Airport Terrain-Induced Turbulence Simulations Integrated with Weather Prediction Data

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The wind environment at an airport is affected by terrain features. In Japan, Shonai Airport is known to frequently have wind shear over the runway due to the turbulence induced by the neighboring hills in winter. In this study, large eddy simulation (LES) is performed to investigate the turbulence around Shonai Airport. The initial and boundary conditions are given according to the weather prediction data by the Japan Meteorological Agency non-hydrostatic model (JMANHM). These data are downscaled and transferred to LES domains, which consider actual terrain features as the boundary conditions on the ground, using the two-way nesting method. The present simulations indicate that terrain features may have a significant influence on the turbulence appearing in flight paths; i.e., aircraft safety may depend on wind direction. In addition, it is shown that the present simulation method can predict the turbulence induced by terrain features based on good agreement of results with the turbulence actually observed using a Doppler radar.

Key Words: Turbulence, Airport, Terrain, LES, Weather Prediction

1. Introduction

The wind environment around an airport is affected by various factors, such as wake turbulence (wingtip vortices, jetwash, etc.) caused by airplanes and wind turbulence (wind shear, downdrafts, updrafts, etc.) caused by meteorological and terrain features. These turbulence problems are major hazards in airport traffic management.

Wake turbulence is generated behind a flying airplane, and it becomes especially strong during takeoff and landing where high lift is required. Therefore, airport traffic management provides a certain separation for departure and arrival to maintain aircraft safety. On the other hand, the demand for air traffic is expected to increase in the coming decades, and it will therefore be necessary to increase the efficiency of airport operations. It is desirable to increase the number of takeoffs and landings by shortening the separation between aircraft without sacrificing the safety of following aircraft.

For this purpose, our research group has been working on understanding the behaviors of wake turbulence at Sendai Airport, Japan. A previous study measured the wake turbulence, which appeared just after an aircraft took off from the runway, using light detection and ranging (LIDAR), which can detect the line-of-sight velocity component of aerosols in the air based on the Doppler shift.1) Another study simulated the wake turbulence by integrating the LIDAR measurement data with computational fluid dynamics (CFD) simulations using a four-dimensional variational data assimilation method (the adjoint method).2) In those simulations, the initial and boundary conditions were adjusted to ensure that the solution obtained by the simulations coincided with real-world measurements. However, LIDAR measurement is only available in a limited number of airports, so CFD simulations of wake turbulence were integrated with weather prediction data in another study.3) These simulations employed a nesting method to bridge the gap of scale between wake turbulence and weather features (horizontal roll convection currents in sea breezes).

The airport wind environment is also affected by terrain features. For example, a previous study in Japan4) indicated that LIDAR measurement revealed the turbulence caused by an aircraft hangar at Haneda International Airport. There have been other reports that Shonai Airport shows a decrease in the in-service rate during the winter season due to low-level wind turbulence, which is caused by interference from a strong seasonal wind (the monsoon) and hills in the vicinity of the airport.5,6) The Japan Aerospace Exploration Agency (JAXA) has conducted measurements of wind turbulence at Shonai Airport using Doppler radar and LIDAR. However, these measurements still have insufficient coverage and accuracy, especially to detect low-level headwind. Therefore, it is necessary to investigate the mechanisms of terrain-induced turbulence using CFD simulations with higher resolution.

There are other preceding and ongoing research activities related to terrain-induced turbulence. In China, Hong Kong International Airport is located on land reclaimed from the sea, lies to the immediate north of steep mountains, and often experiences tropical cyclone passages. Shun et al. presented complex atmospheric flow and terrain-induced wind shear phenomena observed by the Doppler radar installed at Hong Kong Airport.7) Further studies to support their research using high-resolution CFD simulations are expected.

In the United States, the terrain-induced rotor experiment (T-REX) has been organized in the Sierra Nevada mountain
range. It aims to explore the structure and evolution of atmospheric rotors (intense low-level horizontal vortices that form along an axis parallel to, and downstream of, a mountain ridge crest) and associated phenomena in complex terrain. The T-REX offered field operations using aircraft to measure an atmospheric system from the ground to upper tropospheric–lower stratospheric altitudes. Although those field operations were supported by real-time numerical model forecasts, the T-REX considered larger-scale phenomena than those that are locally seen around airports and should be investigated in our research group.

In the present study, large eddy simulation (LES) around Shonai Airport is performed using the two-way nesting method. In this simulation, higher resolution terrain data are placed in the simulation domain to simulate the turbulence induced by the neighboring hills. First, turbulence simulations are performed with uniform background flow conditions. Next, the turbulence simulation is integrated with the weather prediction data on the date when the turbulence is actually observed by the Doppler radar. This study validates how similar the present simulation results are to a real-world turbulence phenomenon.

2. Simulation Conditions

Shonai Airport is located near the west coast of northeastern Japan (Fig. 1). This airport is known to have wind shear over the flight path frequently in winter due to the turbulence of the neighboring hills, which are located to the north of the airport. In all the simulations, we consider the time range from 07:30 to 08:30 on February 6, 2010 in Japan standard time (JST), when turbulence is actually observed by the Doppler radar located beside the end of the runway (RWY27); the wind direction is west-northwest and the wind speeds reach 26 kt (13.4 m/s) on average with a maximum of 41 kt (21.1 m/s) on the ground.

3. Numerical Methodologies

This simulation employs the two-way nesting method to integrate LES with weather prediction, which are simulated using different governing equations and models in different zones with different scales. Figure 2 shows the simulation domain and the flowchart considered in the two-way nesting method. Specific descriptions of the two-way nesting method employed here are given in the sections 3.1 and 3.2.

3.1. Weather prediction

Weather prediction is conducted in the largest zone (denoted as JMANHM (∆50m) in Fig. 2(a)), which has dimensions of 3,450 × 3,200 × 500 m in the east-west (x), north-south (y), and vertical (z) directions, respectively. The mesh points are allocated evenly every 50 m in the x and y directions and at z = 10, 30 and 52 m, and every 25 m from z = 75 to 500 m in the z direction. For simplicity,
Fig. 3. Plots of wind velocity predicted by JMANHM (contour: velocity magnitude [m/s]; vector: velocity direction).

Fig. 5. Isosurface plots of the vertical component of wind velocity [m/s] under uniform background wind conditions.

Fig. 7. Isosurface plot of the vertical component of wind velocity [m/s] under conditions integrated with weather prediction data.

Fig. 9. Contour plots of wind velocity magnitude [m/s].
terrain features are represented as a flat bottom surface in this zone.

This study employs the Japan Meteorological Agency non-hydrostatic model (JMANHM), and the fully compressible atmospheric equations with the Lambert conformal projection are solved to obtain the momentum, perturbation pressure and potential temperature as prognostic variables using the horizontally implicit-vertical implicit (HI-VI) time integration scheme. Some physical processes, such as the land surface process, boundary layer turbulence process and cloud microphysical process, are also implemented in JMANHM. The initial conditions are given at 00:00 on February 6, 2010 JST, using the mesoscale model (MSM) of the Japan Meteorological Agency. The boundary conditions on the ground are given by the global 30 arc second elevation data set (GTOPO30) provided by the United States Geological Survey.

Figure 3 shows the plots of wind velocity at the altitude of 50 m and three sequential time points (07:30, 08:00 and 08:30 on February 6, 2010 JST), which are predicted using JMANHM. Northwesterly winds seem to be dominant in these plots. At the lower altitude of 10 m, JMANHM estimates wind speeds of 13.4 m/s on average and 16.1 m/s at maximum. In a global sense, these results almost agree with the actual wind direction (west-northwest) and speeds (13.4 m/s on average and 21.1 m/s at maximum) on the ground observed by the Doppler radar. Therefore, this study considers these data to be valid for the initial and boundary conditions settled in the following turbulence simulations.

3.2. LES

JMANHM allows global estimation of the wind environment around Shonai Airport. However, it still has insufficient temporal and spatial resolutions to capture the local structures of wind turbulence due to the simple consideration of terrain features. To address these issues, LES of turbulence is conducted in two smaller zones, denoted as LES (Δ18m) and LES (Δ6m) in Fig. 2(a). The dimensions of the former are 2,340 × 1,620 × 306 m in the x, y and z directions, respectively, and the mesh points are allocated every 18 m evenly in all directions. The dimensions of the latter are 1,590 × 1,050 × 246 m in the x, y and z directions, respectively, and the mesh points are allocated every 6 m evenly in all directions. These zones contain terrain data, represented by the staircase mesh shown in Fig. 4, based on the digital elevation model provided by the Geospatial Information Authority of Japan.

The present LES solves the Favre-filtered Navier-Stokes equations for compressible air, in which the subgrid-scale turbulence is modeled using the Smagorinsky model with Shen's special treatment to suppress inmoderate production of eddy viscosity at vortex centers. The convective terms are evaluated using Roe’s upwind flux difference splitting (FDS) scheme, in which fourth-order accuracy is obtained by the monotone upstream-centered schemes for conservation laws (MUSCL) based on the primitive variables without flux limiters. The viscous terms are evaluated via second-order central difference. Time integration of the Navier-Stokes equations is performed using the fourth-order Runge-Kutta method.

The initial and boundary conditions are characterized by the two-way nesting method as follows (see also Fig. 2(b)). For the LES (Δ18m) zone, initial conditions and the boundary conditions at each time step are settled from the weather prediction data given in the JMANHM (Δ50m) zone. The weather prediction data are given at limited locations and times (07:30, 08:00 and 08:30 on February 6, 2010 JST), and linearly interpolated in space and time to settle the initial and boundary conditions for LES at any location and time. Note that finer flow solutions in the LES (Δ18m) zone are obtained by solving the Navier-Stokes equations and not overwritten by coarser weather prediction data in the JMANHM (Δ50m) zone. The simulation is run for the LES (Δ18m) zone from 07:30 to 08:00 JST, and for the LES (Δ6m) zone from 08:00 JST. Similar to the results of the LES (Δ18m) zone, for the LES (Δ6m) zone, initial conditions and the boundary conditions are settled at each time step by linearly interpolating coarser flow solutions obtained in the LES (Δ18m) zone. The time step size in the LES (Δ6m) zone is set to 1/3 of that in the LES (Δ18m) zone to maintain the same Courant number. Note that finer flow solutions in the LES (Δ6m) zone are obtained by solving the Navier-Stokes equations and not overwritten by coarser flow solutions in the LES (Δ18m) zone. As a special treatment to maintain consistency of the flow solutions between each zone, the LES (Δ18m) zone receives finer flow solu-
tions from the LES (Δ6m) zone every nine time steps, and the coarser solutions are replaced with the finer solutions at the mesh points overlapping between these zones.

4. Results and Discussion

First, turbulence simulations around Shonai Airport are performed under uniform background wind conditions with different directions to investigate the effects of the neighboring hills on the turbulence. Next, the turbulence simulation is integrated with weather prediction data and validated by comparison with the actual measurement data of turbulence detected using the Doppler radar on February 6, 2010.

4.1. Under uniform background wind conditions

Turbulence simulations are conducted by assuming spatially and temporally uniform background wind with a constant speed of 13.4 m/s (average wind speed on the ground in the actual measurement by the Doppler radar) as the initial and boundary conditions in the LES (Δ18m) zone, while the weather prediction data given in the JMANHM (Δ50m) zone are not transferred to the LES zones. In addition, the direction of uniform background wind is set to 0, 30 and 60 deg for parametric study. These directions cover the west-northwesterly winds on the ground in the actual measurements of the Doppler radar.

Figure 5 shows the isosurface plots of the vertical (z) component of wind velocity under uniform background wind conditions. The isosurfaces reveal the structures of turbulence caused downstream of the hills when the wind goes around them. These structures move across the RWY27 flight path and seem to influence the safety of landing aircraft at wind directions of 30 and 60 deg. On the other hand, these influences do not seem to be significant when the wind direction is 0 deg and almost parallel to the runway.

Figure 6 shows the profiles of wind velocity magnitude along the flight path under uniform background wind conditions. These profiles contained the averaged values for 30 s as solid lines and the maximum and minimum values as error bars. The flight path, shown as a broken line, is assumed to have a descent angle of 3 deg. Compared to the case with the wind direction of 0 deg, those with wind directions of 30 and 60 deg have smaller averages and larger variations of wind velocity magnitude in almost the whole flight path (0 m ≤ x ≤ 900 m). This is because the flight path is invaded by the unsteady wake flow behind the hills. Therefore, the results indicate that terrain features may have a significant influence on the turbulence appearing in the flight path, i.e., aircraft safety is dependent on wind direction.

4.2. Under conditions integrated with weather prediction data

Turbulence simulations are conducted by downscaling and transferring the weather prediction data given in the JMANHM (Δ50m) zone to the LES zones as real-world environments with non-uniform unsteady background wind conditions.

Figure 7 shows the isosurface plot of the vertical (z) component of wind velocity, which reveals the structures of turbulence caused by the hills, under the conditions integrated with the weather prediction data. These structures move across the flight path due to the northwesterly winds, as shown in Fig. 3.

Figure 8 shows the vertical (z) profiles of wind velocity magnitude under the conditions integrated with the weather prediction data. These profiles are sampled at five different locations (A, B, C, D and E shown in Fig. 8(a)) at four different times (08:02:45, 08:02:55, 08:03:05 and 08:03:15 JST). Locations D and E show larger variations of wind velocity magnitude in the region 0 m ≤ z ≤ 150 m than in the other locations. This is because locations D and E are included in the unsteady wake flow behind the hills as shown in Fig. 7. These results agree with the actual Doppler radar measurements; wind speed was reported previously to show variation of more than 20 kt (10.3 m/s) at the altitude above the runway (elevation = 27 m) from 200 ft (61.0 m) to 400 ft (121.9 m).

Figure 9 compares the contour plots of wind velocity magnitude simulated by the present LES with those observed by the Doppler radar (courtesy of Dr. Naoki Matayoshi and Dr. Masahiko Sugiura in the Aviation Program Group, JAXA). These plots are drawn on two different planes, which are scanned by the Doppler radar with elevation angles of 4.5 deg and 7.5 deg. The Doppler radar data has missing values due to the interference of terrain features, which are plotted in white. Open circles with black broken
lines in Fig. 9 indicate the streaks of turbulence from the hills. The streaks appear at almost the same locations in the present LES and the radar measurement, although one of the streams disappear due to missing radar measurement data. In addition, these streaks show almost the same turbulence structure; the present LES results have a maximum velocity magnitude of 26.1 m/s, while the radar measurements indicate a maximum velocity magnitude of 30.4 m/s. There is a 14.1% quantitative discrepancy of the maximum velocity magnitude between the present LES and the actual radar measurement. It is caused by the terrain features represented as the staircase mesh, and it is expected that it can be reduced by employing a terrain-fitted curvilinear mesh system.

Figures 8 and 9 indicate that the LES integrated with weather prediction data can simulate the local structures of turbulence, which involve temporal and spatial variations of wind velocity along the flight path due to interference of terrain features. Such turbulence structures cannot be simulated only by JMANHMH without consideration of actual terrain features. Therefore, the present simulation method has an important role in the enhancement of aircraft safety during flights around hilly areas in windy seasons.

5. Conclusions

This study implemented LES around Shonai Airport considering terrain features, and simulated the turbulence induced by neighboring hills. This study employed the two-way nesting method to integrate LES with weather prediction by JMANHMH, each of which was implemented by solving different governing equations in different zones with different scales. First, turbulence simulations were performed with uniform background flow conditions, and it was suggested that terrain features may have a significant influence on the turbulence appearing in the flight path; i.e., aircraft safety is dependent on wind direction. Next, the turbulence simulation was integrated with the weather prediction data, and it was shown that the present simulation can predict the turbulence induced by terrain features. The results agreed well with the turbulence actually observed using the Doppler radar.

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References

4) Yamamoto, K.: Observation of Low-level Wind Shear without Precipitation by Doppler LIDAR for Airport Weather, *Tenki*, 56, 10 (2009),


