally, we solved the two-dimensional Poisson equation before the DA procedure to approximate pressure from the observation of horizontal and vertical winds. By the assimilation of horizontal and vertical winds and the derived pressure, the accuracy of the estimation improved in comparison with the estimation without assimilating pressure. These results suggest that the vortices were well-captured owing to the increase in the observation-based information, and the DA could correctly filter out the observation errors from the derived pressure.

To summarize, we proposed a method for CAT reproduction using LIDAR observation and CFD. We validated the method numerically in an identical-twin experiment, estimating the turbulence in 3D flow configuration.

Keywords: Clear Air Turbulence, LIDAR, Data Assimilation