

SIMULATION OF THREE-DIMENSIONAL SEPARATION WITH A ZONAL NEAR-WALL APPROXIMATION

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Key words: LES, Near-wall modelling, Zonal Two-layer modelling

Abstract. *The focus of the paper is on the performance of an approximate 'zonal' near-wall treatment applied within a LES strategy to the simulation of flow separating from a three-dimensional hill at high Reynolds numbers. In the zonal scheme, the state of the near-wall layer of the flow is described by parabolized Navier-Stokes equations solved on a sub-grid embedded within a global LES mesh. The solution of the boundary-layer equations returns the wall shear stress to the LES domain as a wall boundary condition. Simulations are presented for grids containing between 1.5 and 9.6 million nodes, the one on the finest grid being a pure LES. The comparisons included demonstrate that the zonal scheme provides a satisfactory representation of most flow properties, even on the coarsest grid, whereas the pure LES on the coarsest grid completely fails to capture the separation process.*

1 INTRODUCTION

Three-dimensional separation from curved surfaces frequently occurs in external aerodynamics, ship hydrodynamics, turbo-machinery and all manner of curved ducts, curved aero-engine intakes being one example. Unlike separation from a sharp edge, that from a curved surface is always characterised by a highly convoluted and patchy separation area, which moves rapidly in time and space as a consequence of upstream turbulence and Kelvin-Helmholtz instability provoked by the separation process. Separation may also be intermittent and even periodic, being associated with von-Karman vortex shedding and/or Taylor-Goertler vortices. Because the separation location is not fixed by a specific geometric feature – say, a sharp corner or edge – its characteristics depend sensitively on the outer flow and also the reattachment process, if occurring at all. In circumstances in which geometric three-dimensionality is relatively weak, a closed recirculation region may arise following separation. This is the case, for example, in a spanwise uniform, unswept cylinder or surface bump which is confined in the spanwise direction by walls that are perpendicular to the cylinder or the bump. In more complex conditions, the

surface of the body interacting with the flow will be highly three-dimensional, as is the case with highly-loaded swept wings and fan blades, strongly curved circular ducts and three-dimensional smooth (hill-shaped) constrictions in conduits. In such cases, the separation pattern tends to be much more convoluted, featuring, in the mean, a wide range of topological entities such as curved detachment and attachment lines and nodes, focal points and saddles (Perry and Chong [15], Hellman and Hesselink [10]). Large vortical structures are shed from the surface over a substantial surface area around the mean separation line. Hence, the turbulence is distinctly non-local, and its dynamics are important. The boundary layer approaching the separation region is subjected to strong skewing and normal straining, with consequent major changes to the turbulence structure. Finally, strong streamwise vorticity and associated flow curvature within and downstream of the separated region provoke further complex interactions between the mean strain and the turbulence field.

A generic laboratory flow that combines all above features is that around a hill placed in a duct, as shown in Fig. 1. This flow has been examined extensively over several years by Simpson *et al.* [20] and Byun & Simpson [4], using elaborate LDA techniques, and it is increasingly viewed as a key 3D test case for prediction procedures. The hill is subjected to a boundary layer of thickness roughly one half of the hill height, one consequence of this thickness being that the structure of the boundary layer can be expected to be highly influential to the downstream evolution of the flow. The Reynolds number, based on hill height and free-stream velocity, is 130,000. As the boundary layer interacts with the hill, it is subjected to strong skewing prior to separation on the leeward side of the hill. The flow detaches, in the mean, along a separation line, roughly half-way between the hill crest and the hill foot. This merges into focal points on the leeward hill surface. Streamwise-oriented vortices are shed from the focal points, and these evolve alongside the legs of a strong horseshoe vortex formed at the upstream foot of the hill. Hugging the hill's leeward side is a closed thin recirculation region, which reattaches close to the leeward foot of the hill.

Attempts to compute this flow with RANS methods, whether undertaken in a steady or an unsteady mode, have not been successful. For example, Wang *et al.* [29] report an ex-

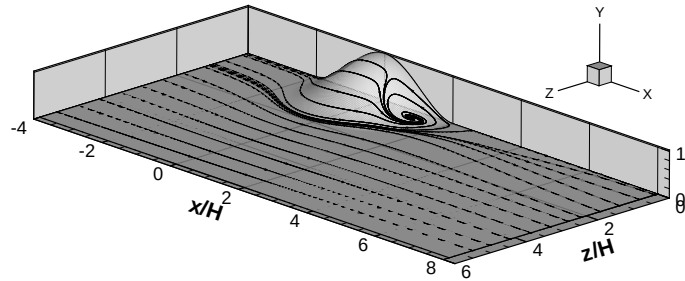


Figure 1: Flow over a three-dimensional hill.

tensive study with various non-linear eddy-viscosity and second-moment-closure models, all giving seriously excessive separation, insufficient rate of post-reattachment recovery and wrong flow structure downstream of the hill. Attempts to induce shedding-like behaviour, within the RANS framework, through the introduction of periodic excitation in the inlet flow, invariably led to a steady flow after the excitation ceased. Similarly unsuccessful RANS results were also reported by Persson *et al.* [16] in a recent study. The defects noted above are not entirely surprising, as none of the models accounts for the dynamics of the large-scale, highly energetic motions unavoidably accompanying unsteady separation.

Large-eddy simulation naturally captures, at least in principle, the dynamics of the separation process. However, the simulation of wall-bounded flows at practical Reynolds numbers faces almost untenable resource challenges, because the near-wall grid density required for the near-wall structure to be resolved rises roughly in proportion to Re^2 . When gross features of the resolved flow are substantially affected by near-wall shear and turbulence, as may be the case herein, the quality demands of the numerical mesh, in terms of density, skewness, cell aspect ratio and inter-nodal expansion ratio, are especially stringent and further increase the computational costs.

Approaches that aim to bypass the above exorbitant requirements are based either on wall functions or hybrid or zonal RANS-LES schemes. The use of equilibrium-flow wall functions goes back to early proposals of Deardorff [9] and Schumann [19], and a number of versions have subsequently been investigated, which are either designed to satisfy the log-law in the time-averaged field or, more frequently, involve an explicit log-law or closely related power-law prescription of the instantaneous near-wall velocity (e.g. Werner & Wengle [31], Hoffman & Benocci [11], Temmerman *et al.* [23]). These can provide useful approximations in conditions not far from equilibrium, but cannot be expected to give a faithful representation of the near-wall layer in separated flow. The alternative of adopting a RANS-type turbulence-model solution for the inner near-wall layer is assumed to offer a more realistic representation of the near-wall flow in complex flow conditions at cell-aspect ratios much higher than those demanded by wall-resolved simulations.

The best-known realization of the combined RANS-LES concept is Spalart *et al.*'s [21] DES method. This is one of a class of 'seamless' methods, the most elaborate forms of which being based on based on a spectral RANS-LES partitioning (Shiestel and Dejoan [18] and Chaouat and Schiestel [6]). The DES scheme is designed to return a RANS solution in attached flow regions and revert to LES once separation is predicted. This is done by arranging the wall-parallel cell dimensions Δx or/and Δz to be much larger than the wall-normal distance Δy , the consequence being an outward shift of the RANS-LES switching position $y_{int} = \min(y_{wall}, C_{DES} \times \max(\Delta x \Delta y \Delta z))$ away from the wall and a dominance of the RANS scheme. This concept of extensive steady patches co-existing, seamlessly, with unsteady resolved portions raises important question marks against physical realism in areas in which separated regions border boundary layers and in post-reattachment recovery. Also, in general flows, the streamwise grid density often

needs to be high to achieve adequate resolution of complex geometric and flow features, both close to the wall (e.g. separation and reattachment) and away from the wall. Thus, another problem with DES is that the interface can be forced to move close to the wall, often as near as $y^+ \sim O(50 - 100)$, in which case RANS and LES regions co-exist even in fully attached flow. In such circumstances, it has been repeatedly observed, especially at high Reynolds numbers, that the high turbulent viscosity generated by the turbulence model in the inner region extends, as subgrid-scale viscosity, deeply into the outer LES region, causing severe damping in the resolved motion and a misrepresentation of the resolved structure as well as the time-mean properties. The DES method has recently been applied to the 3d-hill flow considered in the present paper by Persson *et al.* [16] with some measure of success, in so far as the DES solutions were found to be materially closer to the measured data than those obtained with RANS.

A hybrid method allowing the RANS near-wall layer to be pre-defined and to be interfaced with the LES field across a prescribed boundary has recently been proposed by Temmerman *et al.* [22]. With such a method, one important issue is compatibility of turbulence conditions across the interface; another (related one) is the avoidance of 'double-counting' of turbulence effects – that is, the over-estimation of turbulence activity due to the combined effects of modelled and resolved turbulence. A general problem often observed with this type hybrid scheme is an insufficient level of turbulence activity just beyond the interface, as a consequence of the near-wall RANS model misrepresenting the near-wall (streaky) structure and the fact that the turbulence in the LES region close to the interface is not sufficiently vigorous, because this region is subjected to wrong or distorted structural information at the interface. Several attempts have thus been made to inject synthetic turbulence into the interface in an effort to at least partially recover the influence of the small-scale structures lost by the application of the RANS model. Alternative approaches have been proposed by Piomelli *et al.* [17], Davidson and Billson [7], Davidson and Dahlstrom [8]. While these measures have some beneficial effects, in terms of reducing mean-velocity anomalies, they do not and cannot - cure the most of the defects arising from the inevitable misrepresentation of the turbulence structure near the wall. They are also not practically usable in a general computational environment.

It is arguable that any near-wall approximation that circumvents a detailed resolution of the near-wall structure cannot be expected to return a physically correct spectral state and, therefore, cannot provide the correct 'boundary conditions' for the LES portion above the approximated near-wall layer. It can further be claimed, with some justification, that the most that a near-wall model can be expected to provide is a realistic representation of the wall shear stress, and that this should be the only quantity that is fed into the LES procedure. This is the basis of a second group of approaches terms 'zonal schemes'. Like hybrid strategies, zonal schemes involve the application of a RANS model in the near-wall layer. However, they involve a more distinct division, both in terms of modelling and numerical treatment, between the near-wall layer and the outer LES region. Such schemes have been proposed and/or investigated by Balaras and Benocci [1], Balaras *et*

al. [2], Cabot and Moin [5] and Wang and Moin [30]. In all these, unsteady forms of the boundary-layer (or thin-shear-flow) equations are solved across an inner-layer of a prescribed thickness, which is covered with a fine wall-normal mesh, with a turbulence model providing the eddy viscosity. Computationally, this layer is partially decoupled from the LES region, in so far as the pressure field just outside the inner layer is imposed across the layer, i.e. the pressure is not computed in the layer. The principal information extracted from the RANS computation is the wall shear stress, which is fed into the LES solution as an unsteady boundary condition.

2 THE TWO-LAYER ZONAL SCHEME

The objective of the zonal strategy is to provide the LES region with the wall-shear stress, extracted from a separate modelling process applied to the near-wall layer. Computationally, this layer is partially decoupled from the LES region, in so far as the pressure field just outside the inner layer is imposed across the layer, i.e. the pressure is not computed in the layer, which results in a major saving of computational resources. The principal information extracted from the RANS computation is the wall shear stress, which is fed into the LES solution as an unsteady boundary condition. A schematic of the method is shown in Fig. 2.

At solid boundaries, the LES equations are solved up to a near-wall node which is located, typically, at $y^+ = 50$. From this node to the wall, a refined mesh is embedded into the main flow, and the following simplified turbulent boundary-layer equations are solved:

$$\underbrace{\frac{\partial \rho \tilde{U}_i}{\partial t} + \frac{\partial \rho \tilde{U}_i \tilde{U}_j}{\partial x_j} + \frac{\partial \tilde{P}}{\partial x_i}}_{F_i} = \frac{\partial}{\partial y} [(\mu + \mu_t) \frac{\partial \tilde{U}_i}{\partial y}] \quad i = 1, 3 \quad (1)$$

where y denotes the direction normal to the wall and i identify the wall-parallel directions (1 and 3). The left-hand-side terms are collectively referred to as F_i .

In the present study, either none of the terms or only the pressure-gradient term in F_i

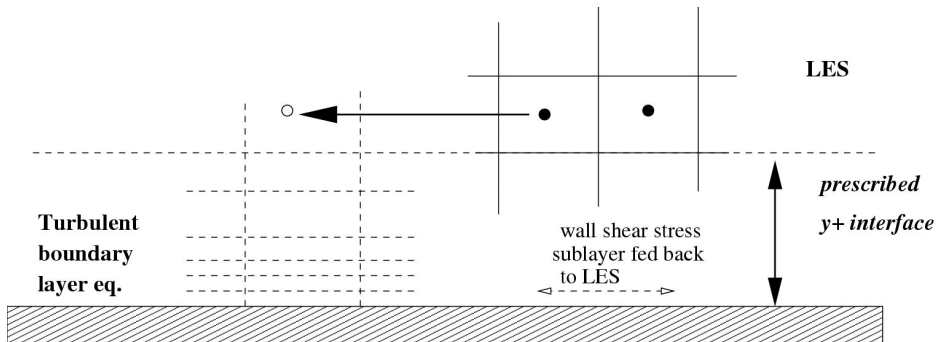


Figure 2: Schematic of the two-layer zonal scheme.

has been included in the near-wall approximation. The effects of including the remaining terms are being investigated and will be reported in future accounts. Depending on the terms included, equation (1) can be solved algebraically or from differential equations, resulting in different degree of simplifications. The wall shear stress is then evaluated from the solution.

The eddy viscosity μ_t is here obtained from a mixing-length model with near-wall damping, as done by Wang and Moin [30]:

$$\frac{\mu_t}{\mu} = \kappa y_w^+ (1 - e^{-y_w^+/A})^2 \quad (2)$$

The boundary conditions for equation (1) are given by the unsteady outer-layer solution at the first grid node outside the wall layer and the no-slip condition at $y = 0$. Since the friction velocity is required in equation (2) to determine y^+ (which depends, in turn, on the wall-shear stress given by equation (1)), an iterative procedure had to be implemented wherein μ_t is calculated from equation (2), followed by an integration of equation (1).

3 THE COMPUTATIONAL LES FRAMEWORK

The computational method rests on a general multiblock finite-volume scheme with non-orthogonal-mesh capabilities allowing the mesh to be body-fitted. The scheme is second-order accurate in space, using central differencing for advection and diffusion. Time-marching is based on a fractional-step method, with the time derivative being discretized by a second-order backward-biased approximation. The flux terms are advanced explicitly using the Adams-Bashforth method. The provisional velocity field is then corrected via the pressure gradient by a projection onto a divergence-free velocity field. To this end, the pressure is computed as a solution to the pressure-Poisson problem by means of a three-dimensional V-cycle multigrid algorithm operating in conjunction with a successive line over-relaxation scheme. The code is fully parallelised using MPI and was run on several multi-processor computers with up to 256 processors.

4 THE SIMULATED CONFIGURATIONS

The three-dimensional circular hill, of height-to-base ratio of 4, is located on the bottom wall of a duct, as shown earlier in Fig. 1. The size of the computational domain is $16H \times 3.205H \times 11.67H$, with H being the hill height. The hill crest is $4H$ downstream of the inlet plane. One typical numerical mesh is shown in Fig. 3.

The inlet conditions required particularly careful attention in this flow, because the inlet boundary layer is thick, roughly 50% of the hill height. As indicated in Fig. 4, the mean flow was taken from a RANS simulation that accurately matched the experimental conditions (Wang, *et al.* [29]). The spectral content was then generated separately by superposing onto the mean profile fluctuations taken from a separate precursor boundary-layer simulation performed with a quasi-periodic recycling method and rescaling the fluctuations by reference to the ratio of the friction velocity values of the simulated boundary

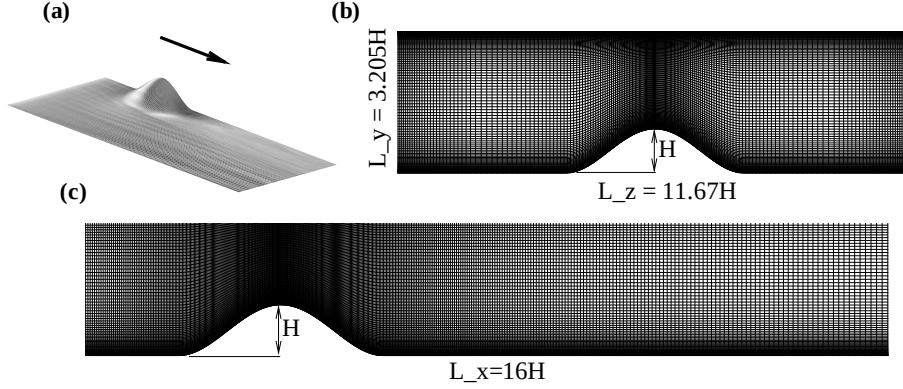


Figure 3: Numerical grid: (a) perspective view of the computational domain (half); (b) grid in $y-z$ plane at $x=0$; (c) grid in $x-y$ plane at $z=0$.

layer, at $Re_\theta = 1700$, and the actual boundary layer ahead of the hill, at $Re_\theta = 7000$. Although the fluctuations only roughly match the experimental conditions at the inlet – as can be seen from the turbulence-kinetic-energy profiles in Fig. 4 – specifying this reasonably realistic spectral representation proved to be decisively superior to simply using uncorrelated fluctuations (Li, *et al.* [12]), even if the latter could be matched better to the experimental profile of the turbulence energy. Because the upper and side walls of the domain were far away from the hill, the spectral state of the boundary layers along these walls was ignored.

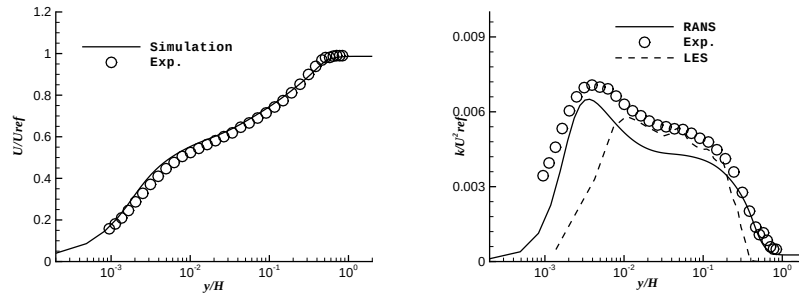


Figure 4: The mean-velocity and turbulence-energy profiles at the inlet plane of the three-dimensional hill domain.

Table 1 summarizes the simulations performed for the three-dimensional hill. First, in order to provide reference results, additional to the experimental data, pure LES computations, without wall modelling, were performed on a mesh of 9.6 million nodes with both the constant-coefficient, van-Driest-damped Smagorinsky model and its dynamic variant. Despite this seemingly fine resolution, these simulations are not, in fact, fully

Case	Grid	SGS Model	y^+ of interface or near-wall-node location
Fine-grid LES	$448 \times 112 \times 192$	Dynamic	5-10
Fine-grid LES	$448 \times 112 \times 192$	Smagorinsky	5-10
Log-law WF	$192 \times 96 \times 192$	Dynamic	20-40
Two-layer zonal	$192 \times 96 \times 192$	Dynamic	20-40
Coarse-grid LES	$192 \times 96 \times 192$	Dynamic	20-40
Two-layer zonal	$192 \times 64 \times 128$	Dynamic	40-60
Two-layer zonal (with dp/dx_i)	$192 \times 64 \times 128$	Dynamic	40-60
Coarsest-grid LES	$192 \times 64 \times 128$	Dynamic	40-60

Table 1: Grids, modelling practices and interface locations for the three-dimensional-hill simulations.

wall-resolving, as the y^+ values at the wall-nearest nodes upstream of the hill were of order 5. These simulations also display a non-negligible sensitivity to subgrid-scale modelling, which reinforces the observation that resolution is wanting. With wall models, the aspect ratio of the near-wall grid is (supposedly) no longer a crucial constraint for LES, and major savings in computational costs can be achieved by reducing the grid resolution in the streamwise and spanwise directions. This was realised with meshes of 3.5 and 1.5 million nodes that were used with the zonal near-wall model. Zonal-scheme simulations on the finer mesh were performed with and without the pressure gradients included in the near-wall approximation. One further pure LES computation was undertaken with the coarsest mesh of 1.5 million nodes with no-slip conditions imposed at the walls. Finally, a simulation was performed on the 3.5-million-node mesh with a conventional log-law-based wall function at the hill wall. In the discussion to follow, the 9.6-million, 3.5-million and 1.5-million node meshes are referred to as fine, coarse and coarsest, respectively.

5 RESULTS AND DISCUSSIONS

Prior to a consideration of results obtained with the near-wall approximations, attention is directed briefly to the pure LES solution on the 9.6-million-node mesh, some of which have already been reported by Tessicini *et al.* (2005) [27]. Although this mesh may be regarded as fine for the Reynolds number in question, it is, in fact, too coarse and one that compromises the accuracy of the simulation. As noted previously, the nodal plane closest to the wall is at a distance of $y^+ = 5 - 10$, while the streamwise-to-wall-normal cell-aspect ratio is of order 80 near the wall. This grid is thus found to render the simulation sensitive to sub-grid-scale modelling, especially very close to the wall, where the asymptotic variation of the subgrid-scale viscosity and stresses can be very important. This sensitivity is illustrated in Fig. 5, which shows the mean velocity-vector fields across the hill centre-plane. With the Smagorinsky model, separation occurs too early and gives rise to a more extensive recirculation zone, which results in a slower pressure recovery in

the wake following the separation and consequent differences in the flow fields downstream of reattachment. The dynamic model gives a shorter and thinner recirculation zone, in better agreement with the experimental observations.

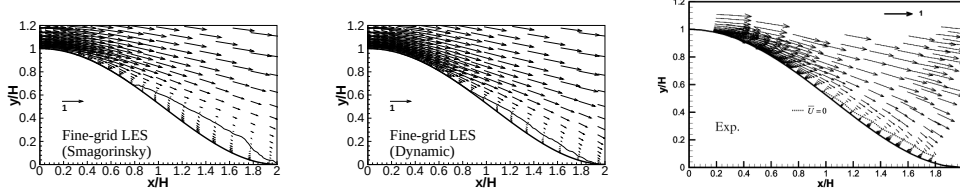


Figure 5: Velocity fields across the centre-plane in the leeward of the hill - comparison between fine-grid LES solutions using different SGS models and the experiment.

Despite the broadly satisfactory results derived with the dynamic model, some caution is called for when assessing the physical fidelity of the results. The use of the dynamic model poses uncertainties when it is applied on an under-resolving grid, because the near-wall variation of the Smagorinsky constant, following spatial averaging, is quite sensitive to the near-wall grid, and that grid is too coarse in the present LES computation. The fact that the dynamic model nevertheless performs better than the constant-coefficient variant is due to the former returning a better representation of the required wall-asymptotic variation of the Smagorinsky viscosity ($O(y^3)$). An estimate of the grid density required to yield a sufficiently well wall-resolved near-hill representation suggests the need for a grid of 30 – 50 million nodes, an extremely expensive proposition in view of the modest Reynolds number.

Statistical results obtained with the wall-functions and zonal two-layer near-wall approximation are given in Figs. 6 to 13. In all these figures, the version of the zonal scheme used is that *without* the pressure gradient; separate comparisons between the versions that include and exclude the pressure gradient will be given at the end. These figures show, respectively, profiles of the pressure coefficient along the hill surface at the centre-plane, pressure contours on the hill surface, velocity-vector fields across the centre-plane, flow-topology maps on the leeward side of the hill, velocity profiles in the cross-flow plane at the downstream location $x/H = 3.63$ and contours of turbulent kinetic energy at that same location at which experimental data are also available. Furthermore, some images of instantaneous flow features are given in Figs. 14 to 15, and these will support a discussion of some specific features of the unsteady motions.

Fig. 6(a) shows that, except for the coarsest-grid (1.5 million nodes) pure LES, all simulations predict the pressure-coefficient distribution reasonably well. The magnified views provided in Fig. 6(b) and (c) reveal, in particular, that the inflexion in the C_p curves, associated with the weak separation on the leeward side of the hill, is well captured. The benefit of using wall models becomes especially evident in the case of extremely poor spatial resolution, on the 1.5 million-node mesh, where the use of no-slip conditions results in a grossly erroneous prediction of the separation process. In fact, as will be

shown below, an fully attached flow is predicted, and an excessively fast pressure recovery after the hill crest is returned. In contrast, applying a wall model on the coarsest grid results in the resolution of the separation process and thus a reasonable representation of the pressure-recovery process.

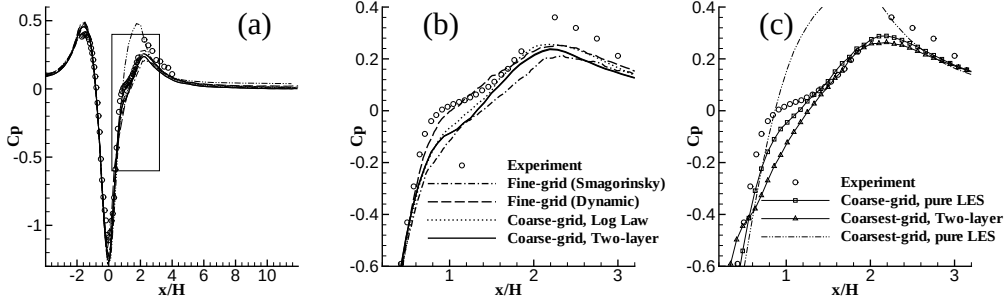


Figure 6: Pressure coefficient along the hill surface at the centre-plane: (a) full view; (b) and (c) zoomed-in view around the region where separation occurs.

Broader views of the pressure field are given in Fig. 7, which show contour plots of c_p above the hill. The circles in these plots indicate the foot of the hill. The predicted fields, two derived from coarse-grid simulations and one from a fine-grid simulation, agree well with the experimental results of Simpson *et al.* [20].

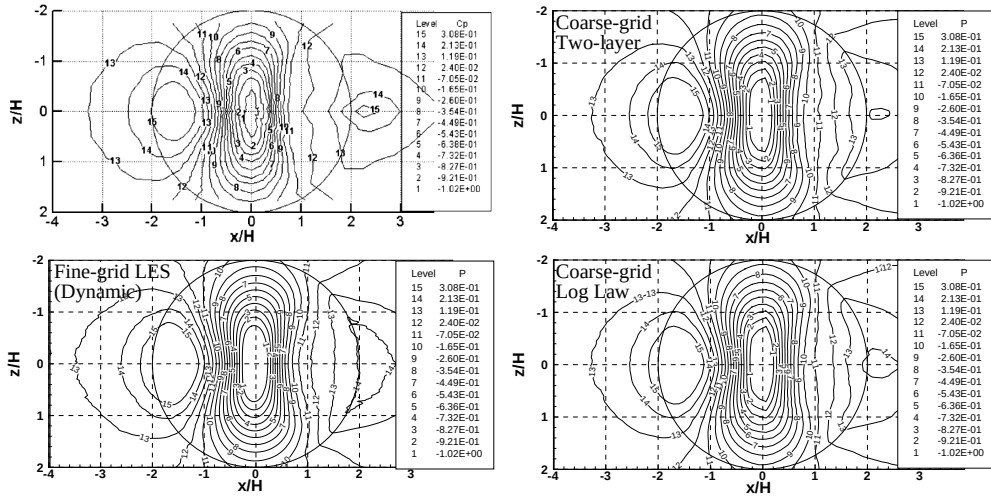


Figure 7: Contours of the pressure coefficient on the hill. Comparison between the experiment [20], two coarse-grid simulations and one fine-grid simulation.

According to the experiment, the flow in the symmetric plane separates about 1 hill height ($x/H = 0.96$) after passing over the hill crest. The separation zone is very shallow, and the flow reattaches at the foot of the hill at $x/H = 2.0$. In the fine-grid simulations as

well as all simulations using wall models, the size and extent of the recirculation zone on the leeward side of the hill agree fairly well with the experimental results, as shown in Fig. 8. With poor spatial resolution and no-slip conditions, the recirculation zone predicted is either too small - as is the case for the coarse-grid LES on the 3.5 million-node mesh - or entirely absent - as is the case for the 1.5-million-node coarsest mesh.

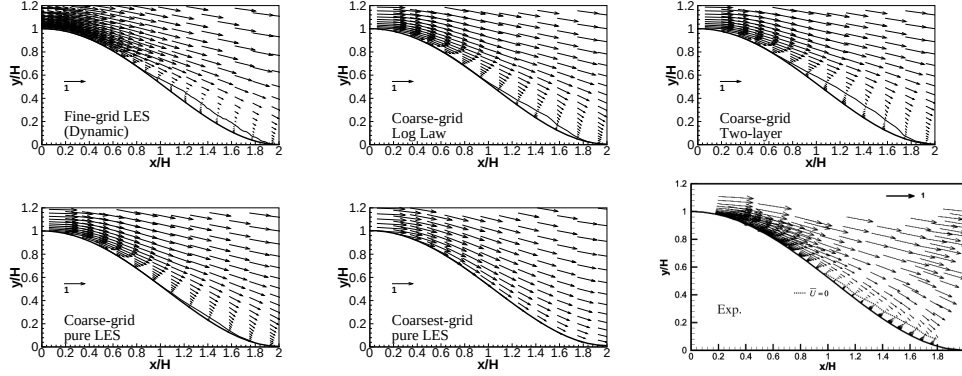


Figure 8: Velocity field across the centre-plane in the leeward of the hill - comparison between pure LES solutions, wall-model solutions and the experiment. The zero- U -velocity lines are good indications of the recirculation zone size.

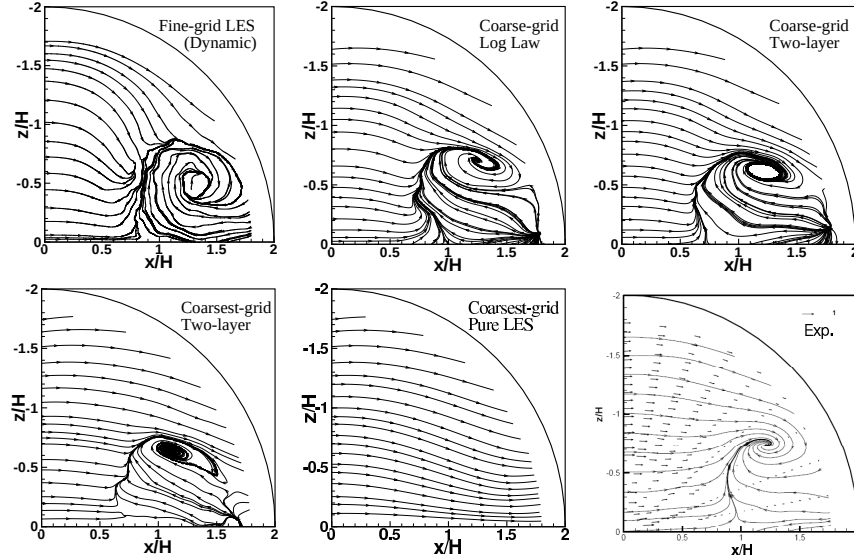


Figure 9: Topology maps predicted by the wall models, relative to the pure LES and experiment.

Fig. 9 demonstrates that the simulations with the near-wall approximations also give a broadly faithful representation of the flow topology. The LDA experiment by Byun & Simpson [4] reveal the presence of a pair of counter-rotating vortices detaching from the

leeward side of the hill and centred at approximately $x/H = 1.2$ and $z/H = \pm 0.7$. This feature is well captured by the simulations, especially by those involving wall models. With the combination of the coarsest-grid and the no-slip conditions, the topology is seen to be characterised streaklines identifying a fully attached flow. This is not surprising, as the wall-normal height of the cells closest to the wall are comparable with the thickness of the separation zone. However, with the zonal model, a realistic representation of the wall shear stress is returned, and the correct vortical structures is recovered.

Downstream of the hill, in the wake region, one major flow feature is a pair of counter-rotating streamwise vortices, shown in Fig. 10. These originate from the vorticity in the boundary layer upstream of the hill and generated from the hill itself. The simulations are in fairly close agreement with the experimental data. One discrepancy arises, however, around the location $y/H = 0.7$ and $z/H = \pm 0.3$, where the LDA measurement clearly indicates the existence of secondary vortices. Neither the simulations performed by the present authors, nor the CFD studies performed by other researchers [3], predict these secondary vortices. An unpublished, preliminary POD study, recently performed by Tessicini [26] using 194 LES snapshots, reveal a 'first mode' POD feature that suggests that the vorticity shed from the focus on the hill surface is propagated approximately to the location at which the measurements return the secondary vortex. If the validity of this link is confirmed, then the conclusion must be that lack of resolution prevented the secondary vortex from being visibly captured; the vorticity may be present, but may be smeared to an extent preventing the vortical feature from becoming evident.

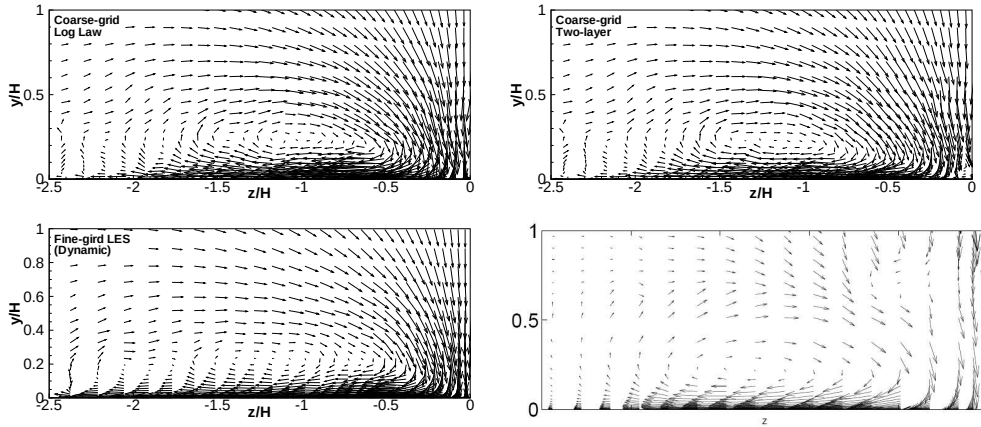


Figure 10: Velocity vectors at $x/H = 3.63$ in the wake.

To study the wake statistics in detail, streamwise- and spanwise-velocity profiles at various spanwise locations on the plane $x/H = 3.63$ are shown in Fig. 11. A magnified view of the streamwise velocity on the centre plane, providing a greater degree of differentiation, is given in Fig. 12. Consistent with the earlier results, an excessively large separation zone (as returned by the fine-grid LES with the Smagorinsky model),

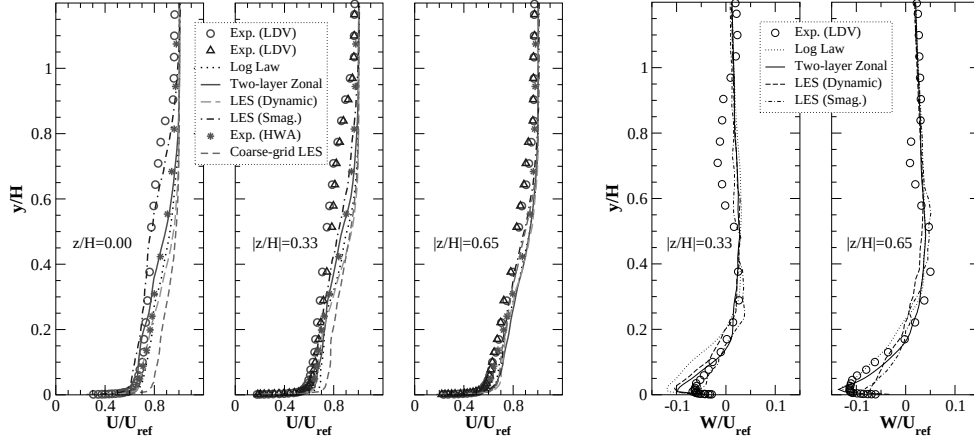


Figure 11: Mean streamwise- and spanwise-velocity profiles at various spanwise locations on the downstream plane $x/H = 3.63$.

goes hand-in-hand with a too slow recovery of the flow in the wake, so that the near-wall streamwise velocity is under-predicted. On the other hand, when a simulation fails to capture the separation (as is the case with the coarse-grid and no-slip conditions), or when the reattachment occurs too early at the foot of the hill, the flow recovers at an excessive rate and the streamwise velocity is over-predicted. All the computations performed either with the two-layer zonal model or with the log-law WF generally give much better results than those performed with no-slip conditions. Again, in the region far away from the wall, beyond $y/H = 0.4$, the predicted velocity profiles are noticeably different from the experimental LDA data [20]. However, they agree closely with hot-wire measurements [13] made in the same flow facility, and this discrepancy remains to be resolved.

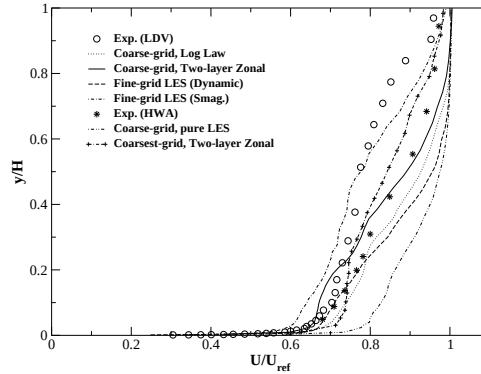


Figure 12: Magnified view of the mean streamwise velocity distribution at $z/H = 0$ on the downstream plane $x/H = 3.63$.

Fig. 13 shows contours of turbulent kinetic energy, normalised by the square of the free-stream velocity, on the same cross-wake plane considered above. Included in the figures are

numerical results obtained from the 3.5-million-node simulations performed with the log-law WF and the two-layer zonal scheme, and these are compared to the experimental in the upper plot. Both computations return a broadly satisfactory agreement with experiment. With the zonal model, the lateral extent the turbulent wake is better predicted, but the central portion of the wake is more highly turbulent than the measured level - roughly 0.035 as compared to 0.025).

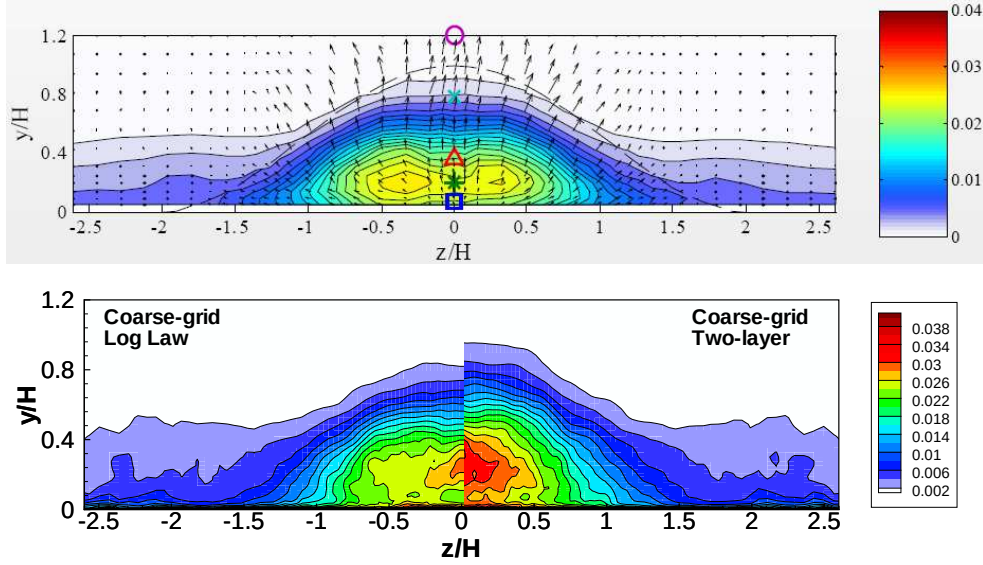


Figure 13: Turbulent kinetic energy distribution at $x/H = 3.63$.

While the statistical results of the flow are evidently in fairly good agreement with the experiments, closer examination of the turbulent structures is desirable to shed light on some of the detailed physics and dynamics of the flow. One particularly influential unsteady process is the shedding (or ejection) of large-scale vortical structures from the leeward side of the hill and their interactions with the downstream boundary layer. This has been the subject of discussion in previous experimental studies. For example, Byun and Simpson [4] have observed very-low-frequency, large-amplitude spanwise meandering motion of the shed vortex structures. Efforts to visualize, identify and analyze these coherent structures from the simulations are far from straightforward, due to the complexity of the flow. Conventional methods to detect the coherent vortices, such as the Q - and λ_2 criteria, do not work effectively for this flow. Also, the subtle nature and the low frequency of any periodic process makes the detection of such a process a difficult task. In the present paper, we confine ourselves to giving a few observations on some unsteady motions in the flow. A detailed study of this subject will be reported elsewhere.

Fig. 14 shows time-space plots of the hill-surface pressure along the line $z/H = 0$. The figure suggests that there exists a weak form of shedding mechanism. Thus, an almost periodic change of pressure field is revealed, with a non-dimensional frequency

$fH/U_{ref} \approx 0.83$. Fig. 15 shows the temporal evolution of the near-wall streamwise velocity at $z/H = \pm 0.4$ at either side of the hill, which reveals a corresponding pattern and also indicates that the shedding is nearly symmetrical, rather than alternating. Clearly, this type of periodicity is unrelated to conventional vortex shedding behind bluff bodies, and their origin is not understood at the time of writing.

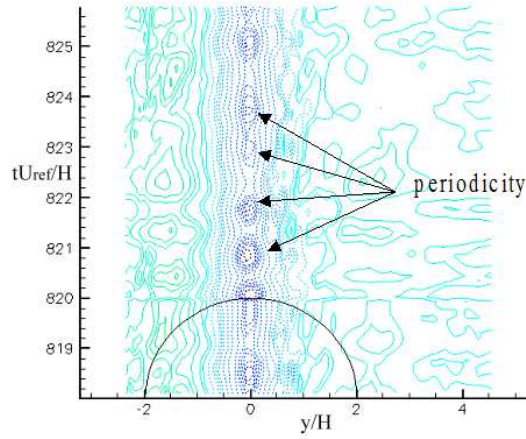


Figure 14: Temporal evolution of pressure field above the hill on the center plane.

All results presented so far for the zonal two-layer model were obtained with the pressure gradient omitted from the solution of the wall-layer equations (1). Clearly, a more general formulation would include the pressure gradient and also the convective terms. The latter extension is the subject of ongoing work. Here, the consequences of including the pressure gradient are briefly considered. Thus, Fig. 16 compares the topology on the leeward portion of the hill surface predicted without and with the pressure gradient in the near-wall model. The two simulations are seen to produce similar global features with slightly different structures in the vicinity of the foci and the reattachment point. Significantly, the inclusion of the pressure gradient leads to a slight shift of the separation line towards the hill crest. This is the expected qualitative response, for the adverse pressure gradient in the separation region results in a reduction in the predicted wall shear stress returned by the extended formulation. Other than these differences, respective flow statistics derived from the two simulations, especially those downstream of the hill in the wake area, have been found to be close, and these comparisons are not included herein. It is appropriate to finally point out that the effects of modifying the wall model, detrimental or beneficial, cannot easily be identified or isolated without the ambiguity that arises from other numerical issues. In particular, all simulations are under-resolved, and the role of the subgrid-scale model in the under-resolved environment has already been pointed out. This is not only a problem with the present extension, but also with that involving the

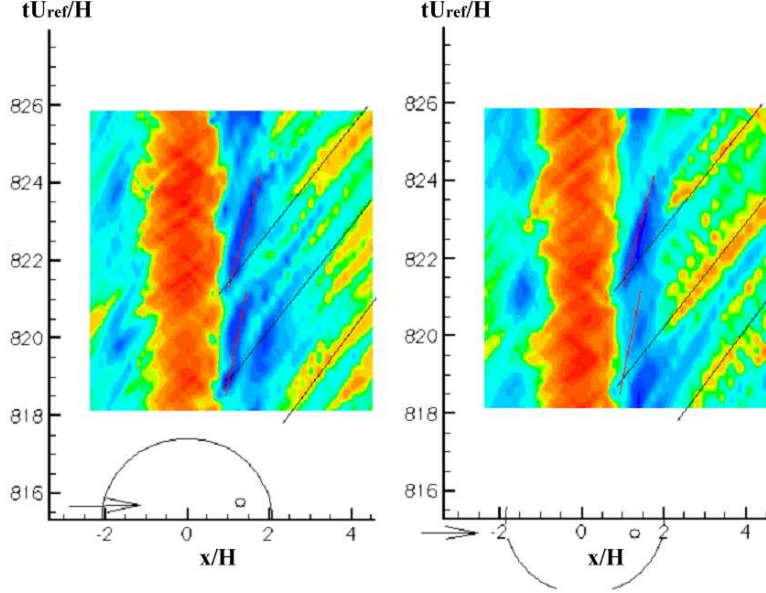


Figure 15: Temporal evolution of vortical structures on top of the hill indicating that the flow is symmetric at instantaneous level.

inclusion of the convection terms in equation (1). The latter makes the model non-linear, non-local and thus much more expensive to solve.

6 CONCLUSIONS

The emphasis of this study has been on the ability of LES to reproduce the challenging process of three-dimensional separation from a gently curved surface. This is, arguably, a very important generic configuration in the context of off-design external aerodynamics. Received wisdom is that such any flow of the type examined is highly sensitive to the details in the description upstream of the separated region i.e. the structure of the boundary layer and the accuracy with which the near-wall layer is resolved.

In the present study, simulations have been performed with grids which, without doubt, do not resolve the flow well (in a conventional LES sense), even with the finest grid of close to 10 million nodes. Moreover, the near-wall region was modelled with a rather crude approximation, which may be regarded as a variation of log-law-based wall functions. Yet, the results obtained are pleasingly close to the experimental observations certainly much closer than achieved with RANS models.

As the predictive quality depends significantly on the resolution of the LES grid, the performance of the subgrid-scale model, especially in the ill-resolved near-wall region, and the spectral description of the inflow, it is difficult to unambiguously isolate and quantify the role of the near-wall model in the favourable outcome of the simulations. However, it is reasonably clear that prescribing, simplistically, a no-slip condition at the

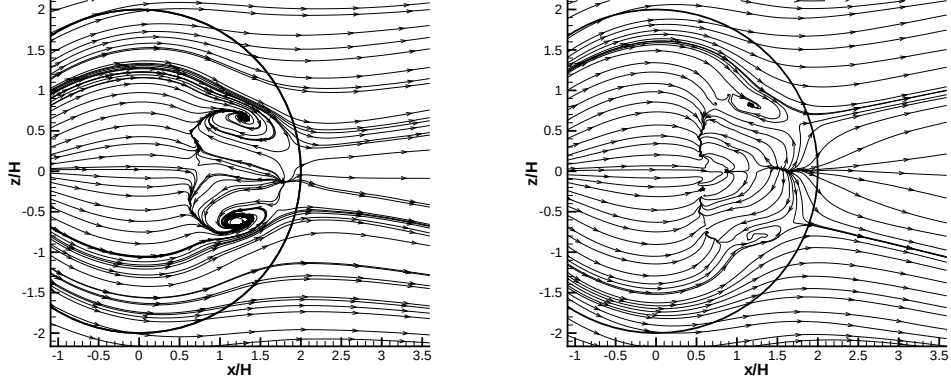


Figure 16: The flow topology predicted by two-layer zonal model with (left) and without (right) the pressure gradient term.

wall in coarse-grid simulations and extracting the shear stress from the predicted near-wall velocity gradient is decidedly inferior to using even simple near-wall models that return reasonable values for the wall shear stress. This is reflected by the outcome of simulation with the coarsest grid of 1.5 million nodes, in which case the use of a no-slip condition resulted in separation being entirely missed. With the near-wall models examined herein, most flow properties are fairly well - indeed, surprisingly well - predicted. In particular, the extent of the separated zone on the leeward side of the hill, the surface-pressure field and the flow topology are well reproduced, and the wake structure is also broadly correct. Inclusion of the pressure gradient in the near-wall model has not been found to have a decisive effect on predictive accuracy.

A specific experimentally-observed feature that has not been resolved is a pair of small secondary vortices lying next to the much larger and dominant primary vortices associated with the interaction of the upstream boundary layer with the hill. These secondary rotational features could be the foot prints of the vortices originating from the focal point on the leeward side of the hill, where separation takes place. A POD study lends support to this supposition, but this study needs to be pursued further before a definite conclusion is offered.

A limited examination of unsteady fields revealed an interesting periodicity in the pressure and velocity fields downstream of the hill crest. This does not seem to be related in any obvious way to conventional shedding: the frequency of the periodic feature does not agree with that of shedding behind bluff bodies, and there is no alternate motion suggestive of conventional vortex shedding. This mechanism remains to be examined further by reference to a detailed analysis of unsteady flow properties.

7 ACKNOWLEDGEMENTS

This work was undertaken, in part, within the DESider project (Detached Eddy Simulation for Industrial Aerodynamics). The project is funded by the European Union and administrated by the CEC, Research Directorate-General, Growth Programme, under Contract No. AST3-CT-2003-502842.

N. Li and M.A. Leschziner gratefully acknowledge the financial support provided by BAE Systems and EPSRC through the DARP project "Highly Swept Leading Edge Separation".

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