Computers & Fluids 39 (2010) 735–738

Contents lists available at ScienceDirect

Computers & Fluids

journal homepage: www.elsevier.com/locate/compfluid

Review

Advances and challenges of applied large-eddy simulation

Roland Bouffanais

Massachusetts Institute of Technology, Department of Mechanical Engineering, 77 Massachusetts Avenue, Bldg 5–326, Cambridge, MA 02139, USA

A R T I C L E I N F O

Article history:
Received 24 November 2009
Received in revised form 30 November 2009
Accepted 1 December 2009
Available online 14 December 2009

Keywords:
Large-eddy simulation
Industrial applications
Best practices
Turbulence modeling

A B S T R A C T

Large-eddy simulation has become one of the most promising and successful methodology that concerns turbulent flows. It is reaching a level of maturity that brings this approach to the mainstream of engineering and industrial computations, while it opens new opportunities and brings new challenges for further progress. These advances and challenges, in the framework of industrial applications, have been the subject of a discussion meeting held at the Royal Society that brought together leading LES experts and industrial practitioners. The outcome of this discussion meeting is reported in a recent issue of *Philosophical Transactions of the Royal Society A*, and is thoroughly reviewed in this article. Advances and challenges of LES applied in industrial applications are concurrently reviewed and further discussed.

Contents

1. Introduction

The vast majority of naturally occurring flows is turbulent. Hence it is instrumental for industrial applications to achieve an accurate modeling of turbulent flows. Large-eddy simulation (LES) seeks to directly calculate the largest and most energetic vortical structures in turbulent flows, while modeling the effects of the smaller-scale eddies. There is no doubt that the field of LES is attracting an ever-increasing attention from the scientific community at large. Not only its own community of LES practitioners has been significantly growing, but more recently communities of industrial partners, engineers and scientists motivating application-oriented 'deliverables' have started implementing LES to achieve more accurate simulations involving turbulent flows as a key component of the whole studied system. Indeed over the last three decades, LES has evolved into a powerful tool of central importance for problems connected to turbulent phenomena at some levels. Despite the numerous challenges still facing LES, one can fairly admit that LES has become one of the most promising and successful methodology available to tackle industrial turbulent flows.

Following up on these trends in the field of applied large-eddy simulation, a discussion meeting was organized by Paul G. Tucker and Sylvain Lardeau and held at the Royal Society in London on 27–28 October 2008. Subsequently the special issue 367 of *Philosophical Transactions of the Royal Society A – Math., Phys. and Eng. Sci.*, entitled "Applied large-eddy simulation", has been published in 2009. It comprises 16 articles (primarily review articles with some new contributions) from leading LES specialists and practitioners, and dealing with a broad variety of topics [1–16]. The objective of this article is to briefly review this special issue and to further discuss the advances and challenges of LES applied in industrial applications.

E-mail address: bouffana@mit.edu

0045-7930/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.compfluid.2009.12.003

2. Facts and trends about LES and its scientific community

The growing interest towards LES is attested by several distinct indicators. First, let us consider the number of articles published annually in international journals. It is noteworthy highlighting that the number of publications per year involving LES at any level has almost increased tenfold since 1980, and threefold since 1990, as can be seen from the histogram appearing in Fig. 1. In parallel to this tremendous increase in journal publications, a noticeable (although not as easily quantifiable) increase in the number of contributed talks in international conferences (targeting both broad and specialized audiences across very different fields of study) is being felt by groups working on turbulence and its modeling. Such a trend is very likely connected to the advent of high performance computing (petaflop machines have appeared and started spreading, and will soon become commonly available) making turbulent flow simulations at high Reynolds number and/or involving complex geometries falling within the realm of feasibility. Finally, in the past 4 years, a relatively important number of monographs dealing specifically with LES have made their appearance in the bookshelves of libraries. Without the pretension of completeness, a non-exhaustive list of those books is given here for reference and in chronological order of publication: Berselli et al., Mathematics of large-eddy simulation of turbulent flows [17]; Sagaut, Large-eddy simulation for incompressible flows: an introduction, 3rd ed. [18]; Wagner et al., Large-eddy simulation for acoustics [19]; Grinstein et al., Implicit large-eddy simulation: computing turbulent fluid dynamics [20]; Meyers et al., Quality and reliability of large-eddy simulations [21]; Ihme, Pollutant formation and noise emission in turbulent diffusion flames: model development and application to large-eddy simulation [22]; Garnier et al., Large-eddy simulation for compressible flows [23]; Jiang and Lai, Numerical techniques for direct and large-eddy simulations [24]. The great variety of LES subfields dealt with in those books is striking.

All the above concordant indicators not only characterize the ever-expanding interest in LES but they also reflect the fact that this simulation technique has reached a certain level of maturity and hence is increasingly being considered and used to solve applied and industrial problems. For these problems, direct numerical simulations (DNS) become totally inappropriate due to prohibitive cost and simulation length, e.g. DNS won't be used as a predictive tool for design purposes for at least several decades to come.

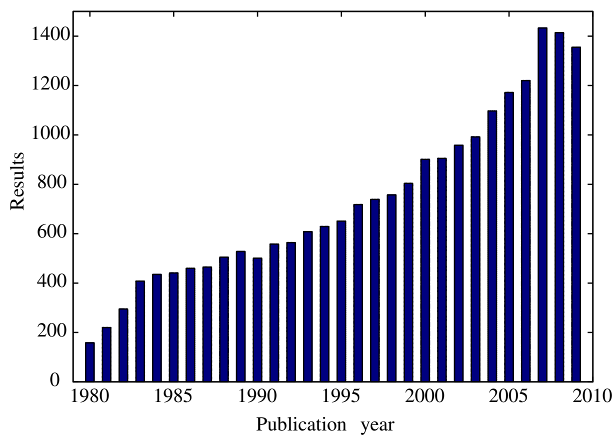

Fig. 1. Histogram of the total number of results for the search query "large-eddy simulation" using Web of Science® for the period 1980–2009 sorted by publication year. Note that the number of results for the year 2009 is not final as the year has not ended at the time of writing. The number of results for 2009 is very likely going to top the histogram for the corresponding period.

Some of the focus in the field of LES has now shifted from theoretical analysis and ever-complexifying subgrid modeling towards more application-oriented implementations. Given the above facts about LES (primarily its achieved maturity level) and this trend, the initiative by P.G. Tucker and S. Lardeau to call a discussion meeting appears both rational and timely. Such an initiative can only be praised given the serious existing gap between the theoretical knowledge about LES, on one hand, and on the other hand the associated practical knowhow in terms of fields of application and implementation details.

3. Background information

It is useful reminding that the key building blocks of any LES can be listed as:

1. A filtering technique applied to the Navier–Stokes equations.
2. A thoroughly-validated closure model (this block encompasses 'traditional' subgrid modeling but also includes other more general closure treatments such as for instance approximate deconvolution models [25], etc.).
3. Supply the boundary conditions with an adequate treatment for enforcing them (i.e. near-wall modeling) and the initial conditions.
4. An appropriate numerical methods to discretize both in space and time the governing equations.
5. Perform the simulation.

according to Berselli et al. [17] and Pope [26]. The overall success of any LES is therefore dependent on three key challenges [17]:

1. Obtain accurate flow averages reflecting the true flow.
2. Minimize the discretization errors.
3. Perform the simulation in a time- and cost-effective manner.

From the standpoint of the above five key building blocks and three key challenges, the articles in the special issue "Applied large-eddy simulation" (except for a single one by Drikakis et al. [15]) deals with most of these aspects except for a central one: the interplay between LES modeling and numerical modeling. To a large extent, this coupling is a serious source of concerns for closure modeling. However, filtering and near-wall modeling are not exempt from defects induced by the space- and time-discretization [26]. This point is further discussed below and is acknowledged by the organizers themselves: "The numerous discretization issues did not feature as prominently at the meeting as they might have done" [1]. This lack of discussion on these topics can easily be justified by the mountain of different numerical methods available to perform simulations.

4. Dealing with the coupling between LES and numerical modeling

The vast breadth of choice in discretization techniques is naturally commendable but also poses tremendous challenges to LES practitioners due to the required high level of technicality. It is not only the specificities of each and every numerical technique which are already a large source of troubles while implementing and performing a numerical simulations, but it is primarily this interplay between the theoretical aspects of LES mentioned above (filtering, closure modeling, enforcement of the boundary conditions) and the practical implementation aspects for the practitioners. It is worth adding here that the influence of the choice of the numerical method for discretizing the problem (item 4 in the above list of building blocks) has cascading effects over all the four other blocks: filtering (be it implicit or explicit) is always connected to the numerical method; the closure models are always directly or indirectly (through filtering) affected by the choice of discretization; obviously the enforcement of boundary conditions (and hence the near-wall modeling) are highly dependent on the numerical scheme; the performance of the simulation is also closely dependent on the numerical framework. This issue of the interplay between LES modeling, on one hand, and on the other hand numerical discretization is commonly and largely overlooked. Too often, members of the LES community move their research forward within a specific numerical framework(s).

5. Is numerical independence achievable and desirable?

The intricate and natural coupling between LES modeling and numerical discretization makes it really difficult for other research groups to assess the feasibility and the pertinence of these advances within their own numerical framework. For instance, consider the thorough and insightful error analysis performed by Geurts and reviewed in [7] in the finite-volume framework. To our knowledge, there is no simple or straightforward way of interpreting or even using these results and conclusions in order to extend and apply them to very different numerical frameworks such as spectral methods or meshfree methods. Two quintessential examples of this strenuous issue are given by the subfields of implicit large-eddy simulation (ILES) [20] and monotone integrated LES (MILES) [14]. Both ILES and MILES are characterized by the intricate coupling between the numerical scheme and the filtering, the closure and near-wall modeling. Such a coupling drastically simplifies the LES implementation but concurrently alleviates the control over the governing parameters of the modeling parts underpinning any LES. As a consequence, MILES and ILES are still leading to unresolvable controversies amongst LES practitioners.

It seems therefore that a rational solution to these issues would be to investigate and discuss the issue of the 'numerical independence' of LES modeling. At this stage, two questions arise: 1. Is numerical independence achievable? 2. Is numerical independence really a desirable feature? The positive answer to question 1 is based on the well-known fact that some groups of numerical methods actually yield very minimal numerical dissipation and dispersion, e.g. spectral and high-order methods [27]. Unfortunately, it is not possible to provide a yes/no answer to question 2 as it touches to some 'quasi-philosophical' decisions taken by the LES practitioner. Obviously, the proponents of MILES and ILES would strongly oppose this concept of numerical independence. However, as we have seen from the answer to the first question asked, such a goal is indeed achievable in specific numerical frameworks and on the top of that, offers the advantages of decoupling the five key building blocks of LES. Such a decoupling dramatically simplifies the development, testing and implementation of each and every block independently of the others. From the collaborative standpoint, there is no doubt that enforcing numerical independence would accelerate the pace of development of LES and contribute to bringing this methodology to the mainstream of engineering and industrial computations.

6. More details about the special issue

Given all the above raised concerns and the remaining challenges faced by LES, it is nonetheless a great source of satisfaction to observe the growing interest for LES amongst the industrial partners. The engineers and scientists in charge of implementing a LES solution adapted to their turbulent problems will certainly benefit from the special issue "Applied large-eddy simulation". However, the targeted audience for this special issue should not be considered to be limited to the aforementioned group but instead this audience should encompass the LES community at large. Some of the general review articles (more specifically [1,2,4,7,8]) serve as a useful reminder of the real challenges for LES to really become the prevailing simulation tool for studying high Reynolds number flow phenomena. These challenges and the framework in which they are embedded are judiciously recalled to our attention in some articles of this special issue. Hopefully this special issue's reminders will convince some LES developers to quit the 'subgrid modeling race'. What is called here the 'subgrid modeling race' is, in our opinion, the excessive research effort placed and focused at devising exceedingly complicated subgrid-scale models, in place of investigating other LES building blocks and challenges. This point is directly acknowledged in [1,2] where it is mentioned: "The number of LES models has increased almost exponentially in recent years" and "the question arises about the effort expended to develop new SGS models, and if this effort would not be better used in other areas".

To help the potential reader make a selective choice, the articles in this special issue can be sorted by topics and applications considered:

- General considerations, from the theoretical, practical and industrial standpoints [1,2,4,7,8].
- Aerodynamics, aeroacoustics and compressible flows [5,6]; aspects of external aerodynamics of trains and cars [10].
- Combustion and reacting flows [13].
- Turbomachinery [3,16].
- Weather forecasting and large-scale geophysics simulations [12].
- Flow mixing processes [14].
- Hybridization and coupling to other methods, e.g. RANS–LES, [9].
- LES and turbulent flow experiments [11].
- Implicit large-eddy simulations [11,15].

7. Outlook and prospects

It is worth noting that by making a selection from the above categorized articles, one will also learn about the future prospects associated with complex LES projects, i.e. with complex geometries and/or very high Reynolds numbers, relevant to the applied and industrial LES practitioners. The most recurrent 'hot topic' and encouraging prospect is the hybridization of LES with other methods such as Reynolds averaged Navier–Stokes (RANS) [1,5,8,9]. The concept behind these hybrid techniques is simple yet powerful, and relies on coupling LES to other complementing techniques, e.g. Hybrid RANS–LES, detached eddy simulation (DES). These hybrid RANS–LES methods provide a very effective way of handling the required high resolution near a boundary or a wall. Such hybrid methods happen to provide time- and cost-effective simulation tools desired by the industrial practitioners. As always there is a price to pay for these nice features of hybrid RANS–LES methods: it is the price of the coupling between the near-wall region where the RANS is performed with the region where LES prevails. This coupling introduces a new level of modeling and constraints in the theoretical formulation and ultimately in its implementation.

8. Challenges faced when transitioning from RANS to LES

All along this review, we have stressed the challenges induced by the compelling interconnection between the different components of any LES. When considering industrial problems with a turbulent character, LES has proved to successfully overcome the limitations of traditional simulation tools such as RANS or unsteady RANS (URANS) for instance. However, for industrial practitioners and numericists the transition from RANS to LES is far from being trivial due to a series of factors inherent to LES itself. The implementation issues, including the choice of filtering, closure modeling and near-wall treatment, certainly pervades the whole transition process.

9. Transdisciplinarity and the wide field of applications of LES

It is important stressing one more instrumental point concerning LES which has not been raised before in this review. Contrary to the discussion above, this point is more general and does not concern exclusively LES. It is a well-known fact that turbulence is ubiquitous in nature and central to many applications. Consequently, as a simulation tool of turbulent systems, LES is applicable to a large range of applications in many very different fields: geophysics, astrophysics, oceanography, combustion, medical sciences, aerodynamics, etc. This transdisciplinary character or LES has the advantage of increasing the size of the community and hence increases the number of users and the associated research funding. The transdisciplinary character of LES is pointed out by Tucker and Lardeau in [1] but the full set of effects induced by this particular feature, over the current and future developments of LES has not been discussed. It is now well-known and documented that transdisciplinarity is a source of difficulties and communication breakdowns between different groups working to achieve significantly different goals [28]. This of course applies to LES practitioners. To exemplify, one may imagine a meeting aimed at sharing best LES practices between scientists studying the aeroacoustic turbulent flow over an airfoil with a group of astrophysicists modeling the deflagration of a supernovae, both groups being LES practitioners. With some imagination one can have an idea of such an hypothetical meeting by reading the following two references [29,30].

The same type of difficulties and communication breakdowns are encountered between LES developers and industrial partners; goals and priorities of the latter are quite different from their counterparts in academia [1]. Somehow, it is not so common in science and engineering to have so noticeably different communities using the exact same tool. It would then be interesting to have a detailed study of these issues and solutions to overcome some of them, available to the LES community.

Ultimately, it is critical keeping in mind that as George E.P. Box wrote: "Essentially, all models are wrong but some are useful" [31]. This quote from George E.P. Box led to a recent statement from Stephen B. Pope, during an invited lecture at the 62nd annual meeting of the Division of Fluid Dynamics of the American Physical Society: "Models of turbulence are inevitably incomplete".

References

[1] Tucker PG, Lardeau S. Introduction: applied large eddy simulation. Phil Trans Roy Soc Lond A – Math Phys Eng Sci 2009;367:2809–18. doi:10.1098/rsta.2009.0065.

[2] Hutton AG. The emerging role of large eddy simulation in industrial practice: challenges and opportunities. Phil Trans Roy Soc Lond A – Math Phys Eng Sci 2009;367:819–2826. doi:10.1098/rsta.2009.0077.

[3] Menzies K. Large eddy simulation applications in gas turbines. Phil Trans Roy Soc Lond A – Math Phys Eng Sci 2009;367:2827–38. doi:10.1098/rsta.2009.0064.

[4] George WK, Tutkun M. Mind the gap: a guideline for large eddy simulation. Phil Trans Roy Soc Lond A – Math Phys Eng Sci 2009;367:2839–47. doi:10.1098/rsta.2009.0063.

[5] Sagaut P, Deck S. Large eddy simulation for aerodynamics: status and perspectives. Phil Trans Roy Soc Lond A – Math Phys Eng Sci 2009;367:2849–60. doi:10.1098/rsta.2008.0269.

[6] Margolin LG. Finite-scale equations for compressible fluid flow. Phil Trans Roy Soc Lond A – Math Phys Eng Sci 2009;367:2861–71. doi:10.1098/rsta.2008.0290.

[7] Geurts BJ. Analysis of errors occurring in large eddy simulation. Phil Trans Roy Soc Lond A – Math Phys Eng Sci 2009;367:2873–83. doi:10.1098/rsta.2009.0001.

[8] Leschziner M, Li N, Tessicini F. Simulating flow separation from continuous surfaces: routes to overcoming the reynolds number barrier. Phil Trans Roy Soc Lond A – Math Phys Eng Sci 2009;367:2885–903. doi:10.1098/rsta.2009.0002.

[9] Davidson L. Hybrid LES-RANS: back scatter from a scale-similarity model used as forcing. Phil Trans Roy Soc Lond A – Math Phys Eng Sci 2009;367:2905–15. doi:10.1098/rsta.2008.0299.

[10] Krajnović S. Large eddy simulation of flows around ground vehicles and other bluff bodies. Phil Trans Roy Soc Lond A – Math Phys Eng Sci 2009;367:2917–30. doi:10.1098/rsta.2009.0021.

[11] Grinstein FF. On integrating large eddy simulation and laboratory turbulent flow experiments. Phil Trans Roy Soc Lond A – Math Phys Eng Sci 2009;367:2931–45. doi:10.1098/rsta.2009.0059.

[12] Cullen MJP, Brown AR. Large eddy simulation of the atmosphere on various scales. Phil Trans Roy Soc Lond A – Math Phys Eng Sci 2009;367:2947–56. doi:10.1098/rsta.2008.0268.

[13] Fureby C. Large eddy simulation modelling of combustion for propulsion applications. Phil Trans Roy Soc Lond A – Math Phys Eng Sci 2009;367:2957–69. doi:10.1098/rsta.2008.0271.

[14] Youngs DL. Application of monotone integrated large eddy simulation to Rayleigh–Taylor mixing. Phil Trans Roy Soc Lond A – Math Phys Eng Sci 2009;367:2971–83. doi:10.1098/rsta.2008.0303.

[15] Drikakis D, Hahn M, Mosedale A, Thornber B. Large eddy simulation using high-resolution and high-order methods. Phil Trans Roy Soc Lond A – Math Phys Eng Sci 2009;367:2985–97. doi:10.1098/rsta.2008.0312.

[16] Eastwood SJ, Tucker PG, Xia H, Klostermeier C. Developing large eddy simulation for turbomachinery applications. Phil Trans Roy Soc Lond A – Math Phys Eng Sci 2009;367:2999–3013. doi:10.1098/rsta.2008.0281.

[17] Berselli LC, Iliescu T, Layton WJ. Mathematics of large eddy simulation of turbulent flows. Berlin (New York): Springer; 2006.

[18] Sagaut P. Large eddy simulation for incompressible flows: an introduction. 3rd ed. Berlin (New York): Springer; 2006.

[19] Wagner CA, Hüttl T, Sagaut P. Large-eddy simulation for acoustics. Cambridge (UK): Cambridge University Press; 2007.

[20] Grinstein FF, Margolin LG, Rider WJ. Implicit large eddy simulation: computing turbulent fluid dynamics. Cambridge (UK): Cambridge University Press; 2007.

[21] Meyers J, Geurts BJ, Sagaut P. Quality and reliability of large-eddy simulations. ERCOFTAC series. Berlin (New York): Springer; 2008.

[22] Ihme M. Pollutant formation and noise emission in turbulent diffusion flames: model development and application to large-eddy simulation. Saarbrücken (Germany): VDM Verlag; 2008.

[23] Garnier E, Adams N, Sagaut P. Large eddy simulation for compressible flows. New York: Springer; 2009.

[24] Jiang X, Lai C-H. Numerical techniques for direct and large eddy simulations. Boca Raton (FL): Chapman & Hall/CRC; 2009.

[25] Stolz S, Adams NA. An approximate deconvolution procedure for large-eddy simulation. Phys Fluids 1999;11:1699–701. doi:10.1063/1.869867.

[26] Pope SB. Turbulent flows. Cambridge (UK): Cambridge University Press; 2000.

[27] Deville MO, Fischer PF, Mund EH. High-order methods for incompressible fluid flow. Cambridge (UK): Cambridge University Press; 2002.

[28] Hirsch Hadorn G, Hoffman-Riem H, Biber-Klemm S, Grossenbacher-Mansuy W, Joye D, Pohl C, et al., editors. Handbook of transdisciplinary research. Berlin (New York): Springer; 2008.

[29] Roepke FK, Hillebrandt W, Schmidt W, Niemeyer JC, Blinnikov SI, Mazzali PA. A three-dimensional deflagration model for type ia supernovae compared with observations. Astrophys J 2007;668(2, Part 1):1132–9. doi:10.1086/521347.

[30] Shen WZ, Zhu W, Sørensen JN. Aeroacoustic computations for turbulent airfoil flows. AIAA J 2009;47(6):1518–27. doi:10.2514/1.40399.

[31] Box GEP, Draper NR. Empirical model-building and response surfaces, wiley series in probability and mathematical statistics. Applied probability and statistics. New York: John Wiley & Sons; 1987.