High-resolution simulation of flow separation from curved three-dimensional surfaces

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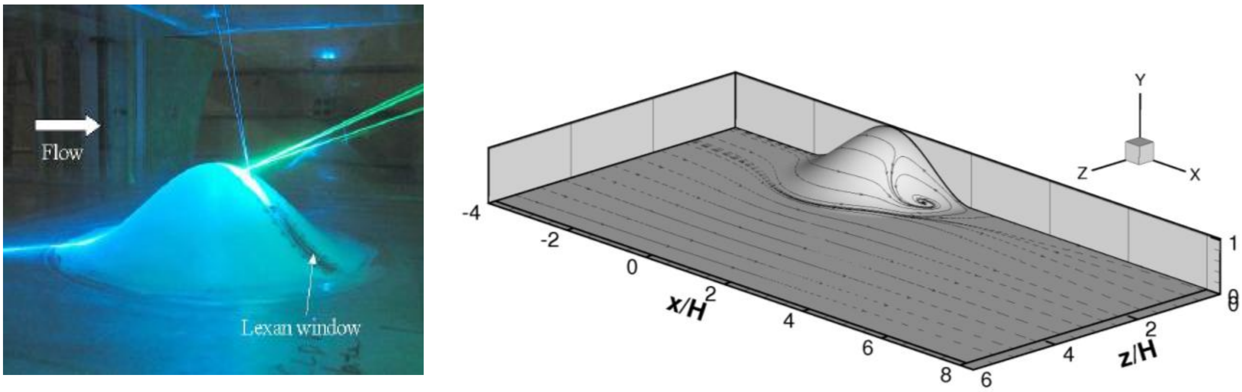
The accurate prediction of turbulent flows separating from curved and otherwise continuous surfaces is one of the most difficult tasks for any computational framework. Among several difficulties, two major ones are the unsteady, spatially varying separation region – usually involving patches of alternately separated and attached flow - and the need to resolve accurately the very thin near-wall layer that contributes greatly to the details of the separation process.

The flow over a three-dimensional, hill-shaped obstacle in a duct contains most generic features encountered in almost all types of three-dimensional separation from continuous, curved surfaces. If the hill is relatively tall, as is the case herein, a closed (time-mean) recirculation bubble arises behind the hill. Moreover, the flow gives rise a variety of complex topological features, such as curved detachment and attachment lines and nodes, focal points and saddles. Large vortical structures are intermittently or periodically shed from the surfaces, resulting in complex wake structure downstream of the obstacles. Such flows are also observed to be sensitive to turbulence in the upstream flow, especially when separation is preceded by a thick turbulent boundary layer, and in the free stream above the boundary layer. All these features pose major challenges to both statistical modelling and time-resolved simulation.



(a) (b)

Fig. 1: Geometry being investigated: (a) experimental arrangement by Simpson et al.; (b) predicted topology on leeward side

The configuration considered here is shown in Fig. 1. This has been the subject of a broad research effort at Imperial College London, with a particular focus on the predictive capabilities of zonal LES-RANS (hybrid) schemes Tessicini et al (2007). It is also a flow that had been observed to be especially poorly predicted by statistical models, even at second-moment-closure level (e.g. Wang et al. (2004)), an observation that has greatly motivated studies of the flow with LES. The Reynolds number, based on hill height and free-stream velocity, is 130000 - a high value for which the viscous wall-layer is of the order of only 0.1% of the hill height. A rich range of experimental data is available, obtained by Simpson et al. (2002) and Byun and Simpson (2005) with elaborate LDA techniques.

Large eddy simulations for this geometry have previously been performed by several groups on relatively coarse grids. These simulations have yielded encouraging results, in terms of flow topology and statistical quantities – certainly in comparison with RANS models, but pose considerable uncertainties in respect of refined near-wall processes, which conceivably influence the details of the separation process. The present simulations have been performed with particular attention to the resolution of near-wall features. An even more refined simulation has recently been undertaken by Garcia-Villalba and Rodi at the University of Karlsruhe, and a joint paper is to appear (Garcia-Villalba et al (2008)). Here, the results of a simulation on a 36.7-million-node mesh, which fully resolves the near-wall region above the bottom surface, are summarised. The hill is subject to a thick incoming boundary layer, extending roughly to 50% of the hill height, which contains fully-established and influential turbulence. This has been accounted for through the imposition at the computational inlet plane of time- and space-resolved turbulent fields from a precursor simulation in which a forcing method is used to enforce the correct mean-velocity and normal-stress profiles given by the experiment, as shown in Fig. 2. This is an important pre-requisite for placing full confidence in the simulation, especially if turbulence budgets are to be extracted from the simulation, as is currently being done.

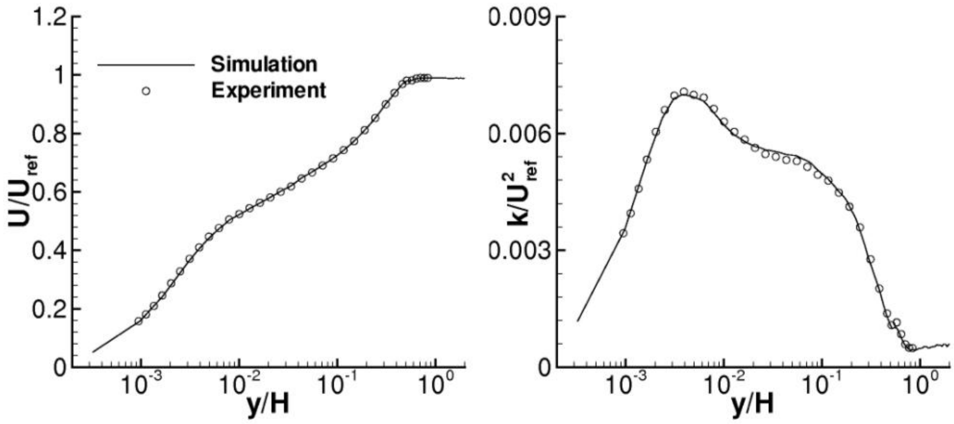


Fig. 2: Statistical properties of the precursor boundary-layer simulation used to prescribe inlet conditions for the main simulation

Presented in Fig. 3 is the pressure distribution above the hill surface on the geometric hill-centre plane, a sensitive indicator of the separation process in the leeward side of the hill. The predicted pressure from the highly-resolved LES (refered to as 'fine-grid' in figures to follow) matches the experimental data better than those of wall-model simulations ('coarse-grid'), as reported in Tessicini et al. (2007).

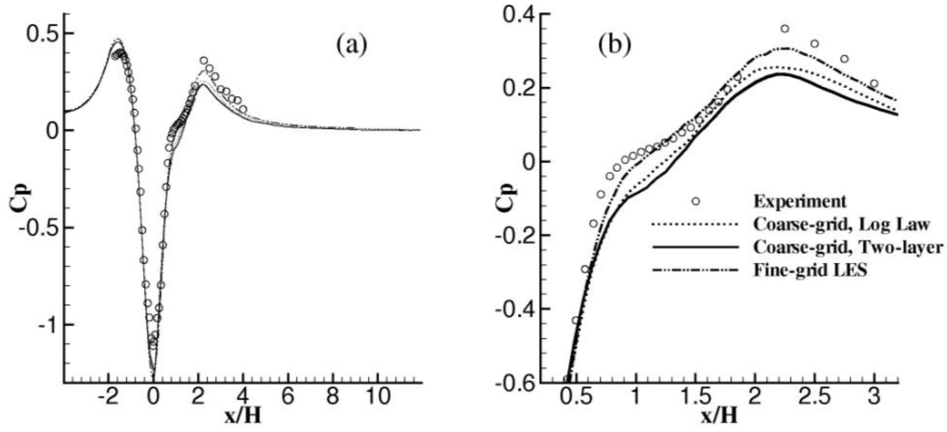


Fig. 3: Pressure distributions over the hill surface on hill centre-plane

Fig. 4 shows the velocity-vector field across the centre-plane, with the recirculation highlighted by the dashed zero-velocity locus. The separation location predicted by the high-resolution simulation is at around *x/H*=0.3. This cannot be recognised from the figure, because the recirculation zone between *x/H*=0.3 and 1.2 is very thin and not visible on the velocity-field plot. The experimental separation point is given as 0.8, but this is likely to be inaccurate, because of insufficient near-wall resolution of the measurements. Garcia-Villalba and Rodi also report a value of 0.3, based on their finest-grid simulation. Fig. 5 shows the topology, obtained from the streakline pattern in the plane $y^+=80$. While the wall-nearest plane lies at $y^+<2$, this plane was chosen for comparison with the experimental plot to take into account the fact that velocity measurements from which the topology was extracted are likely to reflect the flow state somewhat away from the wall, rather than at the wall itself.

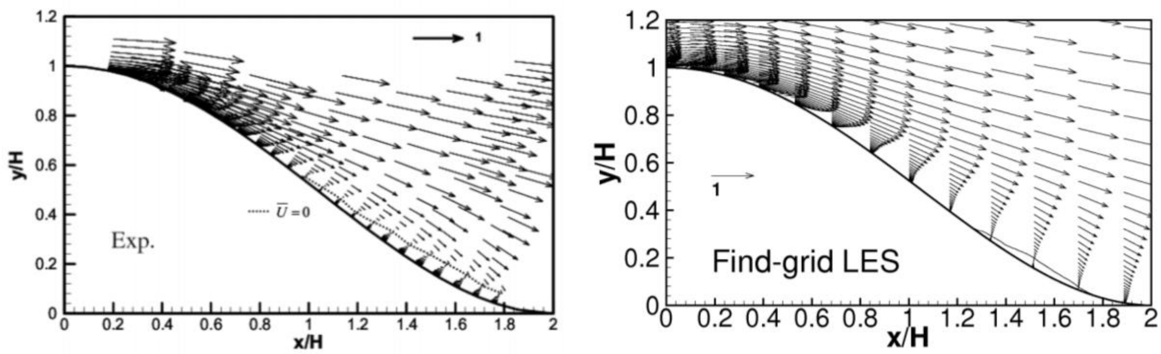


Fig. 4: Flow on centre-plane of hill (dashed line indicates zero-velocity locus)

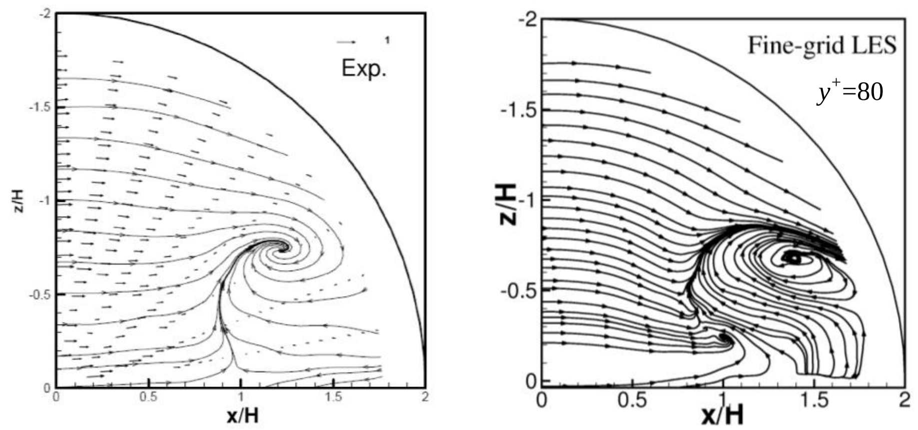


Fig. 5: Topology maps on the leeward side of the hill

References

Byun, G., and Simpson, R.L. (2005) Structure of three-dimensional separated flow on an axisymmetric bump. AIAA Paper 2005-0113.

Garcia-Villalba, M., Li, N., Rodi, W. and Leschziner, M.A. (2007), Highly-resolved large-eddy simulations of the flow separating from a three-dimensional hill in a duct, in preparation, to be submitted to JFM.

Garcia-Villalba, M. and Rodi, W. (2007), Investigation of the turbulent flow separation from an axisymmetric hill, *High Performance Computing in Science and Engineering '07*, W. E. Nagel et al (eds.), Springer, pp. 409-418.

Li, N. and Leschziner, M.A. (2007), Highly-resolved large eddy simulation of separation from a three-dimensional hill, Proc. 11th European Turbulence Conference, Porto, June 2007, pp. 407-409.

Simpson, R.L., Long, C.H., and Byun, G. (2002) "Study of vortical separation from an axisymmetric hill". Int. J. Heat and Fluid Flow, 140, pp. 233-258

Tessicini, F., Li, N. and Leschziner, M.A (2007)., Large eddy simulation of three-dimensional flow around a hill-shaped obstruction with a zonal near-wall approximation, Int. J. Heat and Fluid Flow , 28 (5), pp. 894-908.

Wang, C., Jang, Y.J. and Leschziner, M.A. (2004), "Modelling two- and three-dimensional separation from curved surfaces with anisotropy-resolving turbulence closures, Int. J Heat and Fluid Flow, 25, 499-512.