HYBRID RANS-LES MODELING BASED ON ZERO- AND ONE-EQUATION MODELS FOR TURBULENT FLOW SIMULATION

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ABSTRACT

Two hybrid RANS-LES models, termed HYB0 and HYB1 respectively, have been proposed. The HYB0 model is based on a simple near-wall mixing-length RANS model coupled with the Smagorinsky model in the off-wall LES region. The HYB1 model employs a one-equation model based on the transport equation for the turbulent kinetic energy. With both models, the RANS-LES matching is achieved by an adaptation of the turbulent length scale to patch the RANS-LES interface. The SGS model coefficients have been calibrated in LES for decaying homogeneous, isotropic turbulence. The hybrid approaches are verified in channel flow computations. Both models show reasonable performance of handling the RANS-LES coupling. In the test case with flow separation, the models have demonstrated good capabilities in reproducing the resolved flow and turbulence quantities in comparison with full-resolved LES data.

INTRODUCTION

Over the recent years, increasing attention has been paid to the development of hybrid modeling methodology as an engineering compromise between the RANS and LES approaches, see e.g. Spalart et al. (1997), Davidson and Peng (2003) and Temmerman et al. (2004). With hybrid RANS-LES modeling, unsteady RANS computation is performed in the near-wall region to alleviate the grid resolution, combining with LES applied in the region away from the wall. In the pioneering work of Spalart et al. (1997, 1999), such a modeling approach has been termed Detached Eddy Simulation (DES). Pragmatically, hybrid modeling abandons a full LES resolution of near-wall turbulent structures, which are instead modeled in the context of RANS approaches, usually as a whole in terms of *mean* turbulence scales. Away from the wall and in regions where the flow undergoes massive separation, e.g. in the wake region after a bluff body, the capability of LES in resolving coherent vortical structures is well adopted.

The argument to patch the RANS-LES matching is plausible. Two typical methods have been used. One way is to take the near-wall URANS solution as a time-dependent mean flow motion, and add turbulent fluctuations to the flow on the interface adjacent to the LES region, see e.g. Davidson and Dahlström (2004). This is a method of matching directly the resolved flow motions, and can be termed *flow-matching* method. Alternatively, a commonly used method is to couple the turbulence properties modeled respectively from the RANS and LES modes, whereas the resolved flow field is uniquely treated and being computed from the numerically identical governing equation system. A method as such can be termed *turbulence-matching* method. Note that the matching zone is equivalent to the outer boundary of the near-wall RANS region and to the inner boundary of the off-wall LES region. To ensure a reasonable RANS-LES coupling of the resolved flow properties, in the matching zone the Reynolds stress inherent in the RANS mode must appropriately interact with the SGS stress modeled from the neighboring LES mode.

In some previous work using the turbulence-matching method, see e.g. Davidson and Peng (2003) and Hamba (2003), the modeled turbulence quantities (typically the RANS and SGS eddy viscosities) are directly forced being equal in the matching zone. This may cause a mismatch between the RANS-computed and LES-resolved velocity fields. With the DES by Spalart et al. (1997), see also Nikitin et al. (2002), the matching between the eddy viscosities have been engaged indirectly by the adaptation of a turbulent length scale, based on the same turbulence transport equation. The RANS and SGS eddy viscosities are enabled to be equally matched by imposing a limit on the near-wall RANS length scale (proportional to the wall distance) in such a way that the extension of the outer boundary of the near-wall RANS region is set by the SGS length scale (proportional to the filter size, and thus associated to the local cell size).

In this work, the hybrid RANS-LES modeling methodology with length-scale adaptation is examined using zero- and one-equation eddy-viscosity models. With the zero-equation hybrid method, a near-wall mixing-length RANS model is coupled with the Smagorinsky SGS model. In the second approach, the one-equation (for the turbulence kinetic energy) model is used in both the RANS and LES regions, and the RANS-LES matching is accomplished with length-scale adaptation. The SGS model involved in the hybrid approaches is first calibrated in LES for decaying homogeneous, isotropic turbulence (DHIT). The hybrid models are then examined and tested for turbulent channel flows and for a periodic hill flow with separation.

MODELING FORMULATION

Undergoing time or spatial filtering, the resulting filtered Navier-Stokes equation system may be cast in an identical mathematical formulation with the inclusion of turbulent stress terms, τ_{ij}, due to the nonlinear term, yet these stress terms possess substantially different physical arguments. By a time-filtering (long enough as with an ensemble averaging) in RANS, the Reynolds stresses represent the *time-averaged* effect of turbulence on the mean flow motion. By a spatial-filtering, the subgrid-scale (SGS) stresses indicate the energy transfer between the resolved large-scale turbulent structure and the unresolved SGS turbulence. Provided that an eddy-viscosity based model is used to formulate the RANS turbulent stresses or the SGS stresses, the closure problem becomes a task of seeking for proper turbulence scales to construct the eddy viscosity. Effort has been made here to develop two hybrid models based on eddy viscosity models.

Zero-equation hybrid model

In the near-wall RANS region a simple mixing-length model is used of which its eddy viscosity is defined by

$$\tilde{\mu}_t = \rho \tilde{l}_\mu^2 |S| \tag{1}$$

where $|S|$ is the magnitude of the flow strain rate tensor, and the length scale is proportional to the wall distance y, reading $\tilde{l}_\mu = f_\mu \kappa y$ and $\kappa = 0.41$. To avoid the awkwardness of using wall-shear related quantities for separating and/or reattaching flows, the damping function f_μ is formulated in terms of the ratio of $R_t = \tilde{\mu}_t/\mu$, viz.

$$f_\mu = \tanh\left(\frac{R_t^{1/3}}{2.5}\right) \tag{2}$$

In the off-wall LES region, the Smagorinsky model reads

$$\mu_{sgs} = \rho (C_s \Delta)^2 |S| \tag{3}$$

with $C_s = 0.12$ and $\Delta = \sqrt{(\Delta_{max}^2 + \delta V^{2/3})/2}$, where δV is the local cell volume and Δ_{max} is the local maximum cell size, $\Delta_{max} = \max(\Delta_x, \Delta_y, \Delta_z)$. Note that, for convenience, we have dropped the over-bar which has otherwise been conventionally used to denote a spatial-filtered flow quantity.

The matching between the RANS and LES modes is carried out by modifying the RANS length scale into $l_\mu = \tilde{l}_\mu f_s$ so that $\mu_t = \rho l_\mu^2 |S|$ in the RANS mode, and

$$f_s = \frac{1}{2}\left[\exp\left(-\frac{R_s^{0.75}}{4.75}\right) + \exp\left(-\frac{R_s^{0.3}}{2.5}\right)\right] \tag{4}$$

where $R_s = \tilde{\mu}_t/\mu_{sgs}$. The eddy viscosity, μ_h, in the hybrid model is computed by

$$\begin{aligned} \mu_h &= \mu_t \ \text{ if } \tilde{l}_\mu < \Delta \\ \mu_h &= \mu_{sgs} \ \text{ if } \tilde{l}_\mu \geq \Delta \end{aligned} \tag{5}$$

This model is hereafter termed the **HYB0 model**.

One-equation hybrid model

The transport equation for the turbulence kinetic energy, k, is used in the hybrid one-equation model, which reads

$$\frac{D\rho k}{Dt} = -\tau_{ij}\frac{\partial u_i}{\partial x_j} + \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_h}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] - \rho \varepsilon_h \tag{6}$$

where $\tau_{ij} = -2\mu_h S_{ij} + \frac{2}{3}k\delta_{ij}$. The eddy viscosity, μ_h, and the dissipation rate, ε_h, are formulated by, respectively,

$$\mu_h = C_k \rho L_{\mu h}\sqrt{k} \ \text{ and } \ \varepsilon_h = C_\varepsilon \frac{k^{3/2}}{L_{\varepsilon h}}, \tag{7}$$

where $L_{\mu h}$ and $L_{\varepsilon h}$ are two turbulence length scales in the hybrid k-equation model.

In previous work (Davidson and Peng, 2003), Yoshizawa's SGS k-equation model (hereafter YoLES model) (Yoshizawa, 1986) was used with model constants $\sigma_k = 1.0$, $C_k = 0.07$ and $C_\varepsilon = 1.05$. When applied to simulations of decaying isotropic turbulence, however, it was found in this work that the YoLES model may underestimate the turbulent diffusion so that the resolved turbulence energy is over-predicted at large wave numbers. The model constants have thus been re-calibrated as being $\sigma_k = 1.0$, $C_k = 0.07$ and $C_\varepsilon = 0.6$, with $L_{\mu h} = L_{\varepsilon h} = \Delta = \delta V^{1/3}$ in the DHIT simulation. The model (hereafter MYoLES model) has been employed in the off-wall LES region in the present one-equation hybrid model.

Since we intend to use the same transport equation of k in the near-wall RANS region coupled with the off-wall MYoLES model, the length scales need to be re-adapted in order to model appropriately the near-wall boundary layer by means of RANS mode. The RANS turbulence length scales are denoted here by l_μ and l_ε, respectively, corresponding to $L_{\mu h}$ and $L_{\varepsilon h}$ in its RANS form of Eq. (6).

Let $l_\mu \propto \alpha y$ and $l_\varepsilon \propto \beta y$, where y is the wall distance, α and β are two coefficients to be determined. For a boundary layer flow with local equilibrium, it is noted that, in the RANS mode, $\mu_h = \mu_t = C_k \rho l_\mu \sqrt{k}$ and $\varepsilon_h = C_\varepsilon \frac{k^{3/2}}{l_\varepsilon}$ should match their respective values in the log-layer. This suggests that

$$\alpha = \kappa C_\mu^{1/4}/C_k \ \text{ and } \ \beta = \kappa C_\varepsilon C_\mu^{-3/4} \tag{8}$$

where $\kappa = 0.418$ and $C_\mu = 0.09$. It is apparent that for wall-shearing flows with local equilibrium, i.e. $P_k = \varepsilon$, the values of α and β have ensured that $\frac{-\overline{uv}}{k} = \sqrt{C_\varepsilon C_k l_\mu / l_\varepsilon} = 0.3$ as observed in the experiment.

With the length scale, l_μ, to estimate the RANS turbulent eddy viscosity, it is found that μ_t may become too large when the model is integrated toward the wall. An empirical damping function, f_μ, has thus been designed so that $l_\mu = \alpha f_\mu y$ and

$$f_\mu = 1 - \exp\left[-\frac{\sqrt{R_y} + R_y}{90}\right] \tag{9}$$

where $R_y = \sqrt{k}y/\nu$. The length scale, l_ε, takes $l_\varepsilon = C_\varepsilon C_\mu^{-3/4}\kappa y$ in the near-wall RANS region.

Note that l_μ and l_ε are only used in the RANS region to determine respectively the eddy viscosity and the dissipation rate of k. In the LES region the filter size, $\Delta = \sqrt{(\Delta_{max}^2 + \delta V^{2/3})/2}$, is taken as the characteristic length scale for the SGS turbulence. In order to ensure a proper matching between the RANS and LES modes, a mixed length scale for the RANS mode is defined by $l_r = \sqrt{l_\mu l_\varepsilon}$ so that the coupling is regulated by the following relation

$$\begin{aligned} L_{\mu h} &= \min\{\Delta, \min(l_\mu, l_r)\} \\ L_{\varepsilon h} &= \min\{\Delta, \max(l_\varepsilon, l_r)\} \end{aligned} \tag{10}$$

This one-equation hybrid model is hereafter termed the **HYB1 model**.

RESULTS AND DISCUSSION

The governing equations are discretized on a collocated grid using the 2nd-order central differencing finite-volume method. The solution is advanced in time with the second-order Crank-Nicholson scheme. An implicit, fractional step method is used to solve the discretized equation system.

Decaying homogeneous, isotropic turbulence

In order to examine the SGS models involved in the present hybrid approaches, LES is first performed for the DHIT case in a $(2\pi)^3$-cubic box with periodic conditions in all three directions. The simulation is based on the experiment of Comete-Bellot and Corrsin (1971), from which the energy spectrum at $t = 42$ is taken to generate the initial field using discrete Fourier transform (NTS, 2004).

Figure 1 presents the simulated energy spectra using two different grid resolutions, with 32^3 and 64^3 cells respectively. As shown, the Smagorinsky model gives reasonable predictions for the energy spectra with $C_s = 0.215$ on the 32^3 mesh, while it is somehow too dissipative at higher wave numbers with the 64^3 mesh. By contrast, the YoLES model underestimates the energy dissipation on the coarse mesh, but produces improved energy spectra with the finer mesh. With the MYoLES model, by keeping $C_\varepsilon = 0.6$, C_k has been calibrated with two values, $C_k = 0.07$ and $C_k = 0.09$, respectively. With $C_k = 0.09$ for the 64^3 mesh, similar to the Smagorinsky model, the MYoLES model is too dissipative at higher wave numbers, whereas the prediction is significantly improved using $C_k = 0.07$, yet the energy spectra are overestimated for the coarse grid with this value. Base on further calibration of C_k for turbulent channel flows, we have adopted $C_k = 0.07$ in the MYoLES model incorporated into the HYB1 model.

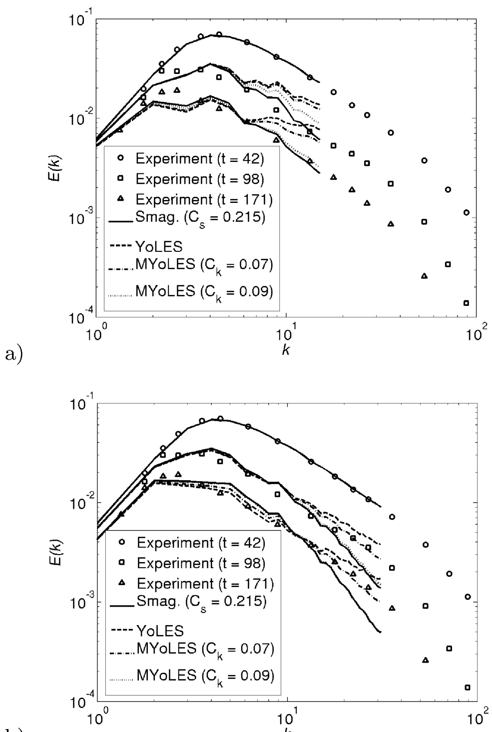


Figure 1: LES for decaying homogeneous, isotropic turbulence. a) with 32 × 32 × 32 mesh. b) with 64 × 64 × 64 mesh.

Turbulent channel flow

The HYB0 and HYB1 models are then examined in computations for fully developed turbulent channel flows. In the results presented below, a fluctuating quantity of the resolved field is denoted by $\phi' = \bar{\phi} - \langle\bar{\phi}\rangle$, and the symbol, $\langle\cdot\rangle$, is used to term the quantities obtained from time-averaging and spatial-averaging over the homogeneous directions.

For the turbulent channel flow, the computational domain has dimensions of 2π, 2 and π in the streamwise (x), vertical (y) and spanwise (z) directions, respectively. The mesh is uniformly distributed in the x and z directions, while being clustered near the wall in the y direction. A mesh of $48 \times 64 \times 32$ is used for $Re_\tau = 395$, yielding $y_1^+ \approx 0.23$, $\Delta x^+ \approx 52$ and $\Delta z^+ \approx 39$. For $Re_\tau = 2000$, the mesh has $64 \times 64 \times 32$ cells, giving $y_1^+ \approx 1.13$ and $\Delta x^+ = \Delta z^+ \approx 196$. By adding a pressure force in the streamwise momentum equation, which ensures a correct Re_τ, a periodic boundary condition has been imposed in the inflow and outflow sections. The periodic condition is also adopted at the spanwise boundaries. The results are compared with available DNS data at $Re_\tau = 395$ (Kim et al., 1987) and with full-resolved LES data at $Re_\tau = 2000$ (Piomelli et al., 2003).

It should be noted here that one of the main purposes with the channel flow computation is to verify the scale-adaptation involved in the present hybrid methods, where the turbulent length scale is switched from the near-wall RANS region to the neighboring off-wall LES region, see Eqs. (5) and (10). Two aspects need to be taken into account. First, the RANS-LES matching should not induce unacceptable discontinuity in the distributions of the computed quantities. Second, the matching should ensure a correct interaction between the RANS and LES modes, for which reasonable flow resolutions should be reproduced by the RANS mode in the near-wall region. The flow in the off-wall LES region may however be under-resolved due to the grid resolution adopted, which is relatively coarse as compared with the mesh enabling a full-resolved LES.

In order to validate the capability in handling near-wall turbulent flows, the RANS modes used respectively in the HYB0 and HYB1 models are first examined in RANS computations for the channel flow at $Re_\tau = 395$. This means that the zero- and one-equation RANS models have been employed over the whole computational domain by taking, respectively, $\mu_h \equiv \tilde{\mu}_t$ in the HYB0 model, $L_{\mu h} \equiv l_\mu$ and $L_{\varepsilon h} \equiv l_\varepsilon$ in the HYB1 model. The computation is converged to a steady solution. Figure 2 presents the RANS solutions to the mean velocity and the turbulent shear stress. As compared with the DNS data (Kim et al., 1987), the HYB1-RANS mode is able to produce very good predictions. With the HYB0-RANS mode, the mean velocity in the log-layer is underestimated, corresponding to a slightly over-predicted turbulent shear stress. Both models are capable of reproducing reasonable predictions near the wall.

In hybrid modeling, the near-wall region is essentially modeled by the RANS mode. This implies that the modeled part of a turbulence statistic quantity (e.g. the turbulent stress) may be dominant over, or comparable with, the resolved part. In the off-wall LES region, by contrast, the SGS model usually entails a modeled part much smaller than the resolved part. Figures 3 and 4 present the results obtained with the two proposed hybrid approaches for turbulent channel flows. The results have been compared with the DNS data by Kim et al. (1987) at $Re_\tau = 395$ and with the LES data by Piomelli et al. (2003) at $Re_\tau = 2000$, respectively. To verify the different contributions, the modeled part and resolved part for the turbulent shear stress have also been plotted, which form the total turbulent shear stress, i.e., $\langle u'v'\rangle_{tot} = \langle u'v'\rangle_{res} + \langle\tau_{12}\rangle_{mod}$. As seen, the time-averaged streamwise velocity, $\langle u\rangle^+$, pre-

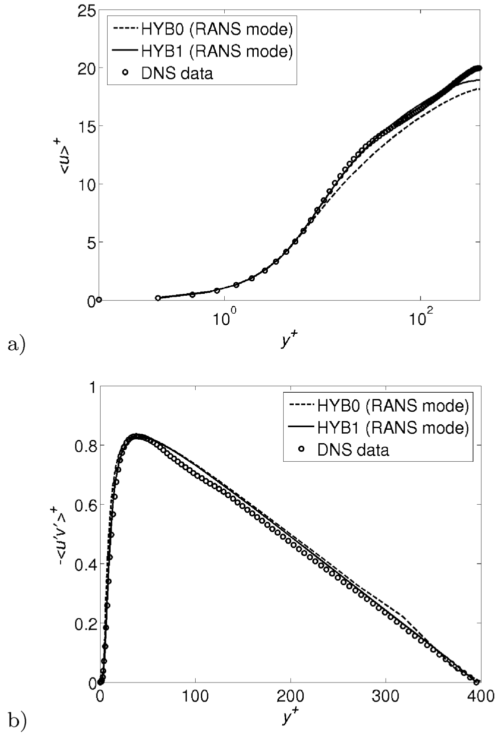


Figure 2: Results from RANS simulations for channel flow at $Re_\tau = 395$ using the RANS modes of the HYB0 and HYB1 models, respectively.

dicted by both approaches shows a reasonable agreement with the DNS or LES data in the near-wall RANS region. Note that for both cases, $Re_\tau = 395$ and $Re_\tau = 2000$, the grid resolution adopted in the LES region is too coarse to enable a full LES resolution. This has been reflected in the over-prediction for the mean velocity in the outer LES region. Similar results can be found in channel flow simulations using DES by Nikitin et al. (2002). The small peak, appearing in the distribution for $\langle u'v' \rangle_{tot}$ obtained with the HYB1 model, arises at the RANS-LES interface, where l_r in Eq. (10) has been adopted to replace l_ε and/or l_μ in the RANS mode. This small discrepancy has not, nonetheless, entailed any sensible effect on the resolved mean flow. As will be shown below, no obvious effect can even be observed on the distribution for $\langle u'v' \rangle_{tot}$ in the periodic hill flow computation.

It should be noted here that the SGS length scale, Δ, has been verified for both models using $\Delta_1 = \delta V^{1/3}$, $\Delta_2 = \Delta_{max}$ and $\Delta = \sqrt{(\Delta_1^2 + \Delta_2^2)/2}$, respectively. The HYB0 model shows little sensitivity to different choices, since the model is able to adjust the RANS and LES eddy viscosities to the same level at the interface by adaptation of the length scale. Using Δ_2 or Δ in the HYB1 model, the predictions obtained are very similar. Some difference has, however, been observed between the results obtained, respectively, with Δ_1 or Δ in the HYB1 model. Different SGS length scales may alter the SGS turbulence modeling in the LES region and, additionally, the location of RANS-LES interface is also justified by this length scale. With $\Delta_1 = \delta V^{1/3}$, for example, the RANS-LES interface occurs in channel flow simulations at $y_m^+ \approx 15$ for $Re_\tau = 395$ and $y_m^+ \approx 37$ for $Re_\tau = 2000$, which is located in or close to the buffer layer. Note that the strategic purpose with hybrid modeling is to avoid full LES resolution of

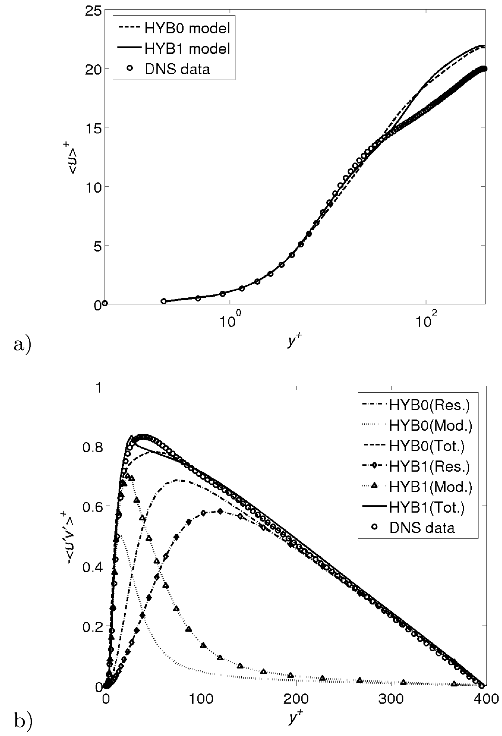


Figure 3: Modeling results for channel flow at $Re_\tau = 395$.

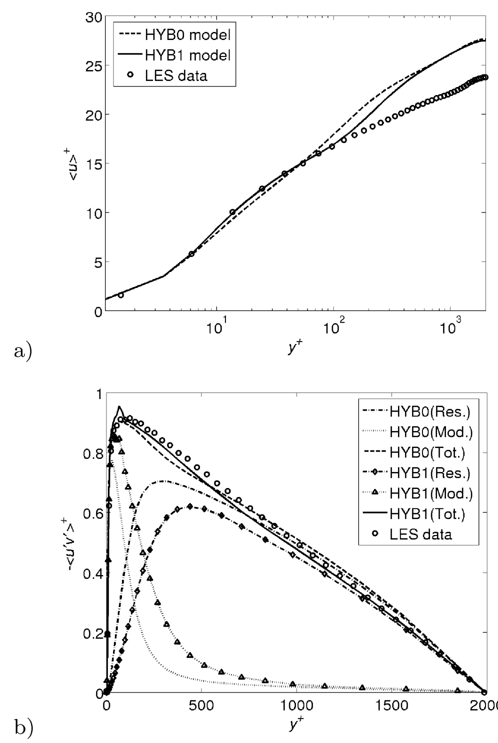


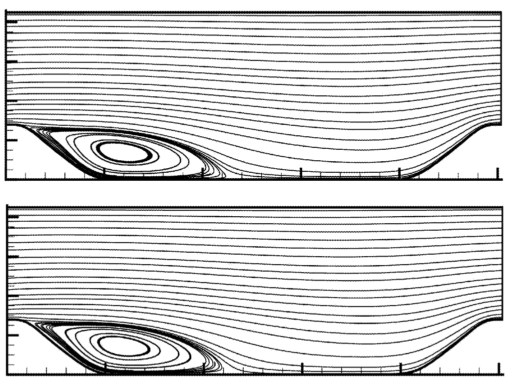
Figure 4: Modeling results for channel flow at $Re_\tau = 2000$.

the near-wall, energetic turbulent structures (e.g. streaks) for high Reynolds-number flows. It is thus plausible to have the RANS mode extended to the log-layer and outer. The SGS length scale $\Delta = \sqrt{(\Delta_1^2 + \Delta_2^2)/2}$ has thus been adopted for both the HYB0 and HYB1 models.

Turbulent periodic hill flow

In this section the proposed hybrid models are applied to a turbulent channel flow with hills periodically mounted on the bottom wall. A periodic segment is taken in the computation with $L_x \times L_y \times L_z = 9h \times 3.036h \times 4.5h$, where h is the height of the hill. The Reynolds number based on the bulk velocity above the hill crest, U_b, and the hill height is $Re = 10595$. The mesh used in the present computation is $112 \times 64 \times 48$. The computed results are compared with the LES data by Temmerman et al. (2003), in which a $196 \times 128 \times 186$ mesh was employed to resolve the wall turbulence.

Figure 5 illustrates the flow streamlines simulated respectively with the HYB0 model (Fig. 5 a)) and with the HYB0 model (Fig. 5 b)). A separation bubble arises on the lean side of the hill, starting shortly after the hill top and being reattached at the bottom wall of the channel. Both models have predicted reasonable locations for the bubble separation and reattachment, as compared with the LES result.



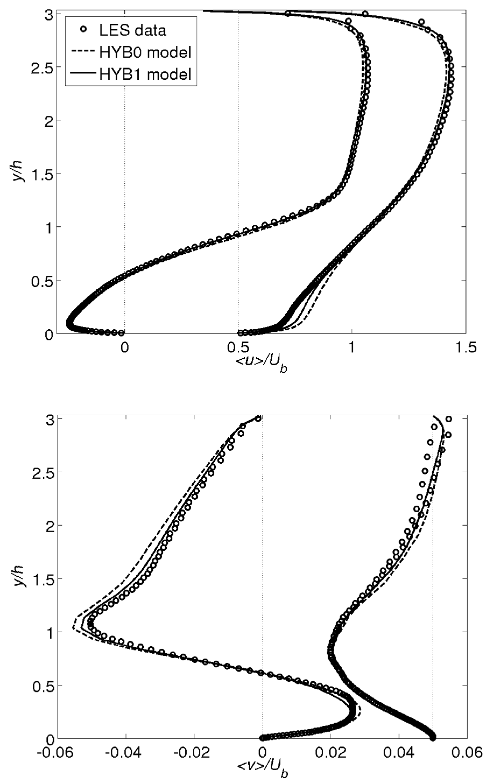
a)

b)

Figure 5: Streamlines of periodic hill flow. Full LES (Temmerman et al, 2003) reproduces locations of separation at $x_{sep.} = 0.22h$ and reattachment at $x_{reat.} = 4.72h$. a). Simulated with the HYB0 model, $x_{sep.} = 0.235h$ and $x_{reat.} = 4.46h$. b). Simulated with the HYB1 model, $x_{sep.} = 0.23h$ and $x_{reat.} = 4.48h$

The flow distributions are presented below at locations $x = 2h$ and $x = 6h$, which have been plotted in the same figure for each computed quantity. In Figure 6, the resolved mean velocities in the streamwise and vertical directions are plotted. In comparison with the LES data, the models have reproduced very good predictions for both velocity components. This is particularly true in the bubble area. At $x = 6h$, both models over-estimate the $\langle u \rangle$-velocity near the channel bottom wall. Above the bubble at $x = 2h$, the HYB0 has slightly over-predicted the $\langle v \rangle$-velocity.

Figure 7 a) presents the resolved turbulent kinetic energy, $\langle k_{res} \rangle$, in comparison with the LES data. The hybrid models give a consistent tendency with the LES for the distributions at both locations, but the value is somewhat smaller than the full LES prediction, except at $x = 6h$ with the HYB0 model which reproduces larger values for $\langle k_{res} \rangle$ near the bottom wall. Note that the hybrid approach employs RANS mode in the near-wall region, where the solution for a turbulent quantity has been partly accounted for by the RANS model along with the resolved part. A comparison is thus made with the total turbulent kinetic energy, $\langle k_{tot} \rangle = \langle k_{res} \rangle + \langle k_{mod} \rangle$, as shown in Figure 7 b). It should be noted that, with the HYB0 model, the turbulent kinetic energy is not solved and the modeled isotropic part of τ_{ij}, i.e. $\tau_{kk}/3$, is negligibly small. The modeled part makes thus no contribution to $\langle k_{tot} \rangle$, which remains



a)

b)

Figure 6: Predictions of time-averaged velocity profiles for the periodic hill flow at $x = 2h$ (left) and $x = 6h$ (right), respectively. a) Mean streamwise velocity. b) Mean vertical velocity.

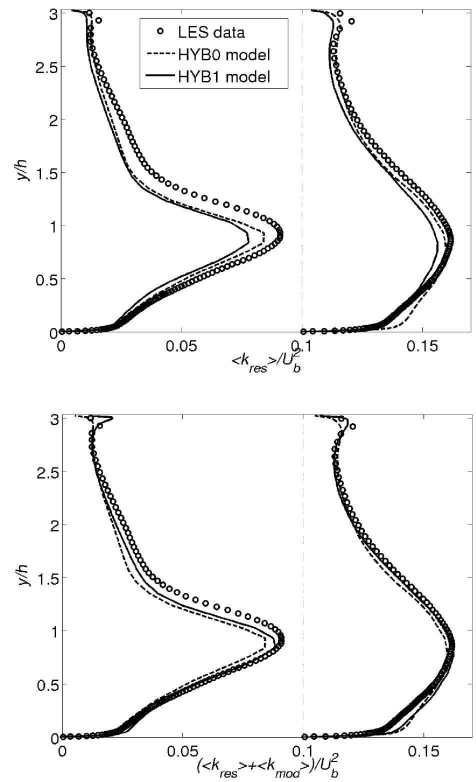
the same as $\langle k_{res} \rangle$. With the HYB1 mode, as shown in 7 b), the modeled contribution is sensible, particularly in the near-wall region, as well as in the shearing region above the bubble as seen at location $x = 2h$. The overall comparison of $\langle k_{tot} \rangle$ with LES is very reasonable.

In Figures 8 a) and b), comparisons with LES data have been made for the resolved and total turbulent shear stress, respectively. Both models give good results, but a slight over-prediction with the HYB0 model for the peak value at location $x = 6h$. As shown, the contribution from the modeled part has somewhat improved the comparison near the top wall.

CONCLUSIONS

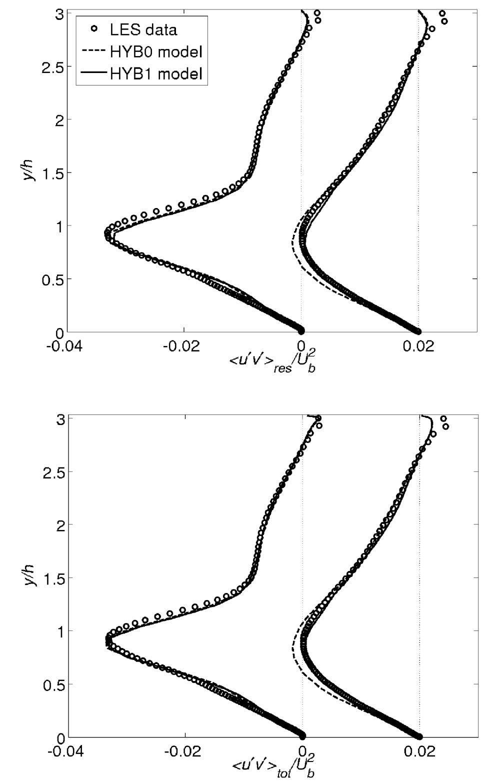
Two hybrid RANS-LES models have been proposed and validated for turbulent flow simulations. The HYB0 model is based on a near-wall mixing-length RANS model coupled with the Smagorinsky SGS model in the LES region. The HYB1 model is a one-equation model based on the transport equation for the turbulent kinetic energy. The SGS model coefficients have been calibrated in LES for the DHIT case. The RANS-LES matching in both models has been accomplished by adaptation of turbulence length scales, which has been verified in turbulent channel flow computations. It is shown that both proposed hybrid approaches have enabled reasonable RANS-LES matching and do not generate unphysical discontinuity in the mean resolved flow.

In modeling of the turbulent hill flow, both models have shown satisfactory performance in reproducing the separation bubble and the mean flow field, as well as the turbulence statis-



(a) (b)

Figure 7: Time-averaged turbulent kinetic energy for periodic hill flow at $x = 2h$ (left) and $x = 6h$ (right), respectively. a) Resolved turbulence kinetic energy, $\langle k_{res} \rangle$. b) Total turbulence kinetic energy, $\langle k_{tot} \rangle = \langle k_{res} \rangle + \langle k_{mod} \rangle$.



(a) (b)

Figure 8: Time-averaged turbulent shear stress for periodic hill flow at $x = 2h$ (left) and $x = 6h$ (right), respectively. a) Resolved turbulence shear stress, $\langle u'v' \rangle_{res}$. b) Total turbulence shear stress, $\langle u'v' \rangle_{tot} = \langle u'v' \rangle_{res} + \langle \tau_{12} \rangle_{mod}$.

tics. The proposed models consist of simple formulations and are easy to implement in practice. Further validations will be carried out in applications to high-Re number turbulent flows.

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