HYBRID RANS/LES : SPATIAL-RESOLUTION AND ENERGY-TRANSFER ISSUES

P.Batten, U.C.Goldberg, S.Palaniswamy and S.R.Chakravarthy
Metacomp Technologies Inc, 650 Hampshire Rd #200,
Westlake Village, California 91361, USA
info@metacomptech.com

ABSTRACT

This paper considers issues relating to the development of hybrid models of turbulence which blend automatically between conventional unsteady Reynolds-Averaged Navier-Stokes (URANS) simulation and large-eddy simulation (LES), according to the local grid density. Several independent research efforts have already been directed toward locally embedded LES, using both zonal approaches and emerging hybrid methods; the latter attempting to capture the switch between LES and RANS within a single modeling framework. This paper reviews some existing developments in the area and identifies several shared philosophies and common goals, as well as a remaining weakness, concerning the transfer of kinetic-energy between unresolved and resolved components. A framework is introduced in an attempt to account for this missing kinetic-energy transfer.

INTRODUCTION

Reynolds-Averaged Navier-Stokes (RANS) equations and single-point turbulence closures continue to dominate the field of engineering predictions of turbulent flow, both for quasi-steady and unsteady flows. Thus, the same RANS models are often entrusted to the task of returning statistical information from flows which display large-scale unsteadiness. However, experience suggests that this leap of faith in RANS is often not justified. Flows involving large-scale unsteady motion may contain many regions where RANS models operate outside their calibration range. In addition, bulk unsteadiness contributes significantly to the time-averaged Reynolds-stress tensor and it seems rather unlikely that the current generation of turbulence models would be capable of providing a universal description for the averaged effects of these large-scale coherent motions. Conventional RANS models may allow some large-scale motion to be captured as part of a time-dependent simulation, but they tend to give an overly-diffusive response to perturbations on time-scales smaller than that associated with the local state of the turbulence. Whilst DNS and traditional LES remain elusive tools for most practical high-Reynolds number flows, in the last few years there has been a growing realization that unsteady flows may not be best served by a technology such as RANS, which imposes limits on the representation of the flow physics which, beyond some measure, cannot be improved by increased temporal and spatial resolution. Thus, there is a strong motivation to explore alternative, intermediate, modeling frameworks.

Although the concept of near-wall modeling has been employed in LES for many years, one of the earliest suggestions for a genuine hybrid LES/RANS method came from Speziale (1996), who proposed a Reynolds-stress transport model in which components of the stress-tensor would be damped by some function of the local mesh spacing in order to recover an LES-type behavior (with the correct DNS limit) on fine grids. Many aspects of Speziale's approach were incomplete, but it nonetheless provided the first framework for hybrid simulations, linking existing LES and RANS technologies.

Following Speziale's proposals, Wernz and Fasel (2000) continued to perform calculations on boundary-layer flows, in which respectable results were reported using RANS with an unsteady forcing to circumvent the natural tendency to return a statistically steady flow. Spalart et al. (1997,2000) have been pursuing their own hybrid method, termed 'Detached Eddy Simulation' (DES), which is formulated as an elegantly simple modification to the one-equation Spalart-Allmaras (1994) RANS model. In the original DES model, the wall-distance, d, is replaced by $d' =$

$\min(d, C_{DES}\Delta)$, with C_{DES} a model constant and $\Delta = (\Delta x \Delta y \Delta z)^{\frac{1}{3}}$ a measure of the local cell-size (a more recent variant of DES, due to Strelets (2001), is based on Menter's SST model). In fine grid regions, DES elevates the destruction terms in the RANS model and thus progressively erodes the local levels of μ_t. This is a little different to Speziale's (1996) proposal in which the Reynolds-stress tensor is instantly damped in refined-grid regions.

Following the work of Speziale (1996), a hybrid approach, termed 'Limited Numerical Scales' (LNS) was outlined in Batten et al. (2000), in which the Reynolds-stress tensor is damped via:

$$R_{ij} = \alpha R_{ij}(m),$$

where $R_{ij}(m)$ is the stress tensor derived from some RANS model and α is a latency factor, used to 'hide' the decaying, resolvable portion of the turbulence kinetic energy from the mean flow. In the original proposal of Speziale (1996), the eddy-viscosity damping was determined as some function of the Kolmogorov scale - an idea which has more recently been pursued by Peltier et al. (2000) and Arunajatesan and Sinha (2001). However, even if the Kolmogorov length scale could be known precisely in arbitrarily complex strain fields, there is no convincing argument for the use of a length scale which does not relate to any resolvable structures. Batten et al. (2000) therefore proposed an alternative (and parameter-free) definition of α:

$$\alpha = \min(lv_{LES}, lv_{RANS})/lv_{RANS}$$

where lv_{LES} is the product of the length and velocity scales used in the chosen LES model and lv_{RANS} is the product of the (realizable) length and velocity scales used in the chosen RANS model. Given the above definition of α, the LNS model behaves in one of only two modes - LES (if $\alpha < 1$) or RANS (if $\alpha = 1$), thus there are no modifications that necessitate a re-calibration in either of these cases. The physical interpretation of the above is that αk corresponds to unresolved and, indeed, *unresolvable* sub-grid turbulence kinetic energy which must, therefore, be modeled. The quantity $(1 - \alpha)k$ is interpreted as *resolvable* turbulence kinetic energy which could, and should, be represented directly, given the local grid resolution.

On structured grids, the LNS mesh-size estimate, L_Δ, is defined as $2\max[\Delta x, \Delta y, \Delta z]$. Hence, whilst LNS can be made to operate in 'detached-eddy simulation mode' by an appropriate choice of mesh (large-aspect ratio near-wall cells will force local RANS behavior), no special significance is placed on wall proximity and the approach allows either LES or RANS methods to be active in any region, depending upon local grid spacing[1].

Example applications of the original LNS scheme, relating to both inherent and forced unsteadiness are shown in Figures 1 through 4. Figs. 1 and 2 show the eddy-viscosity and sound-pressure levels generated in the wake of a low-speed flow over a square cylinder (Batten et al., 2000). Figs. 3 and 4 show the effect of high-frequency synthetic-jet actuators on the separated flow over an airfoil section (Parekh and Glezer, 2000). These high-frequency disturbances typically present difficulties for conventional unsteady RANS, as unsteadiness tends to be strongly suppressed, often to the point where steady results are generated regardless of the spatial or temporal accuracy employed.

Despite the reported successes with existing hybrid RANS/LES methods, all the hybrid approaches outlined above share a common flaw, namely, that resolvable components of turbulence kinetic energy get discarded (through dissipation at the finest scales), in order to satisfy the reduced eddy-viscosity requirements on a fine grid. In reality this dissipated energy corresponds to longer-wavelength structures which should have been resolved directly on the mesh. An interesting paper by Cannon et al. (2000) presents a useful example. Cannon et al. (2000) used two separate models at an interface upstream of a flame-tube combustor, with an unsteady RANS calculation forming the inlet condition to an LES zone within the combustor. Since no additional transport equations were carried into the LES region, the unresolved turbulence kinetic energy was effectively discarded at the inlet. Fortunately, this error was probably not very significant in the application studied by Cannon et al. (2000), since the downstream flow-field was reported as inherently unsteady and therefore likely to have dominated any effect of the unsteady upstream boundary condition. This rather lucky scenario forms a common pattern for almost all flows solved to date using hybrid RANS/LES models. Regardless of whether equations are actually solved for turbulence kinetic energy

---

[1] NB. Beware of the possible confusion over the name 'Detached Eddy Simulation'! It has been pointed out by Spalart (2000), that DES can itself (according to the mesh spacing) operate in a more general mode than simply a near-wall model for LES.

or total energy, current practice implies unresolved kinetic energy being (incorrectly) converted instantly to thermal energy.

TOWARDS EMBEDDED LES

There are certainly many relevant flow scenarios, such as cavities, base-flows, wakes and massive separations, in which flow unsteadiness is inherently strong and self-sustaining. In these situations, existing RANS/LES hybrid methods may require no further modifications in order to show improved predictions, relative to unsteady RANS calculations. However, a caveat that hinders the general applicability of these hybrid methods, is the uncertainty over correct boundary conditions for the LES 'zone' and the subsequent danger of predicting incorrect (even steady) solutions when no strong, inherently unsteady behavior exists to trigger the quasi-steady incoming RANS-type flow. In the following, one possible framework is explored in an attempt to generalize the hybrid methods.

RANS-to-LES Interface Regions

The need for appropriate upstream boundary conditions in LES or DNS is well recognized (see for example, Druault et al. (1999), Lee et al.(1992) and Kondo et al.(1997)). Druault et al.(1999) show the dramatic effect of different inlet treatments in DNS, with great improvements reported by using a linear stochastic estimation based on few sampled inlet time histories. In a general-purpose hybrid LES/RANS scheme, the 'boundary' or 'interface' to a zone need not comprise a single mesh line, but rather any finite-width domain over which the spatial resolution gradually increases. In general, no experimental or DNS time-history data will be available at RANS/LES interface regions (if this were available, the upstream RANS calculation would be redundant) and therefore the model equations need to account for this energy exchange via some form of stochastic reconstruction or synthesis of the unsteady turbulent field which is being represented, in a statistical sense, by the RANS data. The hybrid model would then shoulder the responsibility of automatically transferring the appropriate fraction of turbulence energy into 'resolved' kinetic energy. The resulting method would not constitute a zonal approach, however, since the same set of equations would be solved throughout the entire domain.

The task of synthesizing turbulence is more complex than the development of the basic (hybrid) transport equations, which require few additional modeling assumptions and, at least in the case of LNS, no additional parameters beyond those appearing in the underlying RANS and LES models. The conversion from statistically-steady to unsteady kinetic energy requires some knowledge of the two-point space-time correlation and since this information is not available from single-point RANS closures, further modeling assumptions are needed. However, a number of interesting developments, very relevant to this problem, have already been made in the areas of particle dispersion and acoustics.

Synthesizing Turbulence

One of the earliest attempts at synthesizing turbulence was a Fourier method proposed by Kraichnan (1969), in which an unsteady velocity field was reconstructed in physical space from isotropic turbulence. More recently, Kraichnan's synthesis of turbulence has been extended and applied to the problem of determining the driving sources for acoustics solvers by Karweit et al.(1991), Bechara (1994), Lafon (1997), Bailly et al.(1996,2000) and Kalitzin et al.(2000). However, these Fourier methods do not yet account for anisotropy or convection effects on the reconstructed field and appear difficult to extend to arbitrary (unstructured) meshes. For that reason, an alternative framework has been pursued by the present authors in the context of acoustics simulations. In this approach, a model system of equations is solved for the reconstructed turbulent velocity components, u_i^t:

$$\frac{\partial \bar{\rho} u_i^t}{\partial t} + \frac{\partial \bar{\rho} u_i^t \bar{u}_j}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\bar{\rho} D_\mu \frac{\partial u_i^t}{\partial x_j}\right) + S_i \quad (1)$$

in which the source terms, S_i, (taken from the work of Zhou and Leschziner (1991)) account for the covariance of the velocity fluctuations and the temporal correlation in the small time-step limit. The diffusion term contains a non-linear, anisotropic coefficient, D_μ, designed to coagulate the synthesized blobs of turbulence, mimicking the effect of the spatial correlation in the limit of small mesh-spacings. An example of an instantaneous perturbation-velocity field reconstruction for a backward-facing step flow is shown in Fig.5, based on turbulence statistics obtained from the non-linear Reynolds-stress closure of Craft and Launder (1996).

The above synthesis allows the local convective fluxes to be augmented by the reconstructed velocity fluctuations. This procedure conserves momentum globally, but introduces perturbations into the mean flow. The time averages of these perturbations will be consistent with the underlying Reynolds-stress tensor, provided this is realizable[2]. The disadvantage is the added complexity and additional transport equations. This has motivated a simpler approach in the present context of hybrid RANS/LES models, in which transport equations are eliminated and only the source terms are retained on the cell faces. A length-scale correction, $l_c = \min(\epsilon C_\Delta / k^{1.5}, 1)$, is instead introduced into the perturbation fluxes in order to satisfy, approximately, the spatial-correlation in the limit of small inter-cell distances.

CHANNEL FLOW EXAMPLE

An example calculation is considered for the case of fully-developed turbulent flow in a channel, with a Reynolds number of 3250, based on the channel half-height and bulk velocity. Periodic boundary conditions were used in the spanwise direction, where 64 points were used to cover the span of $2\pi h/3$, with h the channel height. In the wall-normal direction, 64 points were used, clustered to ensure $y^+ < 1$ for the first off-wall nodes. A total of 128 points were used in the streamwise direction (length $10h$), with an unconventional stretching deliberately imposed to force RANS behavior in the first few, highly stretched cells and LES behavior after the rapid clustering at $x = 2.5$ (see Fig.6). Any resolvable fraction of the turbulence energy, $(1 - \alpha)k$, is converted into perturbations in the convective fluxes (see Figs.7 and 8), whilst the statistically-steady inflow was maintained by recycling the RANS profile in the highly-stretched upstream cells and re-introducing this at the inlet, with a correction for the bulk velocity.

Fig.8 illustrates the spanwise velocity component in the channel, showing the initiation of unsteady motion as the fine grid is encountered. Further investigations are needed to examine the required length of the interface zone and quality of predictions there; these are both expected to depend on the fidelity of the synthesized turbulence. Furthermore, attention needs to be turned to the issue of time averages on the reconstructed fluxes when the convective Courant numbers in the smallest cells become larger than unity, as occurs here because of the quasi-steady treatment of the very near-wall region in combination with an implicit, dual time-stepping scheme. In general, the switch from RANS to LES should depend upon both spatial and temporal resolution.

CONCLUSIONS & FUTURE PROSPECTS

This paper has considered the possibility of generalizing the existing class of hybrid RANS/LES methods to allow LES (and therefore DNS) regions to be embedded within larger, statistically-steady, RANS-type flow fields. Although there is an important class of inherently-unsteady flows for which existing hybrid RANS/LES methods can probably be applied without further modifications, it is naturally tempting to pursue a generalization of these models, which would give a plausible response, regardless of the local spatial and temporal resolution.

Specifically considered here, was the issue of interfacing from RANS to LES. The generation of artificial turbulence, ie., the reconstruction of time-dependent velocity fields from statistical data, is an area in which we expect to see significant future developments which would benefit a number of areas, including traditional LES (with or without wall modeling), hybrid RANS/LES, sprays, particle dispersion and acoustics. A synthesis involving a realistic representation of spatial correlations and coherence is likely to be challenging on arbitrary (unstructured and hybrid) grids, as there is an almost infinite number of properties of the Navier-Stokes equations which will not be satisfied by this artificial turbulence. However, even a crude synthesis of the resolvable turbulence kinetic energy may be preferable to the current practice of discarding it outright.

Acknowledgment

The separation-control simulations (Figs. 3 and 4) were performed in collaboration with Dr. D. Parekh at Georgia Tech. Research Institute.

---

[2] In reality, disturbances to the mean flow must start to alter the target anisotropy tensor.

References

Arunajatesan, S., and Sinha, N., 2001, 'Unified Unsteady RANS-LES Simulations of Cavity Flowfields', AIAA-2001-0516.

Bailly, C., and Juvé, D., 2000, 'Numerical Solution of Acoustic Propagation Problems Using Linearized Euler Equations', AIAA Journal, 38(1):22–29.

Bailly, C., Lafon, P., and Candel, S., 1996, 'Computation of Noise Generation and Propagation for Free and Confined Turbulent Flows', AIAA-1996-1732.

Batten, P., Goldberg, U. C., and Chakravarthy, S. R., 2000, 'Sub-Grid Turbulence Modeling for Unsteady Flow with Acoustic Resonance', AIAA-2000-0473.

Bechara, W., Bailly, C., and Lafon, P., 1994, 'Stochastic Approach to Noise Modeling for Free Turbulent Flows', AIAA Journal, 32(3).

Cannon, S., Smith, C., and Lovett, J., 2000, 'LES Modeling of Combustion Dynamics in a Liquid-Fueled Flametube Combustor', AIAA 2000-3126.

Craft, T. J., and Launder, B. E., 1996, 'A Reynolds Stress Closure Designed for Complex Geometries', Int. J. Heat and Fluid Flow, 17: 245-254.

Druault, P., Lamballais, E., Delville, J., and Bonnet, J-P., 1999, 'Development of Experiment/Simulation Interfaces for Hybrid Turbulent Results Analysis via the use of DNS', TSFP-1, Ed. S.Banerjee and J.K.Eaton.

Kalitzin, G., Kalitzin, N., and Wilde, A., 2000, 'A Factorization Scheme for RANS Turbulence Models and SNGR Predictions of Trailing Edge Noise', AIAA 2000-1982.

Karweit, M., Blanc-Benon, P., Juvé, D., and Comte-Bellot, G., 1991, 'Simulation of the Propagation of an Acoustic Wave Through a Turbulent Velocity Field: A Study of Phase Variance', J.Acoustic Soc.America, 89(1).

Kondo, K., Murakami, S., and Mochida, A., 1997, 'Generation of Velocity Fluctuations for Inflow Boundary Condition of LES', Journal of Wind Engineering and Industrial Aerodynamics, 67:51–65.

Kraichnan, R. H., 1969, 'Diffusion by a Random Velocity Field', Physics of Fluids, 13(1).

Lafon, P., 1997, 'Noise of Confined Flows', VKI Lecture Series on Aeroacoustics and Active Noise Control.

Lee, S., Lele, S., K., and Moin P., 1992, 'Simulation of Spatially Evolving Turbulence and the Applicability of Taylorś Hypothesis in Compressible Flow', Phys. Fluids A., 4(7):1521–1530.

Parekh, D. E., and Glezer, A., 2000, 'AVIA: Adaptive Virtual Aerosurface', AIAA 2000-2474.

Peltier, L. J., Zajaczkowski, F. J., and Wyngaard, J. C., 2000, 'A Hybrid RANS/LES Approach to Large-Eddy Simulation of High-Reynolds-Number Wall-Bounded Turbulence', ASME 2000 Fluids Engineering Division Summer Meeting.

Spalart, P. R., 2000, 'Trends in Turbulence Treatments'. AIAA-2000-2306.

Spalart, P. R., and Allmaras, S., 1994, 'A One Equation Model for Aerodynamic Flows', La Recherche Aerospatiale, 1.

Spalart, P. R., Jou, W-H., Strelets, M., and Allmaras, S., 1997, 'Comments on the Feasibility of LES for Wings and on a Hybrid RANS/LES Approach'. 1st AFOSR Int. Conf. on DNS/LES, Advances in DNS/LES, Eds. C.Liu and Z.Liu, Greyden Press.

Speziale, C. G., 1996, 'Computing Non-Equilibrium Flows with Time-Dependent RANS and VLES', 15th ICNMFD.

Strelets, M., 2001, 'Detached Eddy Simulation of Massively Separated Flows', AIAA 2001-0879.

Wernz, S., and Fasel., H, 2000, 'Control of Separation using Wall Jets - Numerical Investigations using LES and RANS', AIAA-2000-2317.

Zhou, Q., and Leschziner, M. A., 1991, 'A Time-Correlated Stochastic Model for Particle Dispersion in Anisotropic Turbulence', 8th TSF Symposium.

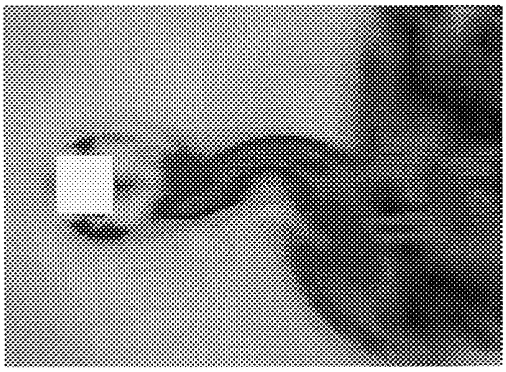

Figure 1: Unresolved component of effective eddy viscosity from LNS simulation of flow in a square-cylinder wake

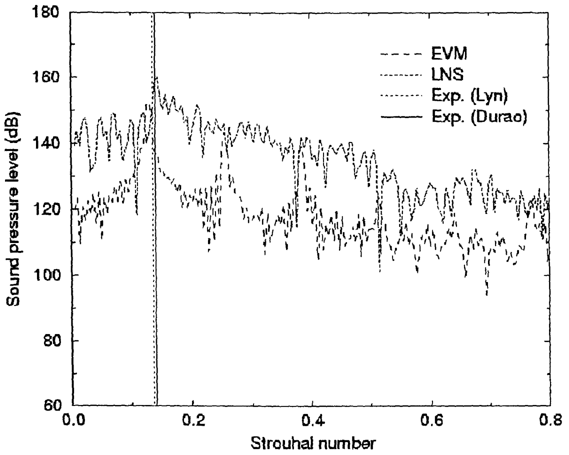

Figure 2: Predicted sound pressure levels for the square cylinder wake

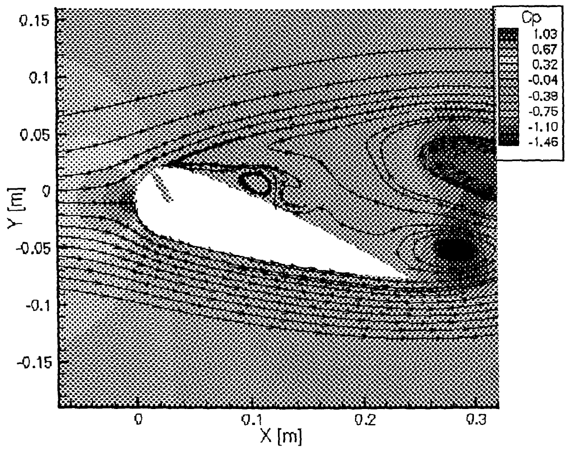

Figure 3: LNS simulation of synthetic-jet control with actuators off

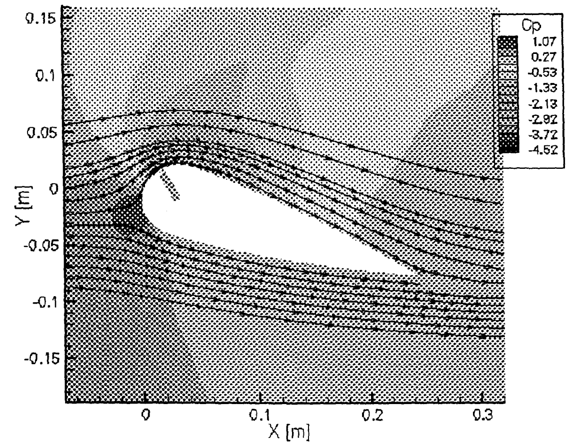

Figure 4: LNS simulation of synthetic-jet control with actuators on

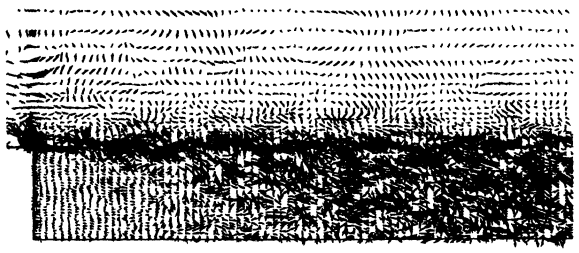

Figure 5: 'Synthesized' turbulent velocity perturbations over a backstep

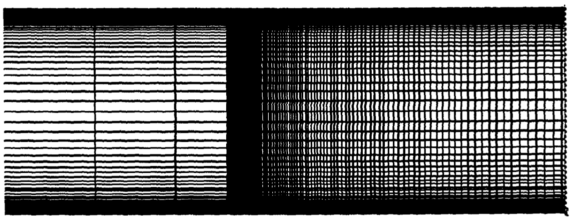

Figure 6: Spanwise-cut through a section of the 3D channel grid showing the rapid clustering at x=2.5

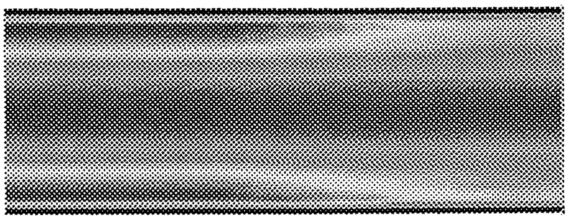

Figure 7: Decay of the unresolved turbulence energy at the x=2.5 region

Figure 8: Development of spanwise velocity showing initiation of unsteady motion in refined-grid region