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Implicit Wall-Layer Modelling in Turbulent Pipe Flow

Rodrigo Vicente Cruz, Eric Lamballais, and Rodolphe Perrin

1 Introduction

In the context of Large Eddy Simulations (LES) of wall-bounded turbulence, the explicit calculation of all the energy containing near-wall eddies is a key point. To accomplish this goal, it is recommended the employment of a mesh resolution between 10 and 100 wall units for the streamwise direction discretization, from 10 to 20 wall units in the spanwise direction, and typically one wall unit in the wall normal direction through a near-wall mesh refinement. When these resolution criteria are too demanding in terms of computational resources, an alternative is to use a discretization that bypasses the inner layer with the aid of a wall-layer model [9, 4].

However, it was shown by [6] that excellent basic turbulent statistics in a pipe flow can be obtained with a mesh resolution coarser than the viscous sublayer without using any explicit wall-layer modelling. In this context, the near-wall regularization is simply performed by means of an original and robust implicit LES (ILES) technique that - without any extra-cost or adaptation in the near-wall region - displays a wall modelling feature. Two Reynolds numbers $Re_\tau = 180, 550$ ¹ were considered when comparing ILES results to unfiltered DNS data of [3].

The term implicit LES refers here to the use of regularization as a substitute of subgrid-scale (SGS) modelling [7, 1]. The originality of the method is found in the built-in numerical dissipation that does not come from the discretization of the convective term, but from the viscous term in the Navier-Stokes equation. This

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¹ Based on the friction velocity u_τ and the pipe radius R .

strategy has also been used successfully by [2, 8] for turbulent plane channel and impinging jet configurations with regular Cartesian meshes, nonetheless, the near-wall behaviour of the implicit SGS modelling was not specifically investigated.

Until now, the aforementioned conclusions about the ILES technique performance were based on comparisons of basic statistics with unfiltered DNS data, which means that even if a good agreement was observed, no rigorous assessment could be made. In the present investigation, this matter is examined at higher Reynolds number ($Re_\tau = 1000$) while determining to what extent it can be generalized in terms of near-wall region bypass. To do so, a *quasi*-DNS database is presented with an original method to easily produce filtered statistics in order to enable rigorous comparisons with ILES at any mesh resolution. The implicit LES results are, thus, analysed in terms of ability to predict near-wall statistics despite the use of very coarse grid for which even the near-wall turbulent production region is fully bypassed.

2 Numerical Method and Computational Configuration

As a generic numerical tool to investigate this concept of implicit LES, the sixth-order flow solver Incompact3d is used. Thanks to its features of kinetic energy conservation² and flexibility for the application of numerical dissipation, this code enables an easy calibration of the implicit SGS modelling. In particular, the role of its scale selectivity has been shown in [7] through rigorous comparisons with DNS results based on a priori and a posteriori analysis with a particular attention to distant triad interactions between SGS and very large scales [1]. In addition, it was shown by [7] that the present implicit LES technique is equivalent to the use of spectral vanishing viscosity (SVV), ensuring high-order accuracy and flexible application. In previous studies using the method [7, 1], the validation framework was based on the Taylor-Green Vortex problem as a prototype of wall-free turbulent flow.

As in [6], a regular Cartesian mesh is combined with the use of an immersed boundary technique to discretize the pipe geometry while considering periodic boundary conditions in the three spatial directions. A one-dimensional reconstruction method [5] is used inside the solid to ensure the smoothness of the solution everywhere in the computational domain. This feature clearly improves the accuracy of compact finite difference schemes as used in the code Incompact3d.

3 Filtered quasi-DNS Database

Quasi-DNS of pipe flow is performed at $Re_\tau = 1000$ in order to, afterwards, produce the filtered benchmark database for comparison with ILES results. A mesh

² In the discrete and inviscid sense up to the time advancement error.

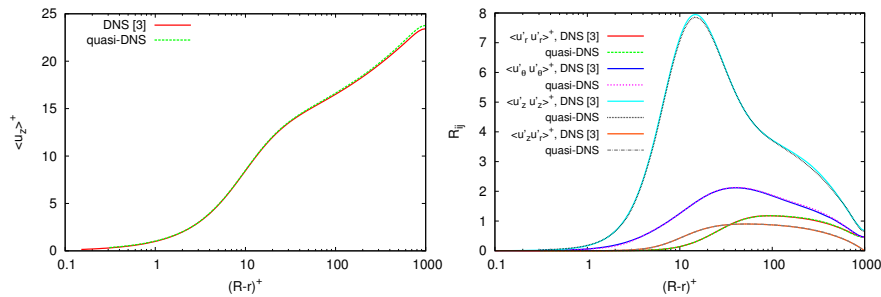


Fig. 1 Mean velocity (left) and Reynolds stresses profiles (right) for the quasi-DNS at $Re_\tau = 1000$ compared to DNS statistics of [3].

of $n_x \times n_y \times n_z = 768 \times 768 \times 1920$ cells was used, corresponding, in wall units to $\Delta x^+ = \Delta y^+ = 2.9$ and $\Delta z^+ = 13$. The term *quasi* is naturally used due to the employed mesh resolution, however, as shown in figure 1, thanks to the success of the technique, a very good agreement with DNS data of [3] is found.

As in [1], the filter is chosen to take the implicit SGS dissipation into account using a spectral Pao-like closure. By specifying the ratio between DNS and LES mesh resolutions, this Pao-like closure provides the spectral transfer functions that are used to define the targeted LES solution. Thus, this targeted solution is determined rigorously and consistently with the artificial dissipation implicitly introduced by the error differentiation in the present ILES framework [7]. The use of periodic boundary conditions enable the application of the present homogeneous filter defined in the Fourier space. The filter is applied once in every direction to take the anisotropy of the LES mesh into account. Following this procedure, a consistent framework is established for rigorous comparisons between LES and filtered DNS data.

The filter effect over streamwise- z and normal- xy directions separately is shown in figure 2. Acting as a pre-analysis, this information guided the choice of interesting mesh resolutions based on the levels of energy $k = \frac{1}{2} \langle u_i u_i \rangle$ to be potentially captured when the viscous and even near-wall production regions are bypassed. It is important to emphasize that the application of filter in normal- xy directions is only possible thanks to the solution smoothness provided by the reconstruction. As shown in figure 3, if no extension of the fluid solution is made into the solid zone before filtering, the no-slip condition is poorly ensured and near-wall region results are not reliable, a problem that is strongly reduced with the reconstruction. Nonetheless, reconstruction's ability to ensure the success of normal direction filtering is limited to not so high values of the filter-width, as shown in figure 2-left by the abnormal near-wall behaviour when data is filtered at a corresponding cell size $\Delta x^+ = \Delta y^+ = 24$. For $\Delta x^+ = \Delta y^+ = 15$, the unrealistic near-wall rising of the turbulent kinetic energy k can be avoided, but persistent velocity fluctuations are observed close to the wall with for instance $k^+ \approx 0.156$ at $(R-r)^+ \approx 1.03$ to be compared to $k^+ \approx 0.124$ for the reference non-filtered value. Here, we have chosen to limit our analysis to $\Delta x^+ = \Delta y^+ = 12$ for which the filtering procedure produces also $k^+ \approx 0.124$ at this near-wall location.

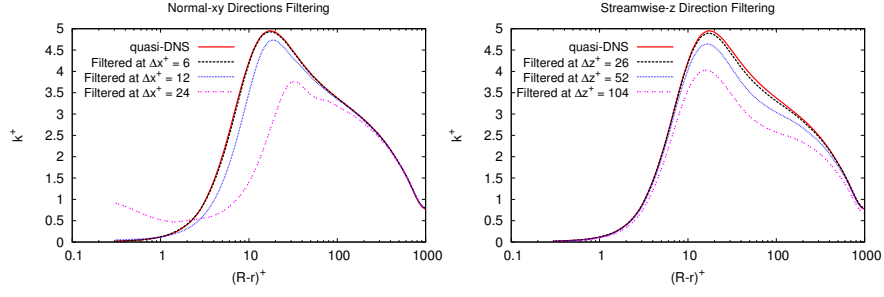


Fig. 2 Turbulent kinetic energy from filtered quasi-DNS at different mesh resolutions. The drop of energy is analysed for filtering along (left) streamwise- z direction and (right) normal- xy directions.

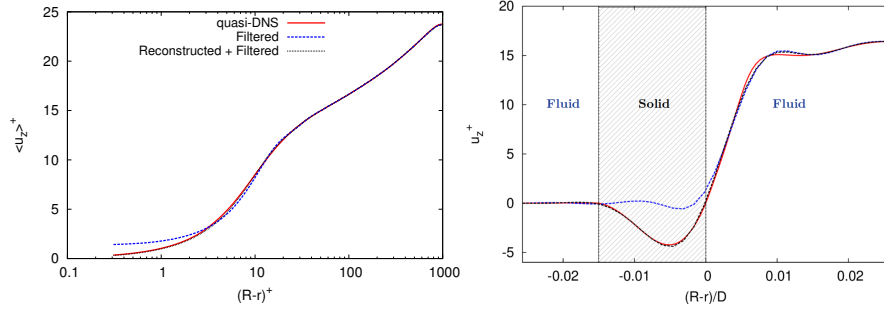


Fig. 3 Comparison of mean (left) and instantaneous (right) velocity profiles demonstrates the effect/necessity of reconstruction on the reliability of data filtered in the normal Cartesian directions (x, y). In this illustration, quasi-DNS data have been filtered at a corresponding mesh resolution of $\Delta x^+ = \Delta y^+ = 12$.

4 LES Results

Before proceeding to the results, it is important to highlight that the term “implicit wall-layer modelling” is used to emphasize the ability of the present methodology to regularize the solution in the near-wall region without any explicit wall model. The improvement brought by the technique is the simple result of a targeted choice of coefficients for the centred compact finite difference scheme used for the discretization of the viscous term in the Navier-Stokes equations [6].

For a Reynolds number of $Re_\tau = 1000$, two implicit LES have been performed using: i) Marginal Resolution: $n_x \times n_y \times n_z = 512 \times 512 \times 1280$ cells, corresponding in wall units to $\Delta x^+ = \Delta y^+ \approx 4.5$, $\Delta z^+ \approx 19.5$; and ii) Low Resolution: $n_x \times n_y \times n_z = 256 \times 256 \times 960$ cells, expressed in wall units: $\Delta x^+ = \Delta y^+ = 12$, $\Delta z^+ = 26$. Mesh resolutions were chosen in order to evaluate the method performance in terms of viscous and near-wall production region bypass respectively. The implicit wall modelling feature of the present approach is evidenced by comparing ILES to no-model LES results performed without any (implicit or explicit) SGS/wall-layer modelling.

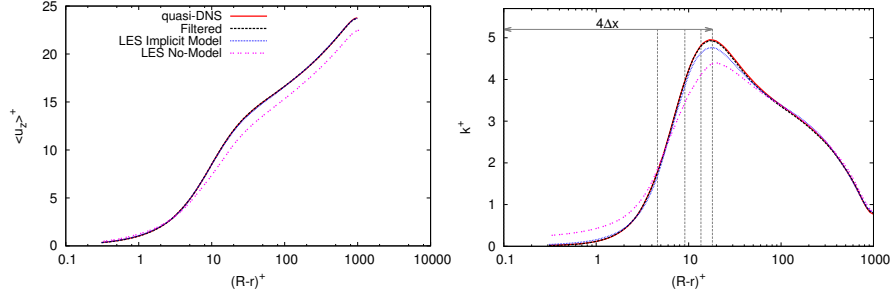


Fig. 4 Mean velocity profile (left) and Reynolds stresses profiles (right) for the Marginal Resolution ILES at $Re_\tau = 1000$. Results are compared to: no-model LES, unfiltered and filtered quasi-DNS statistics.

Beginning with the Marginal Resolution comparisons, in figure 4-right, the deviation between ILES and filtered kinetic energy profiles at the peak points to the existence of numerical/modelling errors. However, the overall precision and agreement of the statistics are the confirmation at high Reynolds number that accurate turbulent statistics can be obtained despite the use of a mesh resolution unable to capture the viscous sublayer. In particular, it can be observed that the peak of k^+ is remarkably well predicted at a level of detail clearly higher than the minimal scale $4\Delta x$ computed with accuracy. When compared to “No-Model” results, numerical dissipation is found definitely necessary so that it can be seen as playing the role, in this context, of an implicit viscous sublayer modelling. To explain this improvement, it must be mentioned that the no-model solution is subjected to small-scale oscillations which make inaccurate the prediction of friction velocity with an overestimation of about +6%. Here, the use of numerical dissipation can remove these spurious oscillations making clearly more accurate the friction velocity prediction with only a deviation of -1% by comparison to DNS.

For the Low Resolution results, for which the mesh choice was based on the results of figure 2, a good prediction of the mean velocity is recovered by the ILES with an acceptable -2% underprediction of u_τ (see figure 5-left). The filtered profile of k^+ in figure 5-right shows that good level of energy could still be captured despite the astonishing value of 12 wall units used for the normal- xy discretization. Even though the profile of k^+ is somewhat irregular in the region of the peak, its amplitude is only underestimated by -11% with a shape captured at a scale evidently smaller than the minimum scale of accuracy $4\Delta x^+ = 48$. In the outer layer, the agreement with filtered DNS is almost perfect. The same cannot be said about the no-model LES for which both mean velocity and kinetic energy profiles are completely unrealistic when such a coarse mesh resolution is used. Based on these observations, it can be concluded that the present implicit SGS modelling has also a feature of implicit wall-layer model through its ability to restore the quality of the wall friction from +24% to -2% while enabling realistic prediction of the fluctuating velocity profiles. Note however that for the present Low Resolution, near-wall turbulent statistics are subjected to errors related to the azimuthal loca-

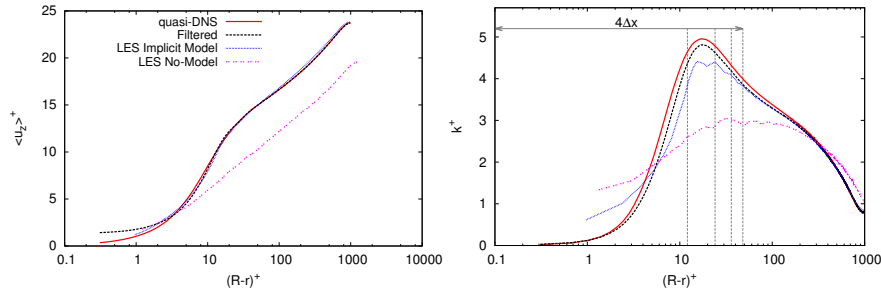


Fig. 5 Mean velocity profile (left) and Reynolds stresses profiles (right) for the low resolution ILES at $Re_\tau = 1000$. Results are compared to: no-model LES, unfiltered and filtered quasi-DNS statistics.

tion of the nodes, especially those close to the cardinal points. These errors, due to the immersed boundary technique, tend to compensate each-other leading to the acceptable k^+ profile presented in figure 5-right. A development is under progress to remove these immersed boundary artefacts making a room for further improvement of the present implicit wall-layer modelling.

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