Large eddy simulation for aerodynamics: status and perspectives

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The present paper provides an up-to-date survey of the use of large eddy simulation (LES) and sequels for engineering applications related to aerodynamics. Most recent landmark achievements are presented. Two categories of problem may be distinguished whether the location of separation is triggered by the geometry or not. In the first case, LES can be considered as a mature technique and recent hybrid Reynolds-averaged Navier–Stokes (RANS)–LES methods do not allow for a significant increase in terms of geometrical complexity and/or Reynolds number with respect to classical LES. When attached boundary layers have a significant impact on the global flow dynamics, the use of hybrid RANS–LES remains the principal strategy to reduce computational cost compared to LES. Another striking observation is that the level of validation is most of the time restricted to time-averaged global quantities, a detailed analysis of the flow unsteadiness being missing. Therefore, a clear need for detailed validation in the near future is identified. To this end, new issues, such as uncertainty and error quantification and modelling, will be of major importance. First results dealing with uncertainty modelling in unsteady turbulent flow simulation are presented.

Keywords: computational fluid dynamics; turbulence modelling; large eddy simulation; aerodynamics

1. Introduction

During the last few decades, most numerical efforts in the field of applied aerodynamics have been focused on the simulation of nominal operational configurations. As a consequence of the rules of design, most practical external flow configurations exhibit only limited separated flow areas and smooth gradients. Therefore, steady methodologies for turbulent flow prediction are able to handle these flow fields with a sufficient degree of accuracy. New industrial needs in aerodynamics deal with transient dynamics of separated flows (e.g. internal flows) as well as the control of noise and the capability to predict unsteady dynamic loads so that the simulation of three-dimensional unsteady turbulent flows is now required. Indeed, this need is becoming an especially

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pressing issue since a wide range of unsteady phenomena that have serious implications in terms of achievable performance, acoustic environment or safety has to be considered, and therefore requires to be accurately predicted as soon as possible in the design cycle of flight vehicles or cars. In such configurations, a steady Reynolds-averaged Navier–Stokes (RANS) solution would not be what the engineer needs.

In addition to the modelling issue, the challenge of handling complex geometries relates not only to computing cost, but also to solution quality in terms of meshing and validation of the computed unsteady field as will be discussed in §§3 and 5.

2. Large eddy simulation and sequels

One of the main properties of a turbulent flow is its multiscale aspect and the concept of kinetic energy cascade is often cited. Direct numerical simulation (DNS) enables one to get an accurate three-dimensional and time-dependent description of all the active scales in the turbulent flow without resorting to any modelling assumptions. The total number of nodes may be scaled as $O(Re_L^3)$, where $Re_L$ denotes the Reynolds number based on the spatial integral scale. Furthermore, if walls are present, the near wall structures need to be resolved leading to an even stronger dependence on the Reynolds number. Unfortunately, turbulent flows encountered in engineering applications exhibit such a wide range of excited length and time scales that DNS remains too costly by several orders of magnitude at relevant Reynolds numbers ($\approx 10^5–10^8$). This is the reason why modelling is necessary to study turbulent flows, prior to solving the Navier–Stokes equations. Nevertheless, DNS remains a research tool which allows one to get significant insight into turbulence physics and to explore control strategies (Moin & Mahesh 1998).

The large eddy simulation (LES) technique relies on a decomposition of the aerodynamic field between the large scales (responsible for turbulence production) and the small scales of the flow, the former being directly resolved while the effect of the latter is taken into account through the use of a model. The primary obstacle to practical use of LES on industrial flows which involve attached wall boundary layers at high Reynolds number remains computational power resources. Indeed, the scales of motion responsible for turbulence production impose severe demands on the grid resolution near solid walls. As an example, the grid extension sizes $\Delta x^+ \approx 50$, $\Delta y^+ \approx 1$ and $\Delta z^+ \approx 15$ are those classically retained in LES to capture the near wall structures. In Spalart (2000), it is proposed that LES of wall turbulence should be considered as a quasi DNS since the resolution of the near wall layer is roughly only 10 times less expensive than DNS. For instance, Spalart et al. (1998) report that full LES of the flow around a three-dimensional wing will not be tractable until the year 2045, even assuming that wall modelling has been achieved.

LES has been applied to many flow regimes, most of them being illustrated on academic configurations, e.g. compressible flows with shock induced separation (Garnier et al. 2001, 2002), compressible cavity flows with complex aeroacoustic couplings (Larchevèque et al. 2003, 2004) and heat transfer in low-speed separated flows (Labbé et al. 2002). Most existing application-driven simulations
deal with simplified or reduced geometries, e.g. thin slices of wings or blades (Manoha et al. 2000; Mary & Sagaut 2002; Raverdy et al. 2003). Among key issues in the field of LES, one can mention the definition of robust subgrid models which perform equally in a wide range of flow parameters (Meyers et al. 2006), the prescription of unsteady turbulent inflow conditions (Sagaut et al. 2004) and the development of subgrid models for new physical mechanisms such as subgrid noise production (Séror et al. 2001).

Hybrid RANS–LES methods have been developed to alleviate this resolution constraint in the near-wall region, another strategy being the use of local increase in the grid resolution (Quémére et al. 2001; Terracol et al. 2001). According to Sagaut et al. (2006), hybrid methods can be classified into two major classes, namely the global and the zonal hybrid methods. Similarly, Frölich & von Terzi (2008) propose to classify the hybrid approaches as unified models and segregated models. Another way may consist in distinguishing weak and strong RANS–LES coupling methods (see figure 1). The zonal hybrid methods are based on a discontinuous treatment of the RANS–LES interface. In practice, information must be exchanged at the RANS–LES interface between two solutions with very different spectral content. The global hybrid methods are based on a continuous treatment of the flow variables at the interface between RANS and LES. These methods, like detached eddy simulation (DES; Spalart et al. 1998) introduce a ‘grey area’ in which the solution is neither pure RANS nor pure LES since the switch from RANS to LES does not imply an instantaneous change in the resolution level. These methods can be considered as weak RANS–LES coupling methods since there is no mechanism to transfer the modelled turbulence energy into resolved turbulence energy. Despite a wide number of approaches (and acronyms), these methods are close to each other (Sagaut et al. 2006; Frölich & von Terzi 2008) and can very often be rewritten as variants of a small group of generic approaches. In practice, they tend to decrease the level of RANS eddy viscosity, thus permitting strong instabilities to develop. Let us note that hybrid RANS–implicit LES approaches are also potentially of great interest.

Figure 1. Classification of unsteady approaches according to levels of modelling and readiness. Adapted from Sagaut et al. (2006).
It is now commonly accepted that hybrid RANS–LES is the main strategy to drastically reduce computational cost (compared to LES) in a wide range of complex industrial applications if attached boundary layers have a significant impact on the global flow dynamics. Again, this raises the challenge of validating unsteady simulations on complex geometries.

3. Need for validation

Computational power has dramatically increased over the last few decades. A consequence of this upsurge in computational power is the rapid increase in the size of subsequent datasets, with unsteady 50–100 million point grid simulations being now conducted with increasing regularity.

As the need for higher accuracy simulations has increased, the computational fluid dynamics (CFD) community has in turn put emphasis on assessing the quality of the results and now focuses a great deal of its effort on validation of advanced methods. Let us remember that the validation of inviscid calculations was primarily focused on the capability to evaluate the wall pressure distribution while the validation of steady viscous calculations was mainly based on the correct assessment of the boundary layer integral quantities. Now the flow-field model has to include a comprehensive unsteady description of turbulence including fluctuations both in pressure and velocities. It is worth adding that numericists have at their disposal the temporal evolution of all hydrodynamic quantities in the entire volume of the flow with the best accuracy which allows a deep investigation of the flow physics.

Disappointingly, many authors present only one-point and first-order statistics to assess their unsteady simulations. This may appear paradoxal since the development of advanced methods is precisely motivated by their potential capability to predict the fluctuating field in complex configurations. Therefore, we introduce in table 1 a classification of the level of validation of unsteady data issued from CFD. Level 1 concerns the comparison of integral quantities such as lift or drag with measurements. The ability of a method to reproduce first-order statistics (e.g. mean velocity profile) and second-order statistics (such as mean squared value, r.m.s. profiles) represents level 2 and 3 respectively. Single-point spectral analysis describes how the r.m.s. levels are distributed in frequency since getting the correct amount of energy does not necessarily mean that the frequency content is well reproduced. Classical spectral analysis (level 4) may be completed with a two-point analysis (level 5) which allows us to get further insight into the spatial organization of the flow at a given frequency. When the nature of the mechanisms of interest is time-dependent, e.g. in transient processes such as flow bifurcation, the random process is said to be non-stationary and may require time–frequency and nonlinear coupling analysis (level 6). Levels 4, 5 and 6 are illustrated in Larchevêque et al. (2003, 2004, 2007), in which both post-processing tools and extensive comparisons with particle image velocimetry and hot wire data are displayed.

In addition, it is worthwhile to stress that comparing numerical data with experiment is by far not trivial, mainly because the datasets are of very different duration. Indeed, experimental time-series often exceed 10 s while 1 s is considered a ‘small eternity’ in CFD. Note the antinomic aspect between the
needs for statistics and the constraints imposed by CFD. Indeed, to perform a statistical analysis in good conditions, the signal has to be well sampled on a sufficient duration because the spectral information needs to be averaged on many blocks to be statistically converged. In practice, unsteady signals issued from CFD are most often oversampled on a short duration (due to high CPU cost). From a statistical point of view, it is strictly speaking not relevant to compare two sequences of data whose duration differs significantly. In other words, a comparison between experiment and numerical data has to be conducted cautiously with full knowledge of the facts.

4. Illustrative examples

We now address the issue of the state-of-the-art knowledge about the use of LES and hybrid RANS–LES techniques to predict the flow in complex three-dimensional systems. We deliberately choose here to include only works published in international peer-reviewed journals, since they have been validated by a commonly agreed selection process and are available to the whole CFD practitioner community. Some exceptions are made for some RANS–LES applications, since only a very few of them have been published in international journals.

LES is now a mature technique (let us recall that the seminal paper by Smagorinsky was published 45 years ago), but most published works in peer-reviewed international journals are restricted to fundamental studies of academic flows and developments related to LES theory. Nevertheless, LES is now used to compute full-scale complex three-dimensional systems. Some significant landmark achievements are reported in the top half of table 2. These applications are recent. A detailed analysis of the related papers reveals that they rely on ‘old’ methods, i.e. on numerical algorithms and subgrid modelling approaches published 10–15 years ago. The delay between the original publication of the methods and their practical use is certainly due to the exponential increase of computing power and the time needed to develop general purpose Navier–Stokes solvers with LES capabilities. As a matter of fact, it is observed that the amount of memory needed for these recent LESs is much larger than those of the landmark DNSs recorded in the early 1990s. But an interesting fact is that LES is successfully used to predict the global behaviour of complex systems in which attached boundary layers are of minor importance, such as a full-scale five-stage centrifugal pump or engine combustor chamber.

Table 1. Levels of validation of simulation techniques: nomenclature.

<table>
<thead>
<tr>
<th>grade</th>
<th>level of validation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>integral forces (lift, drag and pitch)</td>
</tr>
<tr>
<td>2</td>
<td>mean aerodynamic field (velocity or pressure profiles)</td>
</tr>
<tr>
<td>3</td>
<td>second-order statistics (r.m.s. quantities)</td>
</tr>
<tr>
<td>4</td>
<td>one-point spectral analysis (power spectral densities)</td>
</tr>
<tr>
<td>5</td>
<td>two-point spectral analysis (correlation, coherence and phase spectra)</td>
</tr>
<tr>
<td>6</td>
<td>high-order and time–frequency analysis (time–frequency, bicoherence spectra)</td>
</tr>
</tbody>
</table>

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Table 2. Typical LES-like simulations for complex applications. (Validation level nomenclature: \( n \) means that information of level \( n \) (as defined in table 1) is provided in the paper but not compared with reference data (i.e. experimental/DNS data). First and second blocks are related to classical LES and RANS–LES, respectively. \( \alpha \) and \( L \) denote the angle of attack and the length scale, respectively.)

<table>
<thead>
<tr>
<th>configuration</th>
<th>reference</th>
<th>( M_a )</th>
<th>( \alpha (\degree) )</th>
<th>( L ) (m)</th>
<th>( Re_L \times 10^6 )</th>
<th>( N_{xyz} \times 10^6 )</th>
<th>validation</th>
</tr>
</thead>
<tbody>
<tr>
<td>five-stage centrifugal pump</td>
<td>Kato et al. (2003, 2007)</td>
<td>0</td>
<td>—</td>
<td>1</td>
<td>10</td>
<td>37</td>
<td>4</td>
</tr>
<tr>
<td>urban flow</td>
<td>Nozu et al. (2008)</td>
<td>0</td>
<td>—</td>
<td>150</td>
<td>50–100</td>
<td>10</td>
<td>1–2</td>
</tr>
<tr>
<td>torpedo</td>
<td>Fureby (2008)</td>
<td>0</td>
<td>—</td>
<td>—</td>
<td>12</td>
<td>1.5–6</td>
<td>1–2–3</td>
</tr>
<tr>
<td>manoeuvring submarine</td>
<td>Fureby (2008)</td>
<td>0</td>
<td>0–25.5</td>
<td>—</td>
<td>5</td>
<td>4.4–8.6</td>
<td>1–2</td>
</tr>
<tr>
<td>combustor chamber</td>
<td>Boileau et al. (2008)</td>
<td>0.1</td>
<td>—</td>
<td>0.5</td>
<td>0.3</td>
<td>20–40</td>
<td>1–(2)–(3)</td>
</tr>
<tr>
<td>four-valve combustion engine</td>
<td>Richard et al. (2006)</td>
<td>0.2</td>
<td>—</td>
<td>0.1</td>
<td>—</td>
<td>0.6</td>
<td>1–(3)</td>
</tr>
<tr>
<td>landing gear</td>
<td>Hedges et al. (2002)</td>
<td>0.1</td>
<td>—</td>
<td>—</td>
<td>0.6</td>
<td>2.5</td>
<td>2–(3)–(4)</td>
</tr>
<tr>
<td>landing gear</td>
<td>Lockard et al. (2004)</td>
<td>0.2</td>
<td>—</td>
<td>—</td>
<td>0.094</td>
<td>13.3</td>
<td>(2)–(3)–(4)</td>
</tr>
<tr>
<td>missile forebody</td>
<td>Viswanathan &amp; Squires (2008)</td>
<td>0.21</td>
<td>60 and 90</td>
<td>—</td>
<td>2.1</td>
<td>2.1–8.75</td>
<td>(1)–2</td>
</tr>
<tr>
<td>military fighter</td>
<td>Morton et al. (2004)</td>
<td>0.27</td>
<td>30</td>
<td>—</td>
<td>13</td>
<td>3.9</td>
<td>1–(3)</td>
</tr>
<tr>
<td>military fighter</td>
<td>Forsythe et al. (2004)</td>
<td>0.3</td>
<td>65</td>
<td>—</td>
<td>2.85</td>
<td>2.85–10</td>
<td>1</td>
</tr>
<tr>
<td>gas turbine</td>
<td>Medic et al. (2008)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>8–57</td>
<td>2</td>
</tr>
<tr>
<td>afterbody</td>
<td>Deck &amp; Thorigny (2007)</td>
<td>0.7</td>
<td>—</td>
<td>0.1</td>
<td>1.1</td>
<td>8.3</td>
<td>(1)–2–3–4–5</td>
</tr>
<tr>
<td>civil aircraft</td>
<td>Brunet &amp; Deck (2008)</td>
<td>0.82</td>
<td>4.2</td>
<td>0.34</td>
<td>2.8</td>
<td>10</td>
<td>2–3–4</td>
</tr>
<tr>
<td>fighter jet</td>
<td>Chauvet et al. (2007)</td>
<td>1</td>
<td>—</td>
<td>0.044</td>
<td>0.2</td>
<td>11</td>
<td>2–(3)</td>
</tr>
<tr>
<td>supersonic inlet</td>
<td>Trapier et al. (2008)</td>
<td>1.8</td>
<td>—</td>
<td>0.1</td>
<td>2.9</td>
<td>10–20</td>
<td>2–3–4–6</td>
</tr>
<tr>
<td>launcher nozzle</td>
<td>Deck (in press)</td>
<td>6</td>
<td>—</td>
<td>0.013</td>
<td>21</td>
<td>11</td>
<td>1–2–3–4</td>
</tr>
</tbody>
</table>
Hybrid RANS–LES approaches have received increasing attention among turbulence modelling specialists, code developers and industrial CFD engineers. So far, the validation effort has been mainly focused on two-dimensional geometries, the span being treated as a homogeneous direction. These are mandatory problems in relatively simple geometries but are now becoming supported by a wider set of applications on more complicated geometries. For the sake of conciseness, only examples of three-dimensional applications are gathered in table 2.

Several off-design unsteady applications (such as high angle of attack wing aerodynamics or afterbody flows) can now be simulated accurately. Conversely, thin layer separations as well as shock/boundary layer interactions remain challenging configurations. Nevertheless, figure 2 shows that the simulation of the unsteady flow around a civil aircraft configuration is feasible without waiting for 2045. Such a simulation has been performed thanks to the use of a zonal DES approach (Deck 2005) allowing for the reduction of the cost of the simulation compared to a LES by limiting explicitly the extent of the DES zones. Note that from an engineering standpoint, full LES of a complete wing would give too much information in some ‘useless’ regions such as the leading edge or pressure side where traditional RANS modelling is often sufficient. Therefore, the authors promote the use of a zonal treatment of turbulence to treat complex configurations while other authors (Spalart 2009) may differ, but debate is useful.

Figure 2. Zonal detached eddy simulation of the flow over a subscale civil aircraft at 4.2 degree angle of attack (courtesy of V. Brunet, ONERA; from Brunet & Deck (2008)).
Besides, table 2 brings out the fact that the validation (i.e. thorough comparison with measurements) of the unsteady solution is often insufficient (level of validation < 3). This is both surprising and disappointing since the main purpose of hybrid methods is precisely to provide an unsteady description of the flow. On top of this observation, this promotes the acquisition of unsteady databases to validate LES and RANS–LES methods.

An interesting point is that, as far as massively separated flows are addressed and that a detailed description of the boundary-layer dynamics (e.g. prediction of the turbulent heat transfer) is not considered, classical LES seems to be as useful as hybrid RANS–LES methods. Another observation is that the capability of hybrid methods to provide a more accurate description of heat transfer and skin friction in fully three-dimensional complex systems than usual LES (eventually supplemented with a crude algebraic wall model) remains to be assessed. Nevertheless, a recent simulation seems to indicate that some DES variants are able to yield an accurate description of shock/boundary layer interactions at a lower cost than classical LES.

5. Modern validation procedures: uncertainty and error quantification

The above discussion dealt with ‘classical’ validation, i.e. with a procedure in which results coming from a deterministic simulation of an exactly defined system are compared with reference data that are assumed to be perfect and associated with an identical system. In practice, the validation process is much more complex and less accurate. The main reasons are the following. First, really complex systems (such as a five-stage pump) are never perfectly known, in the sense that very fine details of both the geometry and boundary conditions are not available. Therefore, the computational model can never exactly reproduce the physical system. The second problem, which has already been mentioned, is that the CFD and measurements exhibit very different sampling time and sampling frequency, leading to sometimes very different statistical convergence rate and accuracy of quantities selected for comparison. A last uncertainty source originates in measurement errors.

Therefore, uncertainties and errors should be taken into account to perform fully relevant comparisons. A key point is the capability to evaluate the sensitivity of the CFD solution with respect to computational parameters, a reliable solution being a solution with low sensitivity. The computation of the sensitivity amounts to evaluating the gradient of the solution with respect to parameters of interest. Many mathematical methods can be used for that purpose, ranging from local linearization (e.g. adjoint problem-based approaches) to fully nonlinear response surface reconstruction. The latter has been very recently applied to LES. The generalized polynomial chaos approach, which allows for a Galerkin-type reconstruction of the response surface with pseudospectral accuracy, was used by Lucor et al. (2007) to compute the sensitivity of the kinetic energy spectrum in decaying isotropic turbulence with respect to the arbitrary constant which appears in the Smagorinsky subgrid model. A typical output is the probability density function of the energy spectrum at all resolved scales. Another method, namely the Kriging method, which is an optimal statistical linear interpolation technique, was used by Jouhaud et al. (2008) to
investigate the sensitivity of the LES of the flow in the cooling system of an aeronautical engine. Both the numerical stabilization tuning parameter and the Smagorinsky model constant were considered as uncertain parameters, since their optimal values are known to be case-dependent. A typical output here was the prediction of the range of variation of the computed mean flow thanks to the response surface (see figure 3). It is observed that the computed mean velocity field sensitivity varies very significantly, depending on both the location and the

Figure 3. Kriging-based prediction of the range of variation of the LES mean flow in a complex configuration. (a) $X/D=1$; (b) $X/D=8$. Symbols, measurements; solid lines, LES solution computed with standard values of numerical stabilization parameter and Smagorinsky constant; dashed lines, envelope of the LES solution predicted thanks to the response surface. Adapted from Jouhaud et al. (2008).
selected velocity component. The new information retrieved from the response surface is related to the possibility to perfectly match measurements at some point on the computational grid or to globally minimize the discrepancies with experimental values by adjusting computational parameters. In such a case, a validated method is a method whose response surface encompasses reference data. This allows for the definition of optimal LES parameters on a given computational grid.

6. Concluding remarks

As a conclusion, let us emphasize that even if universal methods for industrial unsteady flows will not be available in the near future, useful results for design and understanding of flow physics can be obtained by adapting the level of modelling to the considered problem without waiting for the next generation of supercomputers. The next foreseen challenges in applied numerical aerodynamics will be firstly the capture of the boundary-layer dynamics including transition and pressure-gradient-driven separation issues and secondly the capability to handle accurately geometrically complex configurations with validated unsteady tools. In the near future, if (really) complex configurations are considered, the validation procedure should account for uncertainties and errors which arise from the very definition of the computational model and the postprocessing of data of different nature. Accurate validations of system simulations will also require adequate experimental databases, which are still missing.

References


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