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Spectrally-consistent regularization modeling of turbulent natural convection flows

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Abstract. The incompressible Navier-Stokes equations constitute an excellent mathematical modeling of turbulence. Unfortunately, attempts at performing direct simulations are limited to relatively low-Reynolds numbers because of the almost numberless small scales produced by the non-linear convective term. Alternatively, a dynamically less complex formulation is proposed here. Namely, regularizations of the Navier-Stokes equations that preserve the symmetry and conservation properties exactly. To do so, both convective and diffusive terms are altered in the same vein. In this way, the convective production of small scales is effectively restrained whereas the modified diffusive term introduces a hyperviscosity effect and consequently enhances the destruction of small scales. In practice, the only additional ingredient is a self-adjoint linear filter whose local filter length is determined from the requirement that vortex-stretching must stop at the smallest grid scale. In the present work, the performance of the above-mentioned recent improvements is assessed through application to turbulent natural convection flows by means of comparison with DNS reference data.

1. Introduction

The incompressible Navier-Stokes (NS) equations form an excellent mathematical model for turbulent flows. In primitive variables they read

$$\partial_t u + C(u, u) = D u - \nabla p; \quad \nabla \cdot u = 0,$$

where $u$ denotes the velocity field, $p$ represents the pressure, the non-linear convective term is defined by $C(u, v) = (u \cdot \nabla) v$, and the diffusive term reads $D u = \nu \Delta u$, where $\nu$ is the kinematic viscosity. Preserving the symmetries of the continuous differential operators when discretizing them has been shown to be a very suitable approach for direct numerical simulation (DNS) (see [1][2][3], for instance). However, DNSs at high Reynolds numbers are not feasible because the convective term produces far too many relevant scales of motion. In the quest for a dynamically less complex formulation we consider regularizations [4][5][6] of the non-linearity that preserve the symmetry and conservation properties [7]. In this way, the convective production of small scales is effectively restrained in an unconditionally stable manner. In previous works, we restricted ourselves to the $C_4$ approximation: the convective term in the NS equations (1) is replaced by the following $O(\epsilon^4)$-accurate approximation $C_4(u, v) = C(\pi, \pi) + C(\pi, \pi') + C(\pi', \pi)$, where the
prime indicates the residual of the filter, e.g., \( u' = u - \overline{u} \), which can be explicitly evaluated, and \((\cdot)\) represents a self-adjoint linear filter with filter length \( \epsilon \). Therefore, the governing equations result to

\[
\partial_t u_e + C_4(u_e, u_e) = D u_e - \nabla p_e; \quad \nabla \cdot u_e = 0,
\]

where the variable names are changed from \( u \) and \( p \) to \( u_e \) and \( p_e \), respectively, to stress that the solution of (2) differs from that of (1). Note that the \( C_4 \) approximation is also a skew-symmetric operator like the original convective operator. Hence, the same inviscid invariants than the original NS equations are preserved.

The numerical algorithm used to solve the governing equations preserves the symmetries and conservation properties too. Then, the only additional ingredient is a self-adjoint linear filter [8] whose local filter length is determined from the requirement that the vortex-stretching must stop at the smallest grid scale [9]. The method has already been successfully tested for a variety of configurations [7, 9]. However, two main drawbacks have been observed: (i) due to the energy conservation, the model tends to display an additional hump in the tail of the spectrum and (ii) for very coarse meshes the damping factor can eventually take very small values. These two issues are addressed in the next section.

### 2. Restoring the Galilean invariance: hyperviscosity effect

The \( C_4 \) regularization preserves all the invariant transformations of the original NS equations, except the Galilean transformation. This usual feature of regularizations [10] can be repaired by means of a proper modification of the time-derivative term. With this idea in mind, and following the same principles than in [7], new regularizations have been recently proposed in [11]. They can be viewed as a generalization of the regularizations proposed in [7] where the Galilean invariance is partially recovered by means of a modification of the diffusive term. Shortly, by imposing all the symmetries and conservation properties of the original convective operator, \( C(u, u) \), and canceling the second-order terms leads to the following one-parameter \( O(\epsilon^4) \)-regularization

\[
C_4(u, v) = \frac{1}{2}((C_4 + C_6) + \gamma(C_4 - C_6))(u, v).
\]

Notice that for \( \gamma = 1 \) and \( \gamma = -1 \), \( C_4 \) becomes respectively the \( C_4 \) and \( C_6 \) approximations

\[
C_4(u, v) = C(\overline{u}, \overline{v}) + C(\overline{u}, \overline{v}'), + C(u', \overline{v}), \quad C_6(u, v) = C(\overline{u}, \overline{v}) + C(u, \overline{v}') + C(u', \overline{v}'),
\]

proposed in [7]. Then, to restore the Galilean invariance we need to replace the time-derivative, \( \partial_t u_e \), by the following fourth-order approximation: \( (\partial_t)''_4 u_e = \partial_t (u_e - 1/2(1 + \gamma)u''_e) = G^4_4(\partial_t u_e) \), where \( G^4_4(\phi) = \phi - 1/2(1 + \gamma)\phi'' \). In this case, the new set of PDEs reads

\[
(\partial_t)''_4 u_e + C_4^2(u_e, u_e) = D u_e - \nabla p_e; \quad \nabla \cdot u_e = 0.
\]

Therefore, the Galilean invariance might be restored by simply setting \( \gamma = -1 \). However, this approach suffers from several practical drawbacks [11]. Another possibility relies on modifying appropriately other terms, e.g. viscous dissipation. The energy equation for (5) becomes

\[
\frac{d}{dt} \|u_e\|^2 - 1/2(1 + \gamma)\|u''_e\|^2 = (u_e, D u_e) < 0,
\]

provided that the filter is self-adjoint, \( \|u\|^2 = (u, u) \), and the innerproduct of functions is defined in the usual way: \( (a, b) = \int_\Omega a \cdot b d\Omega \). Therefore, the modification of time-derivative term (6) constitutes a dissipation model. Recalling that \( (G^4_4)^{-1}(\phi) \approx 2\phi - G^4_4(\phi) + O(\epsilon^6) \), we can obtain an energetically almost equivalent set of equations by modifying the diffusive term

\[
(\partial_t u_e + C_4^2(u_e, u_e) = D_4^1 u_e - \nabla p_e \quad \text{where} \quad D_4^1 u = D u + 1/2(1 + \gamma)(D u')'.
\]
In this way, we are reinforcing the dissipation by means of a hyperviscosity term, 1/2(1+γ)(Du')'.
As expected, this basically acts at the tail of the energy spectrum and therefore helps to mitigate
the two above-mentioned drawbacks of the original C₄ regularization. Then, to apply the method
two parameters still need to be determined; namely, the local filter length, ε, and the constant γ.
Hereafter this method is referred as {CD}₄ regularization.

3. Restraining the production of small scales of motion

3.1. Interscale interactions

To study the interscale interactions in more detail, we continue in the spectral space. The
spectral representation of the convective term in the NS equations is given by

$$ C(u, u)_k = i\Pi(k) \sum_{p+q=k} \hat{u}_p \hat{q} \hat{q}_q, $$

where Π(k) = 1 - kk²/|k|² denotes the projector onto divergence-free velocity fields in the spectral space. Taking the Fourier transform of (8), we obtain the evolution of each Fourier-mode \( \hat{u}_k(t) \) of \( u(t) \) for the \{CD\}₄ approximation

$$ \left( \frac{d}{dt} + h^2_4(\hat{g}_k)\nu|k|^2 \right) \hat{u}_k + i\Pi(k) \sum_{p+q=k} f^4_4(\hat{g}_k, \hat{g}_p, \hat{g}_q) \hat{u}_p \hat{q} \hat{q}_q = F_k, \tag{9} $$

where \( \hat{g}_k \) denotes the k-th Fourier-mode of the kernel of the convolution filter, \( \overline{\hat{u}}_k = \hat{g}_k \hat{u}_k \). The mode \( \hat{u}_k \) interacts with modes whose wavevectors \( p \) and \( q \) form a triangle, i.e. \( k = p + q \). Thus, every triad interaction and the k-th mode of the diffusive term are respectively multiplied by

$$ f^4_4(\hat{g}_k, \hat{g}_p, \hat{g}_q) = (\gamma f_4 + (1 - \gamma)f_6)(\hat{g}_k, \hat{g}_p, \hat{g}_q) \quad \text{and} \quad h^2_4(\hat{g}_k) = 1 + \gamma(1 - \hat{g}_k)^2, \tag{10} $$

where \( \gamma = 1/2(1 + \gamma) \), \( f_4(\hat{g}_k, \hat{g}_p, \hat{g}_q) = \hat{g}_k(\hat{g}_p + \hat{g}_q) + \hat{g}_p\hat{g}_q - 2\hat{g}_k\hat{g}_p\hat{g}_q \) and \( f_6(\hat{g}_k, \hat{g}_p, \hat{g}_q) = 1 - (1 - \hat{g}_k)(1 - \hat{g}_p)(1 - \hat{g}_q) \), where 0 < \( f_n \) ≤ 1 (n = 4, 6) and \( h^2_4 \geq 1 \).

3.2. Stopping the vortex-stretching mechanism

Taking the curl of Eq. (5) leads to

$$ \partial_t \omega + C^4_4(u, \omega) = C^4_4(\omega, u) + D^4_4\omega. \tag{11} $$

This equation resembles the vorticity equation that results from the NS equations: the only difference is that \( C \) and \( D \) are replaced by their regularizations \( C^4_4 \) and \( D^4_4 \), respectively. Left-multiplying the vorticity transport Eq. (11) by \( \omega \), we can obtain the evolution of \( |\omega|^2 \). In this way, the vortex-stretching and dissipation term contributions to \( \partial_t |\omega|^2 \) result to \( \omega \cdot C^4_4(\omega, u) \) and \( \omega \cdot D^4_4\omega \), respectively. In order to prevent the local intensification of vorticity, dissipation must dominate the vortex-stretching term contribution at the smallest grid scale, \( k_c = \pi/h \). In spectral space, this requirement leads to the following inequality

$$ \frac{\hat{\omega}_{k_c} \cdot C^4_4(\omega, u)_{k_c} + C^4_4(\omega, u)_{k_c} \cdot \hat{\omega}_{k_c}^*}{2\hat{\omega}_{k_c} \cdot \hat{\omega}_{k_c}^*} \leq h^4_4(\hat{g}_k) \nu k_c^2, \tag{12} $$

where the vortex-stretching term is given by \( C^4_4(\omega, u)_{k_c} = \sum_{p+q=k_c} f^4_4(\hat{g}_{k_c}, \hat{g}_p, \hat{g}_q) \hat{\omega}_p i \hat{q} \hat{q}_q \). Note that \( f^4_4(\hat{g}_{k_c}, \hat{g}_p, \hat{g}_q) \) depends on the filter length \( \epsilon \) and, in general, on the wavevectors \( p \) and \( q = k_c - p \). This makes very difficult to control the damping effect because \( f^4_4 \) cannot be taken out of the summation. To avoid this, filters should be constructed from the requirement that the damping effect of all the triadic interactions at the smallest scale must be virtually independent of the interacting pairs, i.e.

$$ f^4_4(\hat{g}_{k_c}, \hat{g}_p, \hat{g}_q) \approx f^4_4(\hat{g}_{k_c}). \tag{13} $$

1 Hereafter, for simplicity, the subindex \( \epsilon \) is dropped.
This is a crucial property to control the subtle balance between convection and diffusion in order to stop the vortex-stretching mechanism. This point was addressed in detail in [8]. Then, the overall damping effect at the smallest grid scale, $H_4(\tilde{g}_{k_e}) = \int_\Omega (\tilde{g}_{k_e})/h_4^4(\tilde{g}_{k_e})$, follows straightforwardly (with the condition that $0 < H_4(\tilde{g}_{k_e}) \leq 1$)

$$H_4(\tilde{g}_{k_e}) = \frac{2\nu k^2 \omega_{k_e} \cdot \hat{\omega}_{k_e}}{\omega_{k_e} \cdot C(\omega, u)_{k_e} + C(\omega, u)_{k_e} \cdot \hat{\omega}_{k_e}}. \quad (14)$$

3.3. From spectral to physical space

In the previous subsection we applied our analysis on a spectral space. However, the method needs to be applied on a physical domain in $\mathbb{R}^3$. To that end, here we propose to express the overall damping effect, $H_4(\tilde{g}_{k_e})$, as a function of the invariants of the strain tensor, $S(u) = 1/2(\nabla u + \nabla u^T)$. Recalling that the velocity field, $u$, is solenoidal ($\nabla \cdot u = 0$); $tr(S) = 0$ and the characteristic equation of $S$ reads $\lambda^3 + Q \lambda + R = 0$, where $R = -1/3tr(S^3) = -det(S) = -\lambda_1\lambda_2\lambda_3$ and $Q = -1/2tr(S^2) = -1/2(\lambda_2^2 + \lambda_3^2 + \lambda_3^2)$ are the invariants of $S$, respectively. We order the eigenvalues of $S$ by $\lambda_1 \leq \lambda_2 \leq \lambda_3$. Let us now consider an arbitrary part of the flow domain $\Omega$ with periodic boundary conditions. The innerproduct is defined in the usual way: $(a, b) = \int_\Omega a \cdot bd\Omega$. Then, taking the $L^2$ innerproduct of (11) with $-\Delta u$ leads to the enstrophy equation

$$\frac{1}{2} \frac{d}{dt} ||\omega||^2 = (\omega, C(\omega, u)) - \nu (\nabla \omega, \nabla \omega), \quad (15)$$

where $||\omega||^2 = (\omega, \omega)$ and the convective term contribution $(C(\omega, \omega), \omega) = 0$ vanishes because of the skew-symmetry of the convective operator. Using the results obtained in [12] and following the same arguments than in [13], it can be shown that the vortex-stretching term can be expressed in terms of the invariant $R$ of $S(u)$

$$(\omega, C(\omega, u)) = -\frac{4}{3} \int_\Omega tr(S^3)d\Omega = 4 \int_\Omega Rd\Omega = 4\tilde{R}, \quad (16)$$

whereas the diffusive terms may be bounded in terms of the invariant $Q$

$$(\nabla \omega, \nabla \omega) = -(\omega, \Delta \omega) \leq -\lambda_\Delta (\omega, \omega) = 4\lambda_\Delta \int_\Omega Qd\Omega = 4\lambda_\Delta \tilde{Q}, \quad (17)$$

where $\lambda_\Delta < 0$ is the largest (smallest in absolute value) non-zero eigenvalue of the Laplacian operator $\Delta$ on $\Omega$ and $\tilde{\cdot}$ denotes the integral over $\Omega$ (top-hat filter). This approach was proposed in [13]. However, since it provides an upper bound it requires an accurate estimation of $\lambda_\Delta$ on $\Omega$. The latter may be cumbersome on unstructured grids. Alternatively, it may be (numerically) computed directly from $(\nabla \omega, \nabla \omega)$ or, even easier, by simply noticing that $(\nabla \omega, \nabla \omega) = \int_\Omega Q(\omega)d\Omega = 4\tilde{Q}$. However, from a numerical point-of-view, this type of integrations are not straightforward. Instead, recalling that $\nabla \times \nabla \times u = \nabla(\nabla \cdot u) - \Delta u$ and $\nabla \cdot u = 0$, a more appropriate expression can be obtained as follows

$$(\nabla \omega, \nabla \omega) = -(\omega, \Delta \omega) = (\omega, \nabla \times \nabla \times \omega) = (\nabla \times \omega, \nabla \times \omega) = (\Delta u, u) = ||\Delta u||^2. \quad (18)$$

Then, to prevent a local intensification of vorticity, i.e. $||\omega||_t \leq 0$, the inequality $H_4(\tilde{g}_{k_e}) \leq \nu(\Delta u, \Delta u)/(\omega, S\omega)$ must be satisfied. This inequality is the analog to Eq. (14) in physical space. Additionally, the dynamics of large scales should not be significantly affected by the (small) scales contained within the domain $\Omega$, i.e. $(\omega, S\omega) < 0$. Hence, to confine the dynamics of small scales suffices to modify the previous inequality by simply taking the absolute value of its
right-hand-side. Then, from Eq. (16) and recalling that $0 < H_4(\hat{g}_c) \leq 1$, a proper definition of the overall damping factor at the smallest grid scale follows

$$H_4(\hat{g}_c) = \min \left\{ \nu \left\| \Delta u \right\|^2 / |\vec{R}|, 1 \right\}. \quad (19)$$

An interesting feature of this model is that it automatically switches off ($R \to 0$) for laminar flows (no vortex-stretching) and 2D flows ($\lambda_2 = 0 \to R = 0$). The near-wall behavior of the invariants is given by $R \propto y^1$ and $Q \propto y^0$, respectively, where $y$ is the distance to the wall. Consequently, it results into a model that switches off in the wall.

4. Performance of $C_4$-regularization for a turbulent differentially heated cavity

The configuration adopted to illustrate the performance of the $C_4$-regularization method for turbulent natural convection flows corresponds to an air-filled (Pr = 0.7) differentially heated cavity (DHC) of aspect ratio 5 and Rayleigh number $Ra = 4.5 \times 10^{10}$ (based on the cavity height, $L_3$). Apart from this, the $C_4$ method has also been successfully tested for other natural convection configuration. Examples of thereof can be found in [9, 14]. The DNS corresponding to this configuration was carried out on the MareNostrum supercomputer using a $128 \times 318 \times 862$ mesh (the coordinate system is: $x_1$-spanwise, $x_2$-horizontal and $x_3$-vertical, respectively) and presented in [15]. Firstly, we have considered two coarse meshes consisting of $8 \times 14 \times 38$ (RM2) and $8 \times 20 \times 54$ (RM1) grid points, respectively (see Table 1). The meshes are constructed keeping the same grid points distribution as for the DNS but with much coarser spatial resolution. $\gamma_2$ and $\gamma_3$ are the concentration parameters in the horizontal and vertical directions, respectively (for further details about the mesh generation the reader is referred to [9]). Notice that for the coarsest mesh (RM2) the concentration parameter in the $x_2$-direction has been slightly modified in order to increase the grid resolution near the vertical walls. The domain size in the periodic direction is the same as for the DNS, i.e. $L_1/L_2 = 0.1$. In Table 1 the overall Nusselt number, $Nu$, together with the maximum and minimum local Nusselt numbers obtained with the coarse meshes RM1 and RM2 are compared with the DNS reference solution. Regarding the $Nu$, $C_4$ solutions are able to provide good predictions whereas the results obtained with the same meshes but without any modeling are very far from the reference value $Nu = 154.5$. With regard to $Nu_{max}$ and $Nu_{min}$, this tendency becomes even more evident. These two quantities are of interest because they occur in two clearly different parts of the vertical boundary layer. Maximum values occur in the upstream part of the boundary layer where it is still almost laminar whereas minimum values are observed at the most downstream part of the boundary layer where it has become fully turbulent (see Figure 1 right). In order to confirm the reliability of the model on coarse grids, the same DHC problem has been solved on a series of 50 randomly generated meshes where the number of grid points varies within the limits: $8 \leq N_1 \leq 12,$

**Figure 1.** DHC schema (left) and instantaneous isotherms corresponding to the DNS simulation (right).
Table 1. The overall, the maximum and the minimum of the averaged Nusselt number.

<table>
<thead>
<tr>
<th>Mesh</th>
<th>DNS</th>
<th>RM1</th>
<th>RM2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>128×318×862</td>
<td>8×20×54</td>
<td>8×14×38</td>
</tr>
<tr>
<td>γ2 = 2.0, γ3 = 0.0</td>
<td>154.5</td>
<td>223.8</td>
<td>153.4</td>
</tr>
<tr>
<td>γ2 = 2.0, γ3 = 1.0</td>
<td>781.5</td>
<td>520.6</td>
<td>500.4</td>
</tr>
<tr>
<td>γ2 = 2.3, γ3 = 1.0</td>
<td>10.5</td>
<td>60.4</td>
<td>71.0</td>
</tr>
</tbody>
</table>

Figure 2. Left: The overall Nusselt number and the centerline stratification. Right: The maximum vertical velocity and the wall shear stress scaled by $Ra^{-1/4}$ at the horizontal mid-height plane.

16 ≤ $N_2$ ≤ 28 and 44 ≤ $N_3$ ≤ 70, respectively. The concentration parameters, γ2 and γ3 are the same than those used for the mesh RM1 (see Table 1). The number of grid points in each direction has been randomly generated irrespectively of the number of points in the other two directions; therefore, some of the numerical experiments correspond to highly skewed meshes. Results for the overall Nusselt and the centerline stratification are displayed in Figure 2 (left). The very good prediction of $Nu$ for all the tested configurations is remarkable; in contrast, the results obtained without modeling substantially differ from the reference solution. Even more important is the fairly good prediction of the stratification. Notice the inaccuracy of the results obtained with a relatively fine mesh of 32×80×216 (MeshC) grid points. Similar behavior is observed in Figure 2 (right) where the results for the maximum vertical velocity and the wall shear stress at the horizontal mid-plane, $x_3 = 0.5$, are displayed. These two quantities provide valuable information about whether the boundary layer is correctly captured by the model. The $C_4$ solutions predict quite well the (0.430, 0.227) reference solution whereas both quantities are clearly under-predicted when the model is switched off. This behavior can also be observed in the averaged vertical velocity profile displayed in Figure 3 (left). For the results obtained without modeling, the vertical boundary layer is too thick, whereas with the $C_4$ regularization, the solutions obtained with the meshes RM1 and RM2 agree well with the DNS solution. It is noticeable that even for a relatively fine mesh results without model are still far from the reference solution. Figure 3 (right) depicts essentially the same for the averaged temperature.

5. Concluding remarks and future research
Since DNSs simulations are not feasible for real-world applications the $\{CD\}_4$-regularization of the NS equations has been proposed as a simulation shortcut: the convective and diffusive operators in the NS equations (1) are replaced by the $O(\epsilon^4)$-accurate smooth approximation given by Eq. (3) and Eq. (8), respectively. The symmetries and conservation properties of the original convective term are exactly preserved. Doing so, the production of smaller and smaller scales of motion is restrained in an unconditionally stable manner. In this way, the new set
of equations is dynamically less complex than the original NS equations, and therefore more amenable to be numerically solved. The only additional ingredient is a self-adjoint linear filter whose local filter length is determined from the requirement that vortex-stretching must be stopped at the scale set by the grid. This can be easily satisfied in spectral space via Eq.\[13\] provided that discrete filter satisfies Eq.\[13\], i.e. the triadic interactions at the smallest scale are virtually independent of the interacting pairs. This was addressed in detail in [8]. However, in physical space it becomes more cumbersome. To circumvent this, here a criterion based on the invariants of the strain tensor is used. Doing so, the expected behavior of a turbulence model is achieved: it switches off (i.e. $H_4 = 1$) for laminar flows (no vortex-stretching), 2D flows ($R = 0$) and near the walls. In the present paper, the proposed method has been successfully tested for the inertial range for a classical Kolmogorov energy spectrum\[8\].

5.1. Connections between regularization and large-eddy simulation (LES)

Although formally derived from different principles, regularization and LES equations share many features and objectives. Both approaches aim to reduce the dynamical complexity of the original NS equations resulting into a new set of PDE that are more amenable to be numerically solved. The only additional ingredient is a self-adjoint linear filter whose local filter length is determined from the requirement that vortex-stretching must be stopped at the scale set by the grid. This can be easily satisfied in spectral space via Eq.(14) provided that discrete filter satisfies Eq.(13), i.e. the triadic interactions at the smallest scale are virtually independent of the interacting pairs. This was addressed in detail in [8]. However, in physical space it becomes more cumbersome. To circumvent this, here a criterion based on the invariants of the strain tensor is used. Doing so, the expected behavior of a turbulence model is achieved: it switches off (i.e. $H_4 = 1$) for laminar flows (no vortex-stretching), 2D flows ($R = 0$) and near the walls. In the present paper, the proposed method has been successfully tested for a turbulent DHC with $\gamma = 0$ of Eq.[5]. However, this is not the optimal value of $\gamma$. This may be determined by means of a trial-and-error numerical procedure. Alternatively, the constant $\gamma$ can be approximately bounded by assuming that the smallest grid scale, $k_c = \pi/h$, lies within the inertial range for a classical Kolmogorov energy spectrum $E(k) = C_K\epsilon^{2/3}k^{-5/3}$. Doing so, the bound $\tilde{\gamma} \gtrsim 4(8C_K^{-3/2} - 1)$ where $\tilde{\gamma} = 1/2(1 + \gamma)$ and $C_K$ is the Kolmogorov constant was determined in [16]. Preliminary simulations for homogeneous isotropic turbulence presented in [16] seems to point towards the adequacy of this bound. To confirm this result for a broader variety of test-cases is part of our future research plans.
This analysis can be extended further for other differential operators. For instance, \( \tau'(\vec{v}) = 2\nu' S(\Delta \vec{v}) \) and \( \tau''(\vec{v}) = -2\nu'' S(\Delta^2 \vec{v}) \), where \( \Delta^2 \equiv \Delta \Delta \) is the bi-Laplacian operator, would lead to the following hyperviscosity terms in the enstrophy equation

\[
- (\nabla \vec{v}, \nu' \nabla \Delta \vec{v}) \quad \text{and} \quad (\nabla \vec{v}, \nu'' \nabla \Delta^2 \vec{v}),
\]

respectively. Then, following similar reasonings, the values of \( \nu' \), \( \nu'' \) follow

\[
\nu' = \max \left\{ \frac{| \hat{R} | - \nu \| \Delta \vec{v} \| ^2}{- (\Delta \vec{v}, \Delta^2 \vec{v})}, 0 \right\} \quad \text{and} \quad \nu'' = \max \left\{ \frac{| \hat{R} | - \nu \| \Delta \vec{v} \| ^2}{\| \Delta^2 \vec{v} \|^2}, 0 \right\}.
\]

Notice that only \( \nu \) has dimensions of viscosity. Hence, three eddy-viscosity-type LES models have been obtained by simply considering the balance between the vortex-stretching and the dissipation term in the enstrophy equation \([13]\). Namely, (i) \( \tau'(\vec{v}) = -2\nu S(\vec{v}) \), (ii) \( \tau''(\vec{v}) = 2\nu' S(\Delta \vec{v}) \) and (iii) \( \tau''(\vec{v}) = -2\nu'' S(\Delta^2 \vec{v}) \), where \( \nu', \nu'' \) are given by Eqs. \((21)\) and \((23)\), respectively. The models switch off \((R \rightarrow 0)\) for laminar (no vortex-stretching), 2D flows \((\lambda_2 \rightarrow 0 \rightarrow R = 0)\) and near the wall \((R \propto y^+)^1\).

The above described models can be related with already existing LES approaches. Firstly, the model (i) is almost the same as the recently proposed \(QR\)-model \([13]\). Essentially, they only differ on the calculation of the diffusive contribution to the enstrophy equation: instead of making use of equality \([18]\) it is bounded by means of the inequality \([17]\), therefore, the turbulent viscosity is given by \( \nu \propto \lambda^1_{\Delta} | \hat{R} | / \hat{Q} \) instead of Eq. \((21)\). Regarding the models (ii) and (iii) they can be respectively related to the well-known small-large and small-small variational multiscale methods \([17]\) by simply noticing that \( u' = -(\epsilon^2/24)\Delta u + \mathcal{O}(\epsilon^4) \) (see \([18]\), for instance). Similar arguments can be used to relate the regularization models given by Eq. \((8)\) and \( \gamma > 0 \) with the “small-small”-type eddy-viscosity model \( \tau''(\vec{v}) = -2\nu'' S(\Delta^2 \vec{v}) \) and \( \nu'' \) given by Eq. \((23)\). To test the performance of these new turbulence models are also part of our future research plans.

Acknowledgments

This work has been financially supported by the Ministerio de Ciencia e Innovación, Spain (ENE2010-17801) and a Juan de la Cierva postdoctoral contract (JCI-2009-04910) by the Ministerio de Ciencia e Innovación. Calculations have been performed on the IBM MareNostrum supercomputer at the Barcelona Supercomputing Center. The authors thankfully acknowledge these institutions.

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