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A LES/RANS HYBRID SIMULATION OF CANOPY FLOWS

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Abstract. *The performance of a LES/RANS hybrid simulation was investigated in the analysis of a turbulent flow within and above a horizontally and vertically homogeneous plant canopy. The hybrid simulation introduced in this study was as follows: a Reynolds-averaged Navier-Stokes (RANS) approach was adopted in the canopy layer, and a large-eddy simulation (LES) was applied in the other region. A parametric study on the drag coefficient of a plant canopy model in LES was also conducted.*

1 INTRODUCTION

Hybrid simulations which combine large-eddy simulations (LES) with Reynolds-averaged Navier-Stokes (RANS) approaches are now drawing much attention for wall modeling in LES of high-Reynolds-number turbulent flows. Due to the limitations of computer resources, in LES of high-Reynolds-number flows, it is very difficult to adopt high grid resolution with no-slip boundary conditions in the near-wall regions. The hybrid simulation is a method to alleviate the grid resolution in the near-wall regions; i.e., a RANS approach is applied in the near-wall regions as wall modeling, and LES is adopted away from the walls. The performance of such hybrid simulations has been investigated by many researchers, particularly through the analysis of high-Reynolds-number turbulent channel flows (e.g., [1-3]).

In this study, a hybrid simulation was introduced in the analysis of a canopy turbulent flow. However, the motive for introducing the hybrid simulation was to overcome a problem with a canopy model in LES rather than one with wall modeling in LES. The so-called canopy model is introduced in the analysis of building or plant canopy flows. When the canopy model is used, buildings or plants are not directly resolved, whereas drag forces are added into the momentum equations to reproduce their aerodynamic effects. In the case of the canopy model in LES, however, it is unclear how to set an optimum drag coefficient that is included in the canopy model. Unlike the canopy model in RANS, the time-averaged value of the drag coefficient usually obtained with wind-tunnel experiments or field measurements cannot be used with the canopy model in LES. To overcome this problem, a hybrid simulation was introduced in this study; i.e., a RANS approach was adopted in the canopy layer, and LES was applied in the other region. Here, the hybrid simulation was tested in the analysis of a turbulent flow within and above a plant canopy. Furthermore, based on the results of the hybrid simulation, a parametric study on the drag coefficient of the canopy model in LES was conducted.

2 OUTLINE OF COMPUTATIONS

2.1 Flowfield analyzed

A turbulent flow within and above a horizontally and vertically homogeneous plant canopy was analyzed. The computational domain was $10L(x_1) \times 6L(x_2) \times 4L(x_3)$. L is the height of the plant canopy. x_1, x_2, and x_3 are the streamwise, spanwise, and vertical directions, respectively.

2.2 Plant canopy model

The drag forces, f_i, given by

$$f_i = -C_d a u_i \sqrt{u_j^2} \qquad (i, j = 1, 2, 3) \tag{1}$$

were added into the momentum equations to reproduce the aerodynamic effects of the plant canopy. Here, C_d and a are the drag coefficient and the leaf area density, respectively. Note that the ensemble-averaged velocity, $\langle u_i \rangle$, and the grid-filtered velocity, $\overline{u}_i$, are used as u_i in Eq. (1) in the RANS approach and LES, respectively.

2.3 Computed cases

As shown in Table 1, a hybrid simulation and three computations using LES only were performed. The hybrid simulation introduced here was as follows: the k-ε model proposed by Hiraoka et al. [4], which considers the wake production due to the drag of plants, was adopted in the plant canopy layer, and the standard Smagorinsky model, in which the Smagorinsky constant, C_S, was set at 0.1, was applied in the other region. The interface between the RANS (the k-ε model) and LES (the standard Smagorinsky model) was set at x_3 = 0.9L and was located at 0.1L below the interface between the atmosphere and the plant canopy (Note 1).

The standard Smagorinsky model (C_S = 0.1) was used in the whole region in the computations using LES only. The only difference among these LES computations was the value of the drag coefficient, C_d, in the canopy model (cf. Eq. (1)).

Case	Drag coefficient, C_d	Leaf area density, a	Turbulence model
HYB02	0.2	2/L	LES/RANS hybrid
LES01	0.1	2/L	LES only
LES015	0.15	2/L	LES only
LES02	0.2	2/L	LES only

Table 1: Computed cases.

2.4 Numerical methods

The number of grid points was 50(x_1) × 30(x_2) × 44(x_3) in all computations. Uniform grid intervals were used in the x_1 (streamwise) and x_2 (spanwise) directions. The vertical grid intervals in the region of $0 \le x_3 \le 1.5L$ were uniformly set at 0.05L. For the region of x_3 > 1.5L, the vertical grid intervals were gradually stretched.

A second-order central difference scheme was used for the spatial derivatives. For the time integration, a low-storage type third-order Runge-Kutta scheme by Williamson [5] was adopted. The coupling scheme between the continuity and momentum equations was based on the SMAC method. The Poisson equation for the pressure correction was solved by the Bi-CGSTAB method with the preconditioning of the scaling.

2.5 Boundary conditions

Periodic conditions were used for the streamwise (x_1) and lateral (x_2) boundaries. A slip-wall condition ($\bar{u}_3 = 0$, $\partial / \partial x_3 = 0$) was adopted at the upper boundary. A roughness (z_0)-type logarithmic law was applied to reproduce the effect of the ground surface condition. The value of z_0 was set at 0.001L. The flow was maintained by a constant longitudinal pressure gradient.

3 RESULTS AND DISCUSSION

The quantities written as $\langle \cdot \rangle$ below indicate the time- and horizontal plane (x_1-x_2 plane)-averaged values. In the following figures, the solid line denotes the interface between the atmosphere and the plant canopy, and the dashed line, the interface between the RANS (the k-ε model) and LES (the standard Smagorinsky model) in the hybrid simulation.

3.1 Characteristics of LES/RANS hybrid simulation

Fig. 1 shows the vertical profiles of the eddy viscosity, $\langle \nu_{SGS} \rangle$ (Note 2). The values of $\langle \nu_{SGS} \rangle$ are small both within and above the plant canopy in all computations using LES only (LES01, LES015, and LES02). On the other hand, $\langle \nu_{SGS} \rangle$ obtained with the hybrid simulation (HYB02) becomes much larger than those of the computations using LES only within the canopy layer, i.e., in the RANS region of the hybrid simulation. Above the canopy layer, i.e., in the LES region of the hybrid simulation, $\langle \nu_{SGS} \rangle$ predicted by the hybrid simulation becomes small, as it does in the computations using LES only. Such behavior of $\langle \nu_{SGS} \rangle$ obtained with the hybrid simulation is to be expected and can also be observed in the analysis of turbulent channel flows using hybrid simulations (e.g., [2]). The maximum value of $\langle \nu_{SGS} \rangle$ in the RANS region of the hybrid simulation is nearly 50 times as large as $\langle \nu_{SGS} \rangle$ in the LES region.

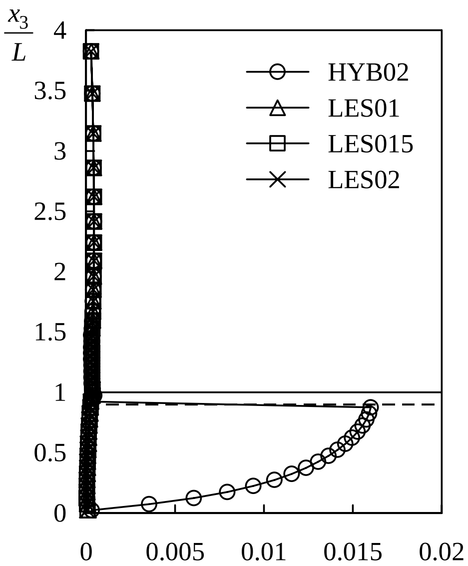

Figure 1: Vertical profiles of $\langle \nu_{SGS} \rangle$.

Figs. 2 and 3 show the vertical profiles of the resolved and subgrid-scale (SGS) shear stresses, $\langle \bar{u}_1' \bar{u}_3' \rangle$ and $\langle \tau_{13} \rangle$ $(= -\langle \nu_{SGS} (\partial \bar{u}_1 / \partial x_3 + \partial \bar{u}_3 / \partial x_1) \rangle)$, respectively. Within the canopy layer, as the profile goes down, the absolute value of $\langle \bar{u}_1' \bar{u}_3' \rangle$ obtained with the hybrid simulation (HYB02) decreases rapidly compared to those of the computations using LES only (LES01, LES015, and LES02). On the other hand, the absolute value of $\langle \tau_{13} \rangle$ (the model component) predicted by the hybrid simulation becomes much larger than those of the computations using LES only within the canopy layer, i.e., in the RANS region of the hybrid simulation. Such behavior of the shear stresses in the hybrid simulation is also to be expected. However, pay attention to the fact that the hybrid simulation predicts a larger absolute value of $\langle \tau_{13} \rangle$ than in the computations using LES only in the region just above the interface between the RANS and LES, where LES is applied in the hybrid simulation. This corresponds to the problem of the accuracy of the velocity profile predicted by the hybrid simulation, as described next.

Fig. 4 shows the vertical profiles of the mean streamwise velocity, $\langle \bar{u}_1 \rangle$; Fig. 5 illustrates the vertical profile of $\langle \bar{u}_1 \rangle$ predicted by the hybrid simulation within the plant canopy ($x_3 / L \leq 1$). Above the plant canopy, where LES is applied in all cases, there are some differences as the profiles go up. The hybrid simulation produces the smallest values of $\langle \bar{u}_1 \rangle$ in the upper region away from the canopy layer (Fig. 4).

Within the canopy layer, as shown in Fig. 5, $\langle \bar{u}_1 \rangle$ obtained with the hybrid simulation increases very rapidly just above the interface between the RANS and LES, where LES is applied in the hybrid simulation. As described before, this corresponds to the overestimation of the SGS shear stress, $\langle \tau_{13} \rangle$, at the same region (cf. Fig. 3). Since the eddy viscosity model is used in LES (as well as in the RANS approach), the steep velocity gradient causes the overestimation of $\langle \tau_{13} \rangle$. Such a steep velocity gradient, i.e., an unnatural mismatch of the velocity profile, near the interface between the RANS and LES predicted by the hybrid simulation has been pointed out by many researchers, especially in the analysis of turbulent channel flows [1-3]. In the application of hybrid simulations, the removal of such a velocity mismatch is the most important issue. In the next phase of this study, we will try to solve this problem by, for instance, introducing additional filtering at the interface between the RANS and LES [2, 3].

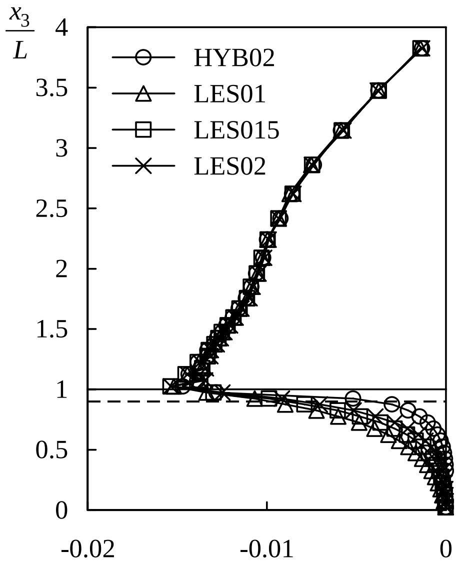

Figure 2: Vertical profiles of $\langle \overline{u}_1' \overline{u}_3' \rangle$.

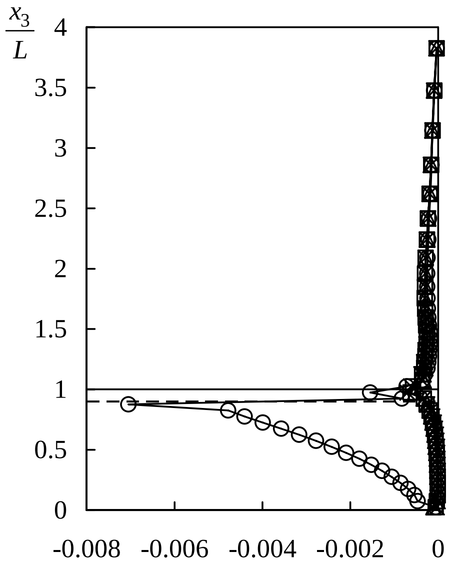

Figure 3: Vertical profiles of $\langle \tau_{13} \rangle$.

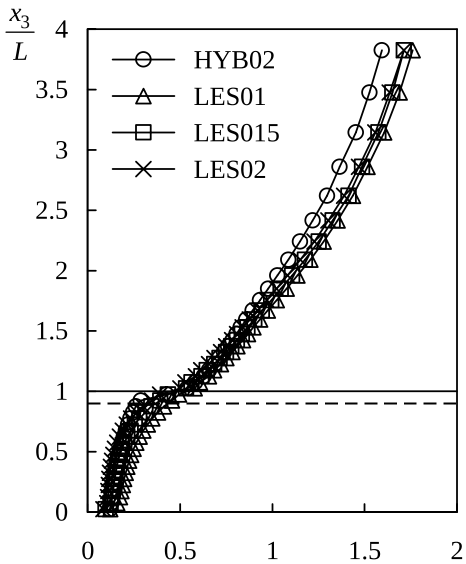

Figure 4: Vertical profiles of $\langle \overline{u}_1 \rangle$.

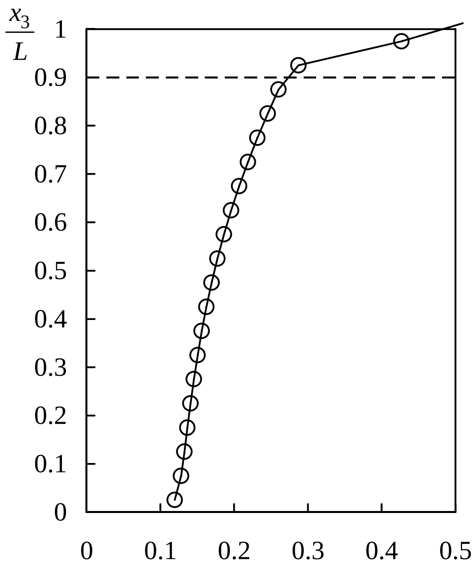

Figure 5: Vertical profile of $\langle \overline{u}_1 \rangle$.

3.2 Effect of the drag coefficient of the plant canopy model in LES

Although the present hybrid simulation has the above-mentioned problem, we will now discuss the effect of the difference in the drag coefficient, C_d, of the plant canopy model in LES based on the results of the hybrid simulation. Fig. 6 shows the vertical profiles of the mean streamwise velocity, $\langle \overline{u}_1 \rangle$, within the plant canopy ($x_3 / L \le 1$). In the computations using LES only (LES01, LES015, and LES02), as the value of C_d becomes larger, the drag force becomes larger, and $\langle \overline{u}_1 \rangle$ thus decreases. The result of LES015, in which C_d is set to 0.15, corresponds best to that of the hybrid simulation, in which C_d = 0.2, except for the region near the interface between the RANS and LES. This comparison allows us to reach the qualitative conclusion that the value of C_d of the plant canopy model in LES should be smaller than the time-averaged value usually obtained with wind-tunnel experiments or field measurements (and also used in RANS approaches). In the next phase of this study, we will conduct a more quantitative investigation into the drag coefficient of the plant canopy model in LES based on the results of an improved hybrid simulation.

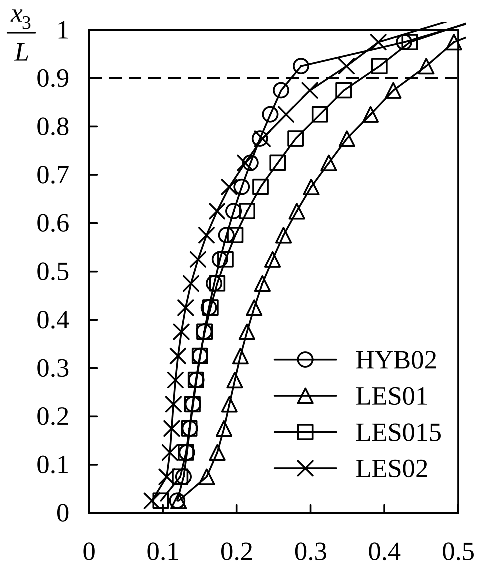

Figure 6: Vertical profiles of $\langle \overline{u}_1 \rangle$.

4 CONCLUSIONS

A LES/RANS hybrid simulation was performed in the analysis of a turbulent flow within and above a horizontally and vertically homogeneous plant canopy in this study. Furthermore, a parametric study on the drag coefficient of a plant canopy model in LES was also conducted based on the results of the hybrid simulation.

The profiles of the eddy viscosity and the shear stresses predicted by the present hybrid simulation showed appropriate behavior as a hybrid simulation. The most serious problem in the application of the hybrid simulation was an unnatural mismatch of the velocity profile, which has often been pointed out in the analysis of turbulent channel flows. The removal of such a velocity mismatch is highly necessary in the application of hybrid simulations. We will try to solve this problem in the next phase of this study.

The comparison between the present hybrid simulation and the computations using LES only allows us to reach the qualitative conclusion that the value of the drag coefficient of a plant canopy model in LES should be smaller than the time-averaged value of the drag coefficient usually obtained with wind-tunnel experiments or field measurements. However, a more quantitative investigation is required in the next phase of this study.

NOTE 1

At first, we set the interface between the RANS and LES at the same height as the interface between the atmosphere and the plant canopy; however, the computation immediately diverged. This was probably due to the strong shear instabilities that occur near the interface between the atmosphere and the plant canopy. As naturally expected, the interface between the RANS and LES cannot be set to such a location.

NOTE 2

The eddy viscosity is generally written as ν_t in RANS approaches. In this paper, however, the notations of quantities followed those conventionally used in LES.

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