Large eddy simulation of flows around ground vehicles and other bluff bodies

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A brief review of large eddy simulation (LES) applications for different bluff-body flows performed by the author and his co-workers is presented. Examples of flows range from simple cube flows characterized by sharp edge separation over a three-dimensional hill where LES relies on good near-wall resolution, to complex flows of a tall, finite cylinder that contains several flow regimes that cause different challenges to LES. The second part of the paper is devoted to flows around ground vehicles at moderate Reynolds numbers. Although the present review proves the applicability of LES for various bluff-body flows, an increase of the Reynolds number towards the operational speeds of ground vehicles requires accurate near-wall modelling for a successful LES.

Keywords: bluff body; ground vehicle; flow control; finite cylinder; three-dimensional hill; bus

1. Introduction

Interaction of bluff bodies such as ground vehicles or buildings with the surrounding fluid always results in regions of separated flow. This characteristic of bluff body flows makes them amenable for large eddy simulations (LES), which can deal with large-scale structures that dominate the flow. However, as these flows are often characterized by high Reynolds numbers and they are always wall-bounded, their prediction by LES is often prohibited by extreme resolution requirements in the near-wall regions.

The present paper is an attempt to illustrate different applications of LES on bluff-body flows performed by the author and his co-workers. This is by no means a complete review, as other researchers have also worked on LES of bluff-body flows.

Although most bluff-body flows contain different flow regimes, the applications in the present paper belong to three groups: flows with sharp edge separations, flows with separations at smooth surfaces and ground vehicle flows. This subdivision is made merely to display differences in resolution requirements, the need for accurate inlet boundary conditions, etc. between different classes of bluff-body flows. The last group, ground vehicle flows, contains both the sharp edge and smooth edge separations, but the main reason for putting them in a special group is the very high Reynolds number.

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It is well known that the success of an LES of wall-bounded flow is very dependent on the resolution of the near-wall flow structures that are responsible for the transfer and maintenance of the turbulent kinetic energy produced near the wall. The near-wall resolution is not only important for the transfer of information from walls into the outer flow but also for transfer of turbulence from the inlet boundary condition (in the case that unsteady turbulent boundary conditions are applied). An approximation of the resolution requirements of a wall-resolved LES of a passenger car is presented in Krajnović (2002). The resulting resolution for only the near-wall region \( y^+ < 20 \), where \( y^+ \) is the wall-normal distance expressed in wall units) was found to be approximately \( 0.61 \times 10^5 \) cells. We should note that this is the lowest limit because the real car has a far more complex geometry than the simplified vehicle body considered in Krajnović (2002). Similar or even larger resolution requirements are valid for other ground vehicles (in particular high-speed trains) and bluff bodies such as tall buildings and chimneys.

2. The surface-mounted cube

The first bluff-body flows computed using LES were square cylinders and cubes such as that in the experiments of Martinuzzi & Tropea (1993). These flows are very suitable for LES as they are dominated by large-scale flow structures and, even better, the separation always occurs at the sharp edge. Thus, it is not by coincidence that these flows were chosen for first bluff-body flows to be computed using LES. Many authors (including the author of the present paper) have exercised different approaches, including various subgrid-scale models, different flavours of turbulent inlet boundary conditions and a number of near-wall approaches, to simulate these flows. However, as long we have somewhat reasonable resolution and numerics and are patient enough to wait for a fully developed flow before starting averaging, it is hard to fail in the prediction of the wake flow behind the body. A good demonstration is given by LES of the flow around a surface-mounted cube at \( Re = 4 \times 10^4 \) based on the incoming velocity and cube height. This flow has been computed by a large number of researchers using different spatial resolutions ranging from some \( 2 \times 10^5 \) to \( 2 \times 10^6 \) computational nodes, different subgrid-scale models from the standard Smagorinsky model to different versions of models with a dynamic procedure of a pure Smagorinsky type or mixed (with scale-similarity model) model (e.g. Krajnović & Davidson 2002b). Although the flow on and behind the cube is not very challenging for the resolution, the upstream boundary-layer is (or more accurately was 10 years ago when these simulations were made). This is why some researchers have used various versions of the instantaneous wall function to represent the near-wall dynamics. All these simulations have shown that the flow downstream of the leading edge separation was predicted fairly well with even very coarse grid and steady inlet boundary conditions (see figure 1; Krajnović & Davidson 2002a). More details about this LES can be found in Krajnović & Davidson (2002a). Of course, without proper resolution of the flow upstream of the cube and lacking the information on turbulence at the inlet, the boundary layer and thereby the resulting horse-shoe vortex around the cube is not accurately predicted. This example illustrates a well-known fact about
LES of wall-bounded flows: ‘It is much easier to predict the flow behind a bluff body in a tunnel than the flow in a tunnel itself when the body is not present in it’. The important contribution of these simulations was not only to show that unsteady wakes of at least some bluff bodies can be predicted using LES but also to demonstrate that LES can be used to isolate instantaneous coherent flow structures and to follow their development as in figure 2a,b.

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3. The three-dimensional axisymmetric hill

Flows with only smooth surface separations are much more difficult to predict with an LES. Such a flow is a three-dimensional hill flow from the experiment of Simpson et al. (2002). Although the geometry looks rather simple, the flow is fairly complex, as depicted in figure 3 by the instantaneous flow structures from the LES (Krajnović 2008a). The flow is governed by the upstream boundary-layer and the curvature of the geometry. The strong velocity gradients in the streamwise and the spanwise directions make the wake flow very complex. In the experiment, no separation was observed on the top of the hill and it was delayed to approximately $x = 0.96 H$. After this separation, a strong deceleration occurs close to the bottom of the hill due to the adverse pressure gradient. The position of the separation is strongly dependent on the upstream boundary-layer, which makes the time-dependent numerical simulation (such as detached eddy simulation (DES) and LES) of this flow very challenging and sensitive to the resolution and inlet boundary conditions. On the other hand, the traditional Reynolds-averaged Navier–Stokes (RANS) modelling suffers from its inability to adjust to the strong variation in the flow regimes and problems in dealing with the strongly time-dependent flow with a wide spectrum of turbulent length-scales. The separation in this flow is governed by the upstream boundary-layer and the curvature of the hill, and the success of an LES is very dependent on our ability to predict the upstream boundary-layer. This means two things: the resolution of the near-wall flow must be sufficient to resolve the near-wall streaks (i.e. $\Delta z^+ \approx 20$), and the turbulence fed at the inlet must be identical to that in the actual experiment. Simulations presented in Krajnović (2008a) demonstrate that not only are these two conditions (the resolution and the inlet boundary conditions) important but also that they are dependent on each other. A comparison of the LES flow from Krajnović (2008a) with the experimental one is given in figure 4. Two different inlet boundary conditions were used in Krajnović (2008a), one steady experimental profile and the other containing the unsteady information from a precursor channel flow simulation. No significant difference in the results was found between the two LESs with different inlets. This was attributed to too coarse a grid resolution. At $Re = 13 \times 10^4$, the required grid is far more than the $15 \times 10^6$ nodes used in LESs presented in Krajnović (2008a). The explanation for such insensitivity of the results to the inlet boundary conditions is in the too coarse spatial resolution. As a result of the coarse numerical grid, the fluctuations that are fed at the inlet are quickly dissipated by the numerical damping on their way downstream. This insensitivity of the LES to the inlet boundary conditions is very different from what was found in hybrid LES–RANS simulations (Davidson 2007), where a large difference was found between the results when steady and time-dependent inlets were used. In a LES–RANS, the RANS region is not capable of mimicking and transporting the correct near-wall dynamics into the LES region by itself. Some extra fluctuations coming from the unsteady boundary conditions seem to be essential for the matching region between the RANS and the LES.
4. The tall finite cylinder

The two bluff-body flows discussed above contain either sharp edge or smooth surface separations. However, most bluff-body flows contain both kinds of separations. A tall, finite, circular cylinder studied in Krajnović (2007) is a typical example of such a flow, where the flow puts different requirements on resolution in different regions. At a Reynolds number of $Re = 2 \times 10^4$, the flow in the middle part of the cylinder is in the so-called subcritical state where the transition occurs in the shear layer. This flow belongs to the second phase of the transition along the free-shear layer characterized by the formation of transition eddies ($1000 < Re < 40000$). Thus, the simulation is assumed to resolve the laminar boundary-layer on the front side of the cylinder, the formation of the transition eddies in the shear layer and the large-scale coherent structure dynamics in the wake (figure 5b). The junction flow at the position where the cylinder is mounted on the floor will produce a thin (due to a thin boundary layer) horse-shoe vortex and the sharp edge free end of the cylinder will result in a massively separated flow (figure 5c). The LES presented in Krajnović (2007) was particularly successful in its prediction and explanation of the downwash process in the near wake (figure 5d) and von Kármán-like shedding of half-arch vortices in the far wake (figure 5e). Such a variety in flow regimes and a wide spectrum of flow scales make simulations of this flow extremely challenging.

5. Flows around ground vehicles

The key difference between the ground vehicle flows and the above discussed bluff-body flows is the very high Reynolds number in vehicle flows. There is no doubt that we are not able (and will be prohibited from doing so for long time to come) to make wall-resolved LES of ground vehicles at operational Reynolds numbers due to the overwhelming computational effort needed to resolve a sufficient turbulence kinetic energy in the flow in order to, for example, get correct separations. This, however, does not exclude the usage of LES for studying flows around vehicles at lower Reynolds numbers, which has been the practice in experimental studies for decades. It is a well-known fact in ground vehicle aerodynamics that, beyond some Reynolds number, the flow around a vehicle (or, more precisely, flows’ global quantities such as forces and moments) becomes independent of the Reynolds number. Such a reasoning about the flow behaviour is what was used in the past by many experimenters and was followed by the author in his LES, to study ground vehicle flows.

(a) The simplified bus

The first ground vehicle flow predicted with LES was that of a simplified bus (Krajnović & Davidson 2003). Although only the smooth geometry of the bus body was used, without wheels, mirrors or any other add-on devices, the resulting flow (figure 6) showed itself to be very complicated. Here it is worth mentioning that making LES of a smooth geometry is probably more challenging than of true detailed geometry from the point of view of the required resolution.
Figure 4. Velocity vectors in plane $z=0$ from: (a) LDV results of Simpson et al. (2002); (b) LES using $15 \times 10^6$ computational nodes; (c) contours of the streamwise velocity component normalized with inlet velocity $U_{in}=27.5$ (m s$^{-1}$) and vectors of secondary velocity components in plane $x/H=3.69$ from experiment (Simpson et al. 2002) and (d) same as (c) from the LES. The view in (c,d) is from behind the hill (reproduced with permission from Krajnović 2008a).

Figure 5. (a) Computational domain. (b,c) An iso-surface of the second invariant of the velocity gradient, $Q=130\ 000$ from the LES in Krajnović (2007). (d,e) Iso-surface of static pressure $p=-0.7$ from the LES in Krajnović (2007). (Time difference between the two pictures in (d) is $\Delta t_s = \Delta t U_{in}/D = 4.6$.)
for the reasons mentioned above. On the other hand, the large computational grid in the detailed geometry is required simply for the reason of representation of the geometry and thereby separated flow regions.

Despite the fact that the body is symmetric in the spanwise direction, the instantaneous flow was found to be very asymmetric (figure 6). This is of course what we should expect. Nevertheless, it was very different from what was depicted in the past in most books of vehicle aerodynamics (showing almost exclusively mean flows). This simulation showed the strength of LES in explaining the flow. The shedding of the vortices from the end of the near-wake separation bubble (figure 6b) is an example of one phenomenon that was made easy to study using the LES from Krajnović & Davidson (2003). The experimental study using hot-wire anemometry indicated the existence of this process by indirect methods (the energy spectrum of velocity signal), but the LES not only predicted the correct pumping frequency but also visually depicted this process, shown in figure 6b.

(b) The Ahmed body

The real proof of the usefulness of LES came with the prediction of flow around a so-called Ahmed body (Krajnović & Davidson 2005a,b) with an angle of the rear slanted surface of 25° (figure 7a). This flow is characterized by the wide spectrum of scales ranging from those of the size of the slanted surface (e.g. cone-like vortices, $T_{13}$), over much smaller hairpin vortices (e.g. $\lambda_2$), to very small flow structures at approximately a central position of the slanted surface (figure 7b). This is the reason why all RANS simulations, as well as DES, failed in the past to predict this flow. One important observation from the LESs presented in Krajnović & Davidson (2005a,b) is that they were made at a Reynolds number that was approximately four times lower than the experimental one. Despite that, the agreement of the results with the experimental data is almost perfect (figure 8). This is partly due to the sufficiently large Reynolds number in the LES (after which the flow does not experience large changes), and also to the sharp edges on the slanted surface that define separations.
If flows around road vehicles at operational Reynolds numbers are out of the reach of LES, flows around high-speed trains are even further beyond the LES capabilities of our computers, partly because of the higher speed and partly because of the great length of trains (i.e. more grid points needed for resolution of the near-wall region). However, even here, it was found that LES is useful for studies at reduced Reynolds numbers. The first application was of a generic train in Hemida et al. (2005), shown in figure 9a,b. The flow was studied at two yaw angles of 35° and 90°, and a comparison of the surface pressure coefficient at one position for a 90° yaw angle is shown in figure 9c. As seen in this figure, there are some differences in $C_p$ values at the roof of the train owing to the presence of the trip wire in the experiment, which was not simulated in the LES (due to the absence of information about the location and the shape of the trip wire). This example shows the sensitivity of LES to geometric details and the need for a detailed description of the configuration used in the experiment. As we will see later in the simulation of the active flow control around an Ahmed body, special
care was taken to duplicate the trip tapes used in the experiment. The LESs of the generic train were later used in Hemida & Krajnović (2008) to study the influence of the shape of the train’s front on the surrounding flow.

(d) The simplified ICE2 train

Two realistic shapes of high-speed trains have already been simulated using LES. In Diedrichs et al. (2008), LES was used to study aerodynamically induced tail vibrations of high-speed trains (Shinkansen 300 and ICE 2) inside narrow double-track tunnels. Figure 10 shows a detail of the results from the LES of the flow around an ICE2 train model under the influence of a cross-wind at a 30° yaw angle from Hemida & Krajnović (2009a). However, both these simulations were at Reynolds numbers that are several orders of magnitude lower than the operational Reynolds numbers. The Reynolds number was nevertheless sufficient to represent the flow phenomena of interest (figure 10).

6. Flow control

An interesting application of LES is for active flow control (Krajnović & Fernandes 2008). The development of an efficient strategy for closed-loop active flow control requires a greater understanding of open-loop active flow control and the flow mechanisms that are likely to produce an increase of the base pressure of ground vehicles. A two-dimensional bluff body with a lateral shape similar to the so-called Ahmed body (figure 11a–c) was used in Krajnović & Fernandes (2008).
Figure 10. (a) The ICE2 model with the positions for comparison with the experimental data. (b) Comparison of the surface pressure between the LES and the experiments at \( x/L = 0.03 \) (i) and \( x/L = 0.44 \) (ii) (reproduced with permission from Hemida & Krajnović (2009a). Solid line, fine grid LES; dashed line, coarse grid LES; circles, experiments.

Figure 11. (a) Geometry of the two-dimensional Ahmed body; (b) zoom of the trip tape; (c) zoom of the actuation slots; (d) velocity vector field and vorticity \( \omega_z \) (i) and an iso-surface of \( p = -12 \) coloured with \( \omega_z \) for natural flow (ii).
Note that, in figure 11b, trip tapes used in the experiments were also represented in the LES. The interaction of the upper and lower shear layers after the leading edges of the two-dimensional Ahmed body results in von Kármán-like instabilities (figure 11d). Such instabilities soon produce two large two-dimensional vortices in alternating order. As the vortices are formed very early in the near wake, the separation bubble (the dead water) is short, producing a low base pressure and large drag.

Two pairs of slots extending in the spanwise direction are used for actuation of the flow (figure 11c). Harmonic actuation was applied to each slot using velocity boundary condition \( \mathbf{u}_A = u_A \sin(\omega_A t)(\cos(\phi)i + \sin(\phi)j) \), where \( \mathbf{i} \) and \( \mathbf{j} \) are the unit vectors in the \( x \) and \( y \) directions, respectively, and the actuation angle, \( \phi \), was 45°, in agreement with the experiments. The actuation amplitude, \( u_A \), can be derived from the expression for the momentum coefficient, \( C_\mu = 4su_A^2/\mu U_\infty^2 \). Not only was good agreement of the LES results with the previous experimental study obtained, but new knowledge was also gained in this

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study. Figure 12a shows that the approach of flow control used in Krajnović & Fernandes (2008) decreased the drag by some 11 per cent. The LES was able to explain the complex interaction of the actuation with the coherent flow structures responsible for forcing symmetric vortex shedding and thereby the delay of the wake instabilities. Comparing figures 11d and 12c we see that blowing postpones the rollover of the shear layer and the formation of strong two-dimensional alternating vortices. On the other hand, the suction leads to strong perturbations of the two-dimensional structures and their breakdown into small coherent structures (figure 12b). Note, however, that even these structures are predominantly two-dimensional. Figures 11d and 12c indicate that the actuation strategy used in the present work is efficient in postponing the vortex formation. For example, it is obvious that, during blowing, the length of the free shear layer in figure 12c is longer than the length in the natural flow case in figure 11d. On the other hand, all large coherent structures are efficiently destroyed during the suction phase (figure 12b). Thus, both cycles desynchronize shear layer dynamics and thereby influence wake dynamics such that the interaction of vortices rolling up from the two shear layers is decreased or delayed. Both result in an increase of the base pressure and a reduction of the drag.

7. Discussion and future perspectives

The material presented above demonstrates the usage of the near-wall resolved LES for an understanding of flow mechanisms in bluff-body flows at moderate Reynolds numbers typical for ground vehicles. Such an approach will however not be feasible in the near future for bluff-body flows at high Reynolds numbers. An application that will be out of reach for wall-resolved LES for decades is high-speed trains. However, there are several flow phenomena of high-speed trains that are in acute need of accurate time-dependent numerical simulations, partly due to the flow that is inherently transient and partly due to difficulties in performing experiments. One such flow is that around a high-speed train under the influence of wind gusts. Owing to the very high Reynolds number, the simulation must include some kind of near-wall modelling. In Krajnović (2008b), the author used DES to compute the flow around a detailed ICE2 train exiting a tunnel in a varying cross-wind profile. A similar approach was applied for the double-deck bus in Hemida & Krajnović (2007, 2009b). Although the simulation includes RANS modelling near the wall, the flow structures obtained are fine scaled (figure 13) and the aerodynamic forces and moments were found to be in agreement with the experimental data.

Several conclusions can be drawn from the LES applications presented here. We can see that the influence of the geometry of the bluff body on the LES is significant. For example, the sharp-edged cube or the Ahmed body reduces the influence of the near-wall structures on the resulting large-scale wake flow. Thus, the resolution can be drastically decreased, making an LES possible. On the other hand, the cylinder flow requires a nearly direct numerical simulation (DNS) resolution in order to predict the transition. The conclusion that can be drawn from this is that special care should be taken in the geometry of the vehicle, which is often simplified in a computational fluid dynamics analysis. Defeaturing of, for example, the underbody geometry of a car or a train by
removing all the small pipes and obstacles and making it flat is perhaps not a good idea in the pre-processing of an LES. All such obstacles will produce separations and probably tremendously decrease the resolution requirements. This is the case in particular for a simplified long train with a flat underbelly without bogies and wheels. The resolution requirements of the near-wall flow on such a train underbelly are similar to those in a flat plate LES. Such resolution is not feasible at the operating Reynolds number of a high-speed train. Representing all the geometric complexity of the vehicle will of course increase the number of computational nodes, but the added nodes will only have the purpose of resolving the geometry and not the near-wall flow. The resolution of the geometry in an LES at high Reynolds numbers requires fewer computational nodes than the resolution of the near-wall flow dynamics. Thus, the geometry of the vehicle should be preserved in an LES.

Another important issue is whether the hybrid LES–RANS approaches, such as DES, are a good alternative for ground vehicle LES. Most hybrid approaches use RANS modelling of near-wall regions, while the LES is used for the flow further away from the vehicle. This means that separated flow on, for example, the underbelly and attached flow on the upper side of the vehicle are treated in a similar way. It would be better to define a hybrid approach where all the separated regions, regardless of the distance from the wall, are treated by LES while the attached flow is simulated using RANS.

Finally, there are bluff-body flow applications such as the flow control discussed above that will certainly gain by wall-resolved LES. Investigations of flow control processes are very dependent on an accurate representation of boundary and shear layers. The resulting separated wake flow in the example of the two-dimensional Ahmed body above is a result of shear layers. It is questionable whether the unsteady RANS or hybrid LES–RANS can be used for such a flow, where the small-scale flow dynamics in shear layers is important.

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