Large Eddy Simulation of Separation from Continuous Surfaces

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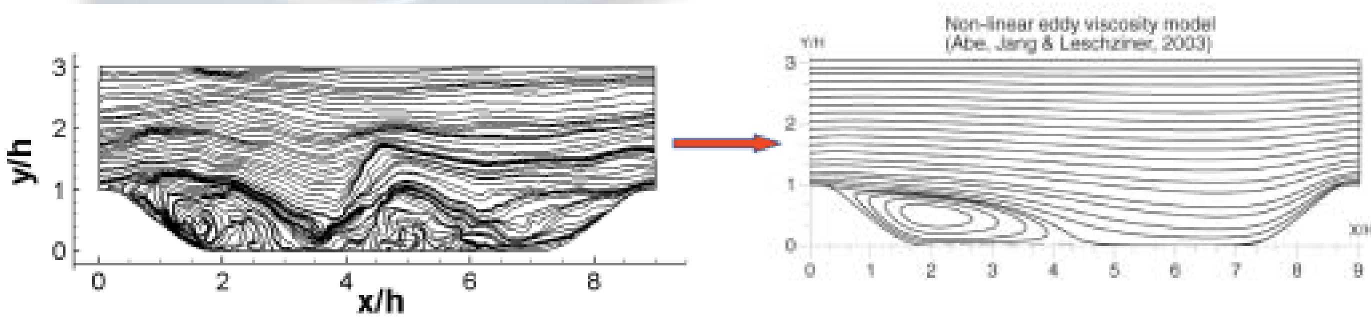
Turbulence is an inherent feature of the large majority of engineering and environmental flows. It stems from inertial instabilities that arise when any fluid is strained at sufficiently high rates – say, by shearing. In simple terms, the motion in a turbulent flow may be thought of as consisting of a mean component with a superimposed field of unsteady, non-repeatable interacting eddies having size and time-scales ratios that span, typically, 3-4 orders of magnitude – that is, the smallest eddies may be as small as 0.01% of the global linear 'dimension' of the flow. The practical importance of turbulence arises from the strong mixing it causes – a process that is central to dispersion, chemical reaction, combustion, frictional losses, drag, and the general behaviour of flows around streamlined and bluff bodies and within passages.

Simulating turbulent flows in realistic conditions is a formidable computational task. It entails the numerical solution of the coupled, non-linear set of (spatially) three-dimensional Navier-Stokes equations that describe the time evolution of the flow of interest over a mesh of nodes, volumes or elements covering the flow domain. Because of the wide range of scales involved, the grids required for most practical flows would need to have of order 10^9-10^{11} nodes to resolve all details, and the extraction of practically important statistical properties would require an integration over 10^6-10^7 time steps. This is not regarded as a tenable approach, either today or in the future.

The alternative route thus taken is one that assimilates all or a part of the unsteady turbulence dynamics into a statistical model. The former option starts with *Reynolds averaging* the Navier Stokes (RANS) equations, to yield equations for the time- or ensemble-mean quantities. A *turbulence model* is then required to determine unknown but crucially important correlations of turbulent velocity fluctuations. The quality of predictions then depends critically on the quality of the turbulence model, and the development of general models is a highly challenging area into which many hundreds of man-years of research have been invested over the past 4 decades (see reference [1]).

The compromise route in which only part of the turbulence is represented statistically is called Large Eddy Simulation (LES). This is based on the notion that all major dynamic effects may be captured by resolving eddies not smaller than about 1% of the relevant global dimension of the flow, while the effects of smaller eddies may be represented by a *subgrid-scale turbulence model*. Although this approach is much more economical than a full-resolving simulation, it is still costly – around 50-100 times higher than computations based on Reynolds-averaged formulations, typically involving 10^6-10^7 nodes and 10^5 time steps and requiring computing times of order 10^4 CPU hours on present multi-processor machines, such as those operated by the CSAR in Manchester, UK.



(a) Simulation

(b) Statistical modelling

Figure 1: Instantaneous and time-averaged view of a flow separating from a duct constriction

While LES allows the unsteady turbulence dynamics to be resolved, extreme events to be captured and the mechanisms leading to particular statistical properties to be understood, it faces a whole range of difficult challenges and limitations in practical conditions, apart from the cost. Thus,

ï LES does not tolerate poor grid quality (high skewness, gradation and aspect ratio) ;

ï LES requires high numerical accuracy, and does not, in particular, tolerate numerical dissipation;

ï LES requires the spectral content of boundary conditions to be specified;

ï The quality of the simulation can depend sensitively on sub-grid modelling, an area far less developed than Reynolds-averaged modelling;

ï LES is very sensitive to the resolution at walls in conditions in which the gross behaviour of the flow depends on the structure of the wall boundary layer.

The last issue poses a particularly serious problem in many important engineering flows at high Reynolds numbers. As the wall is approached, the large scales progressively diminish in size, eventually approaching the scale at which energy is dissipated by viscous friction. In addition, the near-wall structure is highly anisotropic, characterised (in shear flow) by elongated vortical structures. Hence, the grid supporting the near-wall layer must approach one that would normally be used in a full simulation. The requirement that the grid-aspect ratio be constrained to accommodate the above structural features of the near-wall motions quickly leads to economically untenable grids as the turbulence Reynolds number increases beyond 1000.

A case in point is shown in Figure 2. This is a high-lift aerofoil operating at a chord Reynolds number of 2.1 million and at 13.3° incidence, at which marginal stall sets in on the rear end of the suction side. Apart from the need to capture separation, it is important to resolve the laminar-to-turbulent transition which is clearly visible on the front part of the suction side.

The computation shown in Figure 2 (see reference [2]) encompassed only a spanwise segment of 12% of chord, i.e. a very small portion of a practical wing, but required over 5 million nodes, and still was found not to represent the flow especially well. Here, as in other flows in which

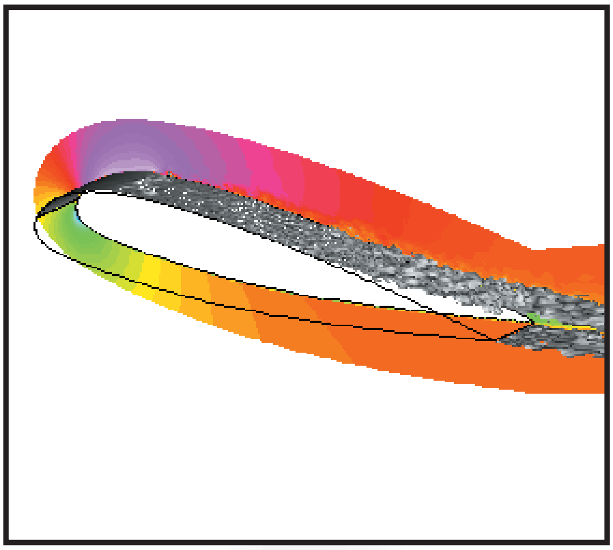


Figure 2: Large Eddy Simulation of a separated flow on a high-lift aerofoil

separation occurs from a continuous curved surface, the challenge is near-wall resolution and the quality with which the thin boundary layer is captured.

Another example is given in Figure 3. This shows the results of three simulations by Temmerman et al [3] with successively fine grids, ranging from 0.6 million to 4.8 million nodes. The sensitivity primarily reflects the resolution of the near-wall region, especially to the location at which the flow separates from the curved surface.

The resolution of separation from three-dimensional curved surfaces is even more demanding than that of the above (statistically) two-dimensional process. Engineering applications in which such separation is of major importance include fuselages, ship hulls and streamlined road vehicles. A generic case is shown in Figure 4. This is the flow around a three-dimensional hill-shaped obstruction in a duct, and the figures convey the flow topology on the hill surface by way of 'skin-friction lines'. Experimental data is available for a Reynolds number which is much too high for the flow to be simulated at acceptable costs, again because of the need to ensure adequate near-wall resolution. Hence, the simulation shown in Figure 4 has been performed at a lower Reynolds number (Temmerman et al [4]). The result shown in Figure 4(a) is a short-time average of the flow, thus conveying the complex turbulent motion in the separated, highly vortical wake, while Figure 4(b) show the statistically (long-time-averaged) state. Figure 4(c) is the result obtained for the same flow conditions with an steady-state RANS

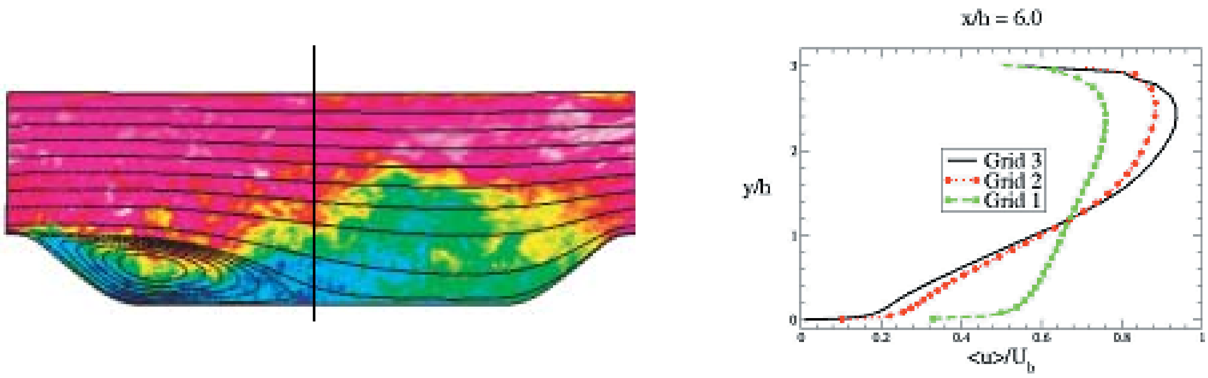
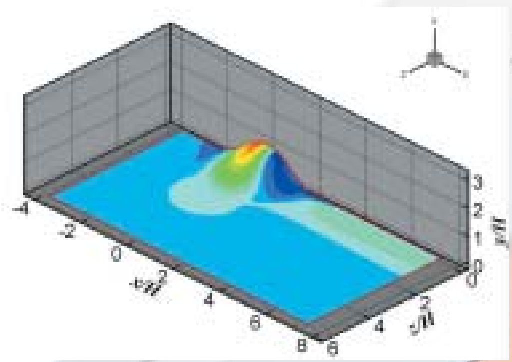
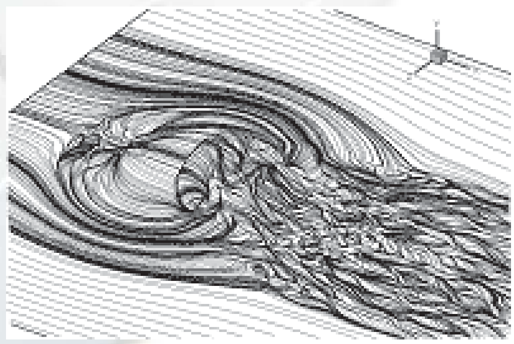


Figure 3: Sensitivity of time-averaged velocity field to grid density in a LES of a separated flow.

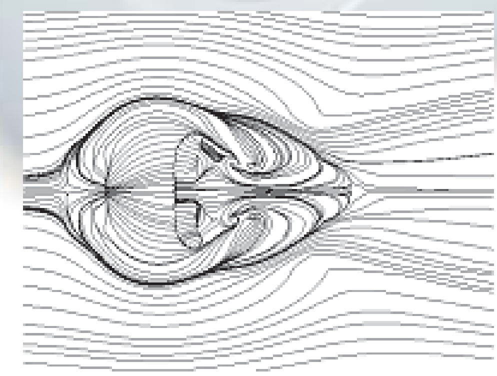
scheme operating in conjunction with an advanced turbulence model based on 'second-moment closure'. This case thus illustrates one important objective pursued by the writers when performing costly simulations, namely to assess the predictive realism obtained with statistical turbulence models that are designed to allow the time-averaged flow to be obtained without the costly computation of the details of the time-dependent turbulence field.



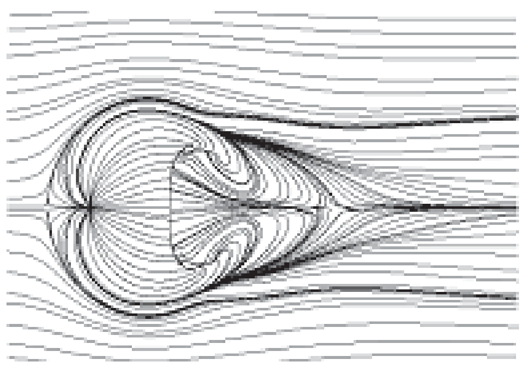
(a) Geometry & pressure contours



(b) LES, short-time average



(c) LES, long-time average



(d) Steady RANS computation

Figure 4: Turbulent separated flow around a three-dimensional 'hill' in a duct – flow topology on hill surface.

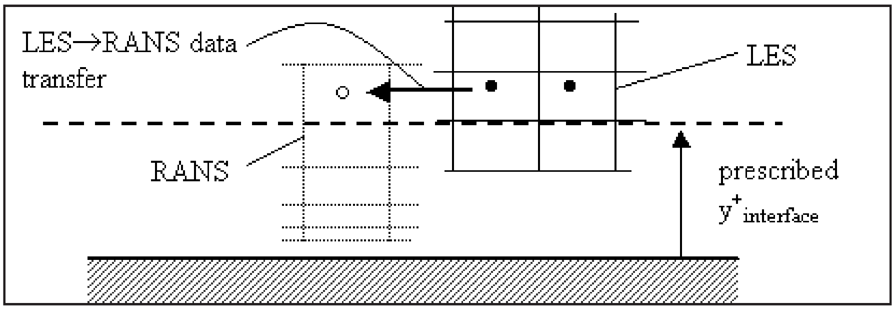


Figure 5: Coupled hybrid RAN-LES strategy.

Against the background of the severe limitations imposed by near-wall turbulence on LES for high Reynolds-number flow in realistic engineering conditions, much research is currently in progress on combining Reynolds-averaging (RANS) in the near-wall region with simulation away from the wall. This idea is rooted in the observation that satisfactory solutions for near-wall flow can be secured with the former strategy even for low-quality grids having very high aspect ratios. The principles of one such an approach – referred to as hybrid RANS-LES – are conveyed in Figure 5.

One crucial issue in this hybrid method is how to achieve compatibility of turbulence-related quantities across the interface, and this is the subject of much debate. As usual, the most challenging environment is one involving separation from continuous surfaces. Thus, Figure 6 shows an application of a hybrid method by Temmerman et al [5] to the flow shown in Figure 3. In this, the RANS-LES interface can be chosen arbitrarily and has here been chosen at grid planes which are well within the turbulent regime. The reference computation, on the l.h.s. of Figure 5 was performed with 5 million nodes, while the grid used for RANS-LES computation contained only 0.6 million nodes. As seen, agreement, although credible, is far from perfect, and further research is in progress in efforts to improve the method.

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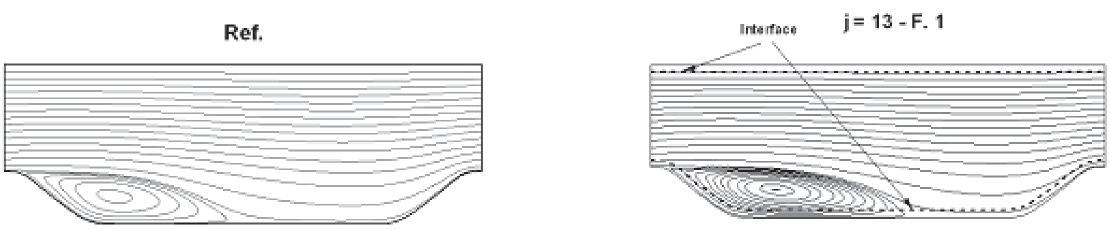

Figure 6: Comparison of solutions obtained with highly-resolved 5-million-node LES (l.h.s.) and under-resolved 0.6-million-node hybrid RANS-LES.