Real-Time Prediction of Wind Conditions and Atmospheric Turbulence for Safe and Efficient Aircraft Operation

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論文内容要約

This dissertation deals with real-time prediction systems of wind conditions and atmospheric turbulence in order to contribute the safe and efficient aircraft operation. One of the features which distinguishes between this work and other researches regarding the prediction of wind fields and the atmospheric turbulence is the real-time prediction systems based on the integrating techniques of observation and simulation. There have been some gaps between the future plan of air-traffic management (ATM) system and the current weather system that are the observation and the forecasting. The real-time weather information is not sufficient for the tactical operation, for example the avoidance tactically hazardous meteorological conditions in flight. There is a great gap between the time scale of the weather informations that is required in the future plan and is provided by recent weather services. Therefore, the real-time prediction systems are developed to support the aircraft operations, which are airborne system, airport system, and all airspace system. The new algorithms for these situations are proposed to provide the real-time weather information.

In chapter 2, an estimation algorithm of airflow vector based on the airborne twin Lidars are proposed and investigated for preview control to prevent turbulence-induced aircraft accidents in flight. The proposed algorithm stores the line-of sight (LOS) wind data with each passing moment, and uses recent and past LOS wind data in order to estimate the airflow vector. The recent and past LOS wind data is used to extrapolate the wind field between the airborne twin Lidars. In addition, the robust least-square method (LSM) and the smoothing spline are applied to remove the error and noise of LOS wind data. Three-numerical experiments were conducted to evaluate the estimation performance of the proposed method. The proposed method has much better performance than simple vector conversions for three-numerical experiments, and the proposed method can estimate accurate two-dimensional distribution of wind fields unlike simple vector conversions. The using the simple vector conversion which is the existing technique has an assumption, which the wind field of area between the twin Lidars is uniform. It is possible

that the assumption of the uniformity would be wrong when the turbulence that has large fluctuation of wind velocity occurs. In the experiment case with error and without noise, the results indicated the performance of the proposed method was able to remain the original performance without the error and noise when the error does not include the unexpected error. When the error includes the unexpected error, the proposed method can satisfy the performance demand and estimate correct wind field although the simple vector conversions cannot estimate correct wind field. Because, the robust least-square method and smoothing spline can work correctly in order to remove the both expected error and unexpected error. In the experiment case with error and noise, it is confirmed that the smoothing spline can filter the noise correctly and reduce the negative effect of the noise. Therefore, the proposed method is much better performance than the simple vector conversion. In addition, it is difficult to estimate the wind field with the very low backscattering coefficient condition by using the both the simple vector conversion and the proposed method. Because, when the backscattering coefficient is quite low, the noise is significantly large to not filter by using the smoothing spline. In summary, the total estimation performance for the overall wind velocity field was improved using the proposed method. The estimation performance and the computational cost of the proposed method can satisfy the performance demand for preview control.

In chapter 3, an integrated method consisting of a proper orthogonal decomposition (POD)-based reduced-order model (ROM) and a particle filter (PF) was proposed for the real-time prediction of low-level turbulence (LLT). ROM is based on proper orthogonal decomposition (POD), and ROM express the entire flow fields by a system of ordinary differential equations, calculated with much lower dimensions than those of the original model. PF was used to compensate for the uncertainty of the ROM based on observations. In this study, the ROM-PF is applied to predict the LLT around Shonai airport in Japan. In Shonai airport, LLT frequently occurs in winter, which often results in flight cancelations or delays. The proposed method was validated using identical twin experiments of the LLT case at Shonai airport in Japan. The results show that ROM-PF reproduces the wind velocity fluctuations similar to those produced by a large eddy simulation with a much lower computational cost. In addition, the time evolution of the wind field obtained using ROM-PF showed that the turbulent spatial structure was expressed accurately in comparison with the reference flow field. It was confirmed that the root mean square error (RMSE) of the head and crosswind velocities decreased over time by repeating data assimilation. In addition, the actual observation of broadband Radar is used for evaluation of the prediction capability. In the first half of the prediction period of actual experiment, the fluctuations of the flow field reproduced by ROM-PF were similar to that of the Radar observations, where ROM-PF reproduced the turbulent structure accurately using the actual Radar observations. In the latter half of the prediction period, the RMSE between the Radar observations and ROM-PF prediction became gradually large over time. Thus, the proposed method revealed usefulness in short-range wind forecasting system around airport.

In chapter 4, a new technique that integrates a low dimensional model (LDM) based on proper orthogonal decomposition (POD) and the flight data of a commercial aircraft was proposed to realize real-time prediction of wind and atmospheric turbulence for aviation safety and efficiency. The proposed technique sequentially assimilates flight data into the LDM and predicts the wind and atmospheric turbulence at lower computational cost than the general numerical weather prediction (NWP). The proposed method can assimilate flight data into the LDM as soon as the flight data is obtained; therefore, the proposed method solves both the DA update interval and computational cost problems. The proposed method leverages NWP results effectively for real-time prediction such as nowcasting. The proposed method is tested and its effectiveness as a real-time prediction of wind and atmospheric turbulence fields is investigated. Two test configurations of a numerical experiment and actual experiments were utilized to evaluate the predicted performance of wind and atmospheric turbulence. The amount of actual flight data from commercial aircrafts that have encountered turbulence is much lower than the amount of data without turbulence. In order to compensate for the lack of actual flight data, a numerical experiment is conducted, i.e., a so-called identical twin experiment, which is widely used for validation of DA methods. The identical twin experiment generates a large amount of pseudo flight data from the reference wind field for evaluation of the predicted performance. The identical twin experiment is able to compare the prediction results with the reference wind field in order to confirm the entire wind field. The results of the experiment show that using a larger number of POD basis vectors can express a wind field that is closer to the reference wind field, and the computational cost is proportional to the square of the number of POD basis vectors. In addition, the proposed technique can reproduce accurate wind fields using longer flight times, and the computational cost is linearly proportional to the flight time. When 16 POD basis vectors and 80 min of flight time are used, the proposed technique can update the wind field approximately every 3 min, and it has drastically lower computational cost than original the NWP. Next, the case studies of experiments that use actual flight data from commercial aircrafts that have encountered turbulence for two cases are conducted, because to investigate the effectiveness of the proposed method, it is not enough to use only numerical experiments. The actual experiments use actual flight data to predict wind and turbulence using the proposed method, and the predicted results are compared with the flight data and ground observations. Actual experiments were conducted for two cases: weather conditions when an extratropical cyclone was approaching Japan, and a stationary front in the sea near Japan. The proposed technique can predict the locations of turbulence, the surface front of the extratropical cyclone, and the magnitude of the jet stream more accurately than the original NWP.

In chapter 5, an algorithm that combines ensemble weather forecasting and aircraft flight data was proposed as wind nowcasting system for safe and efficient aircraft operation. This study uses an ensemble weighted average method based on sequential importance sampling (SIS), which is one of particle filter methods for forecasting the wind field in real-time. SIS is applied to the ensemble data and control run data of European Centre for Medium-Range Weather Forecasts (ECMWF), Japan Meteorological Agency (JMA), Korea Meteorological Administration (KMA), National Centers for Environmental Prediction (NCEP), United Kingdom Met Office (UKMO) for the two case studies that use actual 72 flight data from commercial aircrafts. The results show that SIS is able to forecast better than other four method; Direct Ensemble Average (DEA), Elite Strategy (ES) and Selective Ensemble Average (SEAV) and Weighted Average (SEWE), with average improvements of forecast performance of about 10-15% even at 300 min ahead. It is confirmed that SIS is able to improve predictions by enlarging the weight of high-performing ensemble at a very early stage of prediction. The forecast results in which 1200UTC is used for evaluation are discussed, using flight data up to 0600UTC on February 23 and December 9, 2012, which is approximately half of the forecast target period for cases 1 and 2. Forecast results are also compared with regular observations conducted by radiosondes across Japan (16 locations) at 1200UTC. Compared to forecast results by DEA and ES, results by SIS in case 1 and case 2 forecast wind velocity to a value very close to that recorded in the flight data. In both cases, SIS forecasts the wind velocity greater than that of DEA, and closer to the flight data than that of DEA. In addition, the overall forecast performance between the forecast wind and observation of radiosonde of SIS was slightly better than DEA. In both cases, the forecast performance is significantly improved on points along the flight path and around cruising altitude of the aircraft used for this study. The total forecast performance for the overall wind velocity field was improved using ensemble forecasts and flight data, at computational costs and update intervals similar to those of nowcasting.

Real-time prediction systems of wind conditions and atmospheric turbulence are developed from the above four cases based on the integrating techniques of observation and simulation. These systems will contribute to achieving safer and more efficient aircraft operation than that based on current weather system.