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Eddy resolving simulations in aerospace – Invited paper (Numerical Fluid 2014)

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ABSTRACT

The future use of eddy resolving simulations (ERS) such as Large Eddy Simulation (LES), Direct Numerical Simulation (DNS) and related approaches in aerospace is explored. The turbulence modeling requirements with respect to aeroengines and aircraft is contrasted. For the latter, higher Reynolds numbers are more prevalent and this especially gives rise to the need for the hybridization of ERS methods with Reynolds Averaged Navier–Stokes (RANS) approaches. Zones where future use of pure ERS methods is now possible and those where hybridizations with RANS will be needed is outlined. The major focus is the aeroengine for which the component scales are much smaller. This gives rise to generally more benign Reynolds numbers. The use of eddy resolving methods in a wide range of zones in an aeroengine is discussed and the potential benefits and also cost drawbacks with such approaches noted. The tension when using such computationally intensive calculations in an area where the coupling of components and even the airframe and engine is becoming increasingly important is explored. Also, the numerical methods and meshing requirements are considered and the implications of ERS methods for future numerical algorithms. It is postulated that such simulations are ready now for niche uses in industry. However, to perform the scale of simulations that industry requires, to meet pressing environmental needs, challenges remain. For example, there is the need to develop optimal numerical methods that both map to the accuracy requirements for ERS and also future computer architectures.

1. Introduction

By 2030 the world aircraft fleet is set to double. This gives rise to pressing environmental challenges. This does not just relate emission of greenhouse gasses but also noise. Ever increasing population densities mean that increasing numbers of people live in close proximity to airports. Indeed noise can be more than just an annoyance but also a contributing factor to illnesses such as hypertension.

Simulation is a critical part of aircraft design. Aircraft are sold ahead of actually being built. The expected performance of the aircraft is based around simulations of varying fidelities. Critically, since aircraft and their engines are tremendously large and powerful systems, carrying out representative experimental tests is costly, indeed typically around £1 million [1]. This again makes the role of simulation of extreme importance to aerospace manufacturers. Future, more advanced

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aircraft designs, will involve ever increasing integration of both the aircraft and the engine. This will yet again increase the complexity and expense of experimental tests.

A major difficulty for simulation over the years has been how to accurately and reliably mathematically model turbulence. Turbulence governs drag, heat transfer and also, importantly, much of the acoustics from both the aircraft and the engine.

Traditionally, turbulence has been treated by time averaging the Navier–Stokes equations, after decomposing the flow into a mean and fluctuations about this. This process gives rise to the Reynolds Averaged Navier–Stokes (RANS) equations. These, mean flow equations, contain unknown products of the velocity fluctuations associated with turbulence. These are generally called the Reynolds stresses. These stresses account for the increased drag and shearing in the fluid due to turbulence and also the increased mixing that arises from turbulence. A turbulence model is needed to account these additional stresses. The Boussinesq approximation allows the extra stresses to be accounted for through products of mean velocity gradients (know quantities) and a new quantity called the eddy viscosity. The problem is then shifted to modeling the extreme dynamical complexity of turbulence through an enhanced viscosity term. Alternatively, transport equations can be formulated for each of the potential velocity fluctuation components. This latter, more computationally expensive, option gives rise to the full Reynolds stress model. Halfway houses have also been formulated, that can be considered as compromises between the cost of the full Reynolds stress model and the inaccuracies of the use of using a linear eddy viscosity relationship. These are generally termed non-linear eddy viscosity or explicit Reynolds stress models. The many hundreds of turbulence models available [2] to the engineer gives stark testimony to the battle that both scientists and engineers have had to deal with turbulence.

The other alternative to RANS, i.e. fully modeling the turbulence, is to directly/fully solve for it. This is called Direct Numerical Simulation (DNS). The Navier–Stokes equations are a remarkably exact description of turbulence. They just need solution on a sufficiently fine grid with sufficiently small time steps and all the turbulence will be naturally captured. However, this option, at high Reynolds number, as will be discussed further later, is extremely computationally expensive. A multitude of other alternatives exist. For example, with Large Eddy Simulations (LES), just roughly 10% of the turbulence is modeled – typically using methods close to RANS. The remaining turbulence, the larger scales are resolved as in DNS. Further possibilities exist, where the domain has fully RANS and fully LES zones in different areas. Alternatively, it is possible to increase the approximate, 10% modeled threshold noted for LES, and locally model more turbulence and resolve less – again giving, in a crude sense, a greater RANS bias. These strategies can be used to make the cost of eddy resolving simulations (ERS) more manageable but at the sacrifice of accuracy. Further discussion on such zonalizations in relation to cost is given next.

2. Eddy resolving simulation cost

In the 1970s Chapman [3] proposed that when computers reached about 10^{14} FLOPS, billion cell, three-dimensional, unsteady, calculations would be possible and that these would be able to resolve much of the turbulence energy in the flow. With such simulations much less reliance would be required on turbulence models. Their role either being either to: (a) Globally account for just the small scales of turbulence – LES or (b) Totally model turbulence in under-resolved mesh zones (typically near walls) (DES/hybrid RANS–LES). Fig. 1 shows the methods, cost and modeled scales indicated by shaded regions and the notional percentage of modeled turbulence. Due to the low turbulence model influence and reasonable cost, LES and hybrid methods are attractive for practical use. Since Chapman's 'prophecy', the computer power has continued to dramatically increase. Indeed as pointed out by Jameson [4], computer power has increased by a factor of 1 million in the past 25 years. There seems no reason for this not to continue and exascale computing is due in 2018, opening further opportunities. Fig. 2 shows the performance trends which should continue into 2030. Note there is a delay of around 10 years between the world's most computationally powerful and the 500th most powerful super computer, providing a good indication of future performance.

The key difficulty with the type of eddy resolving simulations implied by Chapman is the resolution of the turbulence near walls. Near walls, there are, in the $y^+ < 60$ zone (note, y^+ corresponds to standard dimensionless wall units for turbulent flows), fine, flow aligned streak like structures as shown in Fig. 3. Pope [5] estimates that for a Boeing 777 at cruise, there are around 0.1 billion of these streak structures, requiring grids on the order of 1 billion cells. Similar estimates for an Airbus A340-300 fuselage suggest around 2 billion streaks [6]. For a large civil aeroengine fan blade, there are about 10^7 streaks. The critical difficulty is that as the Reynolds number increases, a greater range of turbulent scales needs to be resolved. Hence, we observe the well-known approximate cost for LES (Large Eddy Simulation) of wall bounded flows scaling approximately with $Re^{2.5}$, where Re is the Reynolds number. Great impetus to the use of Eddy resolving simulations (ERS) in aerospace was given by Spalart in 1997 [7][8]. In this work a NACA 0012 aerofoil at a high angle of attack is considered. The complete boundary layer is treated with RANS, this covering over the problematic finer scales. Outside the boundary layer, turbulent eddies are resolved. Simulations of this type, described as DES (Detached Eddy Simulation), are shown in Fig. 4, contrasting Re independent wake-type flows and Re dependent boundary layer dominant flows. Spalart's concept was not completely new. For some years various forms of RANS related modeling had been used in conjunction with ERS but not in such an explicit form. The hybridization of a classic industry RANS model with ERS, for a flow of practical aerospace relevance was inspirational to many – including the current authors. Very soon after this, work emerged at the

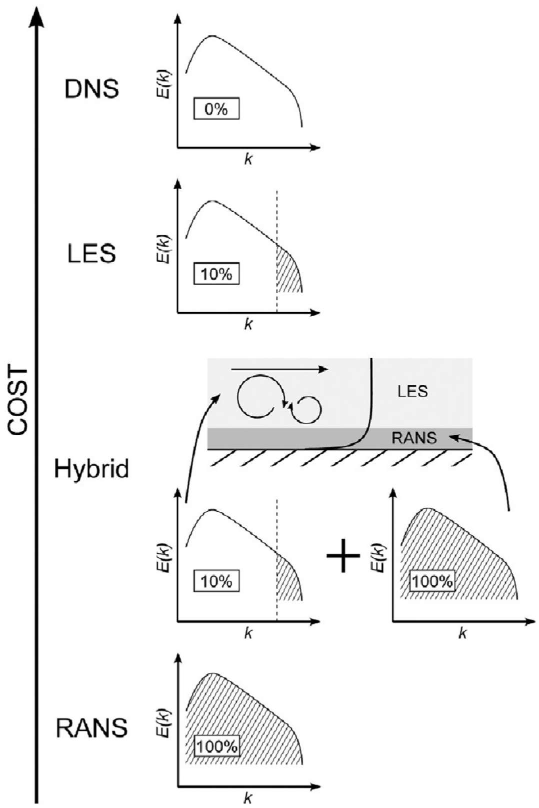

Fig. 1. Increasing cost of resolving different turbulence scales.

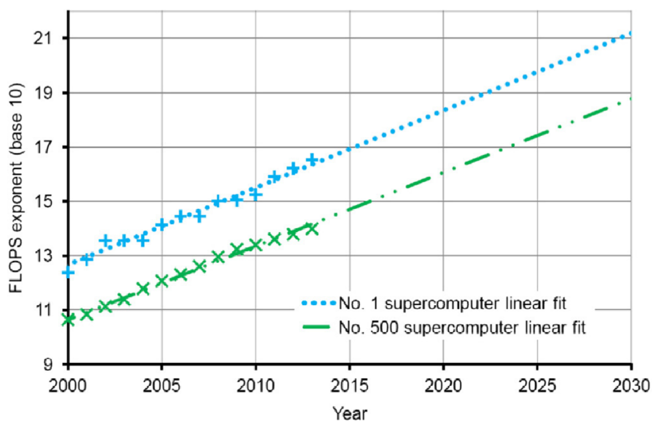

Fig. 2. Computational performance of the world's fastest and 500th fastest supercomputers since the year 2000, extrapolated to year 2030 (measured in floating point operations per second, FLOPS).

US Air Force Laboratory applying the approach to full fighter aircraft configurations, culminating in agreement between real flight test data for tail buffet [9]. Considerable campaigns on missile base flows were also carried out along with landing gear and wings with flaps at high angles [10] to name but a few. Notably, this work focused on massively separated off design flows. These effectively have substantially Reynolds number independent flow physics.

A critical question is how might ERS be used for design conditions? The application of DES, at design, generally, has little attraction. The boundary layer is RANS modeled and there can often be little activity external to it. As noted earlier, reliable RANS modeling is challenging, but for the largely attached boundary layers at design, uncertainties can be manageable. If it was desired to virtually eradicate turbulence modeling errors ERS would be needed but this is impractical for many higher

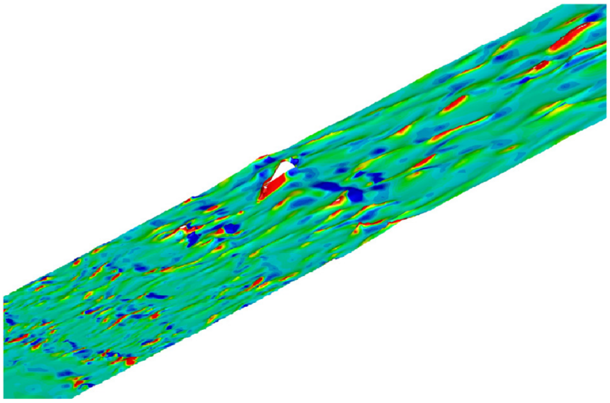

Fig. 3. Near wall streaks which must be resolved using pure LES.

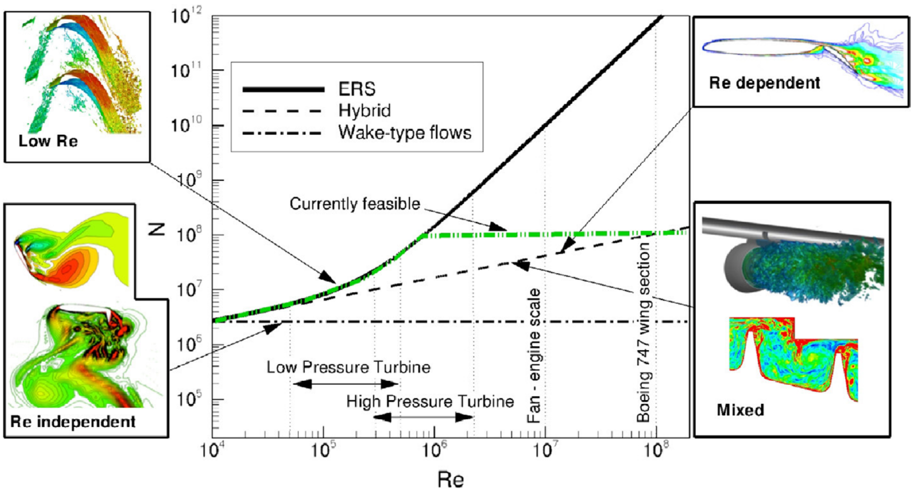

Fig. 4. Grid requirements and suggested modeling of different aeroengine and aerospace flows.

Table 1
Grid requirements for ERS.

Zone	Re_c	N for wall resolved ERS	N for hybrid RANS–ERS	No. streaks
Boeing 747 wing section	10^8	10^{12}	10^8	10^8
Fan, trent 1000	10^7	10^{10}	3×10^7	10^7
Large compressor	2.5×10^6	10^9	2×10^7	–
LPT	3×10^5	10^7	10^7	–

Reynolds number aerospace boundary layers flows. This can be seen from Fig. 4. This plots the grid count against chord based Re. Note the grid counts are just for spanwise sections of extent equal to chord. The estimates are based in Chapman's ideas. For developing boundary layers Chapman's outer layer grid requirement estimates are slightly optimistic but relative to the inner layer scaling costs, this is not that significant. The dashed line gives the hybrid RANS-ERS cost scaling when the RANS layer just extends to $y^+ = 60$–100. The full line is the ERS grid count line. Clearly for a large civil aircraft the use of ERS is not practical for the foreseeable future. However, ERS becomes more practical for wake and low *Re* flows whereas those with high *Re* boundary layer content can be practically tackled using hybrid methods. The "practical zone" is that below the green dash-dot-dot line indicated in Fig. 4, covering a significant range of flows. A direct comparison of grid requirements for different aerospace flows is also presented in Table 1. These are again based on chord based *Re*. Table 1 shows that utilizing RANS for just about 1% of the boundary layer to cover the streaks has vastly reduced the computational cost, but the scale

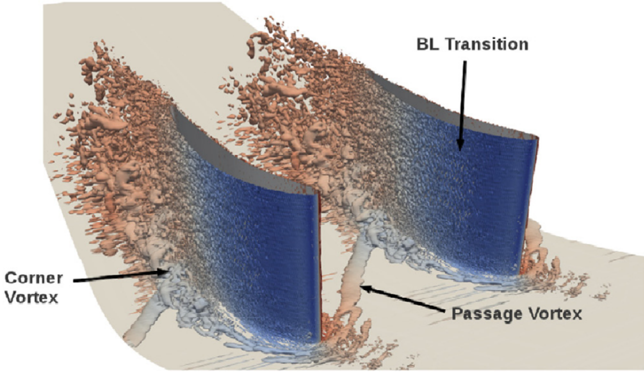

Fig. 5. DES type simulation of a compressor flow.

and speed of aircraft means that unless at off design conditions, eddy resolving methods, relative to potential accuracy benefits come at a heavy cost. Fortunately, the chords of airfoil sections found in the gas turbine that would typically power the aircraft are at least an order of magnitude smaller. Hence this softens the stark ${Re_c}^{2.5}$ cost scaling noted above. What is more, there is much more transitional flow and this is a great challenge to RANS models. Hence for aeroengines the impact/cost for eddy resolving methods is much greater.

Notably, as with airframes, for gas turbine aeroengines, there are niche off design applications where substantial accuracy benefits relative to RANS will be observed. An example of this would be compressor performance near stall, where much flow, akin to that observed in Spalart's pioneering NACA 0012 work will be observed along with a multiplicity of many other complex unsteady vortical physical mechanisms [10]. Fig. 5 shows an example of a DES type simulation of a separated compressor flow. Another example might be the in depth study of novel geometries where little previous data exists.

Also, in the aeroengine, there are a range of Reynolds number independent flow zones. For example, there are the ribbed passages that are essential for cooling the turbine blades which operate at above the melting point of typical metals [11,12]. The propulsive jet – once the nozzle with its boundary layers has been emerged from – is also a Reynolds number independent flow. There are also various seal type flows that arise at blade extremities where rotating and stationary surfaces connect. Of note, many flows cannot always be clearly classified, some having a strong mix of wake and strongly Reynolds number limited flow zones as identified in Fig. 4.

As can be seen from Table 1 clearly even though the typical Reynolds numbers found in gas turbine aeroengines are lower than for an airframe, ERS modeling of a fan, for example, is costly. On the other hand, the Low Pressure Turbines (LPT) at the back of the engine, have a modest *Re*. The flow physics for these is complex and transitional [13], where RANS modeling will be highly unreliable. In this zone it is compelling to start using ERS now in industry [14]. For other non-wake flow zones, the use of ERS in relation to impact over ease is far less compelling. However, as noted at the start, acoustics is also a critical environmental factor. To model acoustics 4th order spatial and temporal velocity correlations, information regarding the turbulence can be necessary. (This is demonstrated by Goldstein [15] through rearranging the Navier–Stokes equations to separate noise generation and propagation terms). Such Information could never be reliably discerned through the use of RANS. Hence acoustics is discussed next.

3. Aeroacoustics

Tonal noise relating to the interface of adjacent blade rows with their relative blade movements can be predicted reliably and economically with RANS. However, as noted above, the broadband noise arising from turbulent eddy interactions is also of some importance. This aspect, for fans at design, makes the use of ERS much more compelling. The high *Re* suggests the need for hybrid RANS–ERS. However, the use of this approach for acoustics is relatively new. Nonetheless, preliminary work suggests correct acoustic spectrum scaling can be found. For example, Ray and Dawes [16] perform Spalart–Allmaras DES and Tucker et al. [17] RANS–NLES of a transonic fan blade section. The flow conditions approximate the mid-span region of a blade rotating close to full speed. At high frequencies, empirical models [18] suggest turbulent boundary layers exhibit a f^{-5} scaling while at intermediate frequencies a f^{-1} scaling. Fig. 6 shows pressure-side surface spectra at 80% chord. The curves show the expected scalings. Hence, broadly the results are encouraging.

The propulsive jet, is, like the fan, another critical noise source. The *Re* for the jet nozzle exceeds that of even the fan. In this zone hybrid RANS–ERS will be essential for many years for the design of realistic systems. However, once the nozzle is emerged from into the Reynolds number independent jet, for acoustics, ERS gives some extreme accuracy benefits relative to RANS. This hybrid approach is shown in Fig. 7(a). The high *Re* near wall region shown in red is modeled with RANS and the wake-type flow downstream is resolved using LES. The temporal pressure gradient (dp/dt) and Ffowcs-Williams Hawkings (FWH) surface used to project sound to the far field, can be seen for a single stream jet in Fig. 7(b). From the FWH surface,

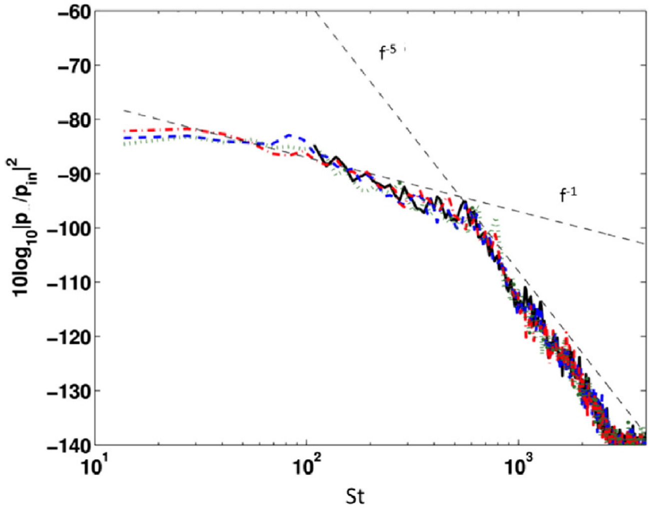

Fig. 6. Blade surface pressure spectra at around 80% chord [17].

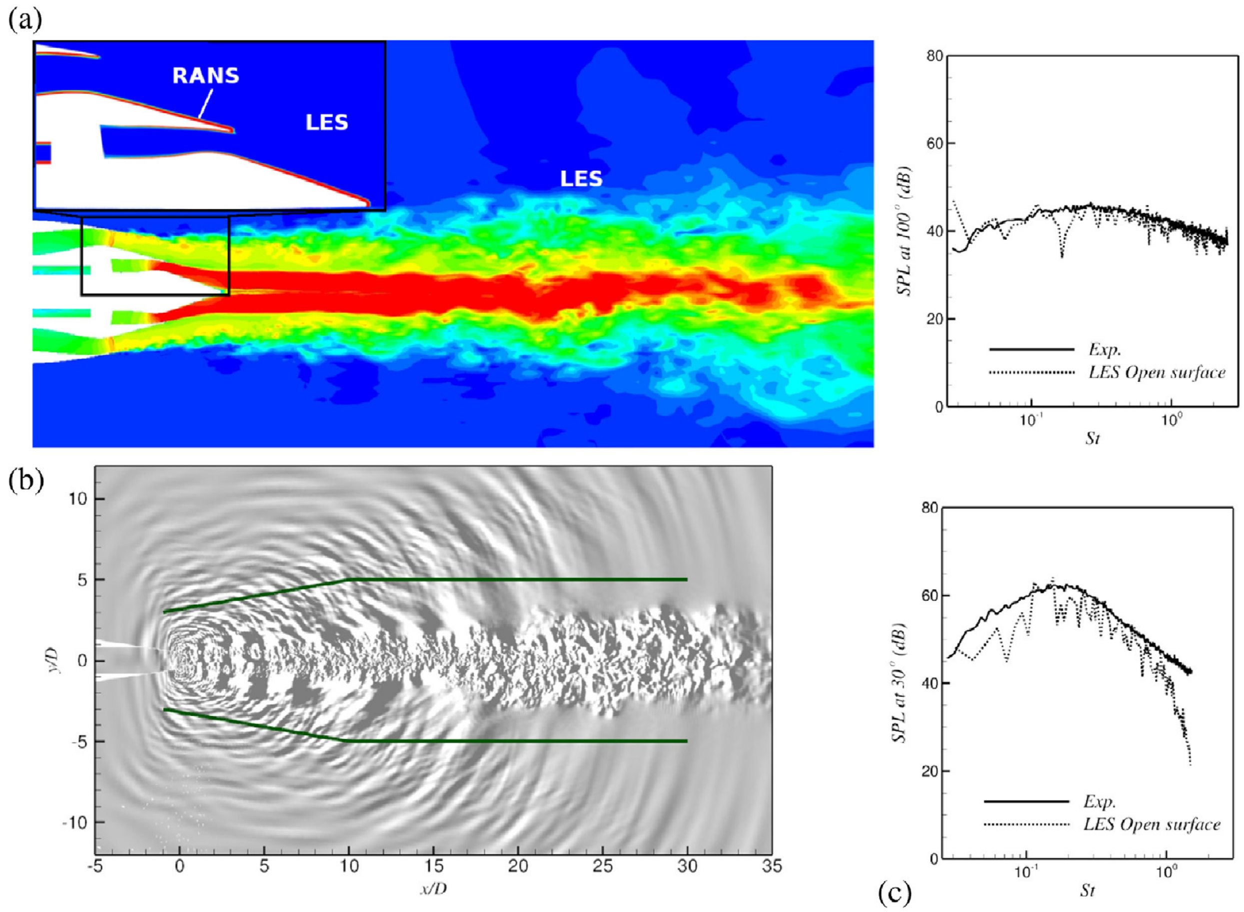

Fig. 7. (a) Hybrid RANS-LES zonalisation for jet nozzle flows (contours indicate axial velocity, the inset indicates the RANS layer), (b) pressure gradient contours and FWH surface, (c) sound pressure level spectra at observer locations of 100 and 30 degrees relative to the jet x-axis.

sound pressure level spectra can be extracted as shown in Fig. 7(c) showing agreement with measured data. As well as sheer scale and grid count there are a range of other challenges that currently reduce the industrial use of ERS. These are discussed below.

4. Computational challenges

4.1. Boundary conditions/problem definition

Unlike RANS, for ERS it can be important to correctly characterize turbulence inflow. There are numerous processes for synthetically generating more idealized turbulence inflow. However, for gas turbines there is much system coupling and this complicates turbulence inflow specification. For such coupled problems the boundary condition requirements go well beyond generating simple synthesized turbulence inflows and preventing outflow reflections. Even for the simple case of an aero engine propulsive jet there are a multitude of upstream turbulence inputs [19]. There are the aspects listed in Fig. 8. Such aspects of modeling real complex inflow are discussed in [10] and are of some importance when considering practical systems.

4.2. Numerical methods

Most aerospace flows are compressible – the expectation being that systems generally exhibit high Mach numbers – M. Hence, the numerical schemes are designed to be efficient and accurate at high M (>0.3). However inroads into numerical schemes are perhaps not as high as expected by Chapman. Indeed, even though there are an extensive range of numerical methods available, most practical compressible flow CFD is made with Roe based ideas [20] and this scheme, when designed, was not intended for ERS. A key difficulty for ERS is that near walls, in the streak zones, that have critical flow physics, $M \to 0$. This means that the Eigen value, in the Roe matrix, scaling the pressure smoothing becomes large. Also the 2nd major issue is that pressure cannot be reliably recovered from density at low M. Hence, more research is needed into developing compressible flow solver methods for ERS. Preconditioning will help, to an extent, but gives rise to excessive numerical stiffness at low M [10]. As shown by Ghosal [21], on theoretical grounds, higher order schemes are ideal. However, there are many successful ERS made with 2nd order solvers. The more critical issue for ERS is kinetic energy conservation. In fact, for ERS, a key attraction of high order is the potential for less data exchange across parallel processing boundaries (although this is dependent on the required stencil size). High order unstructured methods are available [10] but there is little current experience of their use for ERS and understanding of their dissipative properties at high wave number. However, developments are expected with these new schemes. It is also worth bearing in mind that a scheme that is dissipative at high wave numbers could make a useful Implicit LES (ILES) model (see [22]). This implicit model could even be combined with more classical explicit non-linear LES terms that provide back scatter but this is again dependent on the underlying discretisation. Hence mixed LES–ILES computations might be possible. Making classical LES with shocks is a more specialist area, where there has been some success [10] but this area lends itself well to ILES where some upwinding may be used locally near shocks. For more classical LES, with shocks, the development of shock switches that can distinguish between strong gradients from resolved turbulence and those from shocks is an important area of research.

Looking to the future, the way in which algorithms are developed and implemented will have a critical impact on code scalability on parallel architectures. Currently, up to 90% of computational performance is wasted, usually bound by memory and network bandwidth [23,24]. Existing methods may be improved and more efficiently implemented. However, substantial progress must be made in developing algorithms tailored to HPC, in general, avoiding data movement in memory and core-to-core communication. This includes but is not limited to communication avoiding methods such as tiling [23] and potentially, time-parallel methods such as Parareal [25]. So far these methods have seen little use for general turbulent flows,

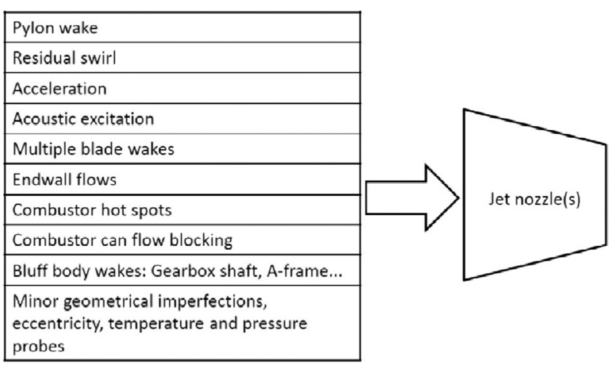

Fig. 8. Potential turbulence effects relevant to a turbulent jet nozzle.

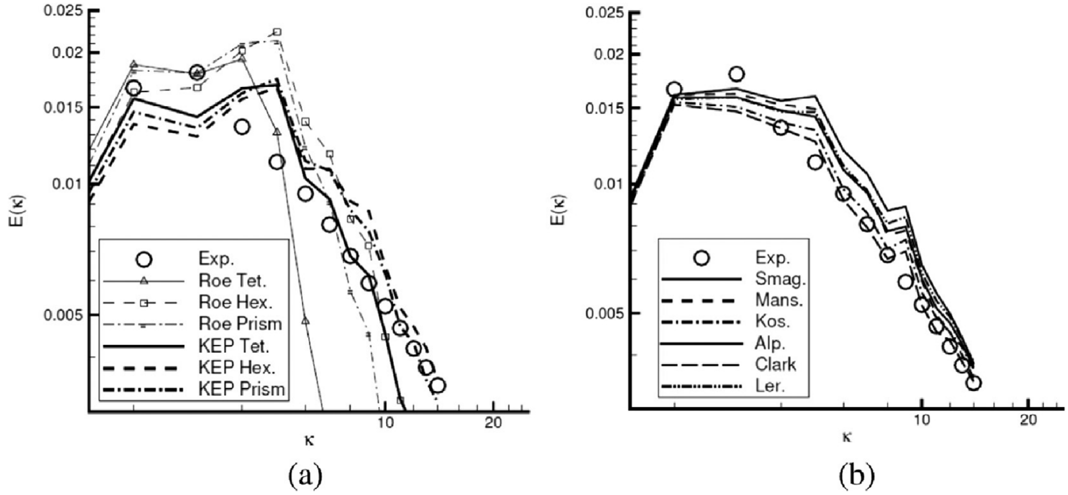

Fig. 9. Homogeneous decaying turbulence spectrum for (a), numerical schemes, (b), SGS models.

but may be fruitful if data dependence (or zones of dependence) are clearly identifiable. Rapidly advancing hardware also provides the opportunity to reduce manual pre- and post-processing effort, such as grid generation and data extraction and manipulation. This should provide significant improvements in end-to-end turnaround times and increased consistency through the use of more advanced, integrated tool chains.

4.3. Grids

Industrial geometries are complex making unstructured grids attractive. However, it is important to note that, as shown in modified equation analysis [22], the grid does effectively alter the equation set being solved. Fig. 9 shows simulations for homogenous decaying turbulence for different cell types in an unstructured flow solver [26]. Fig. 9(a) shows the influence of cell shape and numerical scheme. Cell shape has clearly had an impact and the best cell shape is hexahedral with more triangulated cells giving rise to a substantial loss of energy at high wave numbers. Fig. 9(b) indicates the reduced effect of SGS model when compared to numerical details. However, this cell shape impact can be greatly reduced by improved numerical schemes. For example, typically equations are discretised to conserve momentum. However, for ERS, as noted above, it is important to conserve kinetic energy. Jameson [4] presents a kinetic energy conserving scheme. The application of this scheme can result in substantially less dissipation – especially for the cells with triangulated components. Hence, for ERS it is especially important to consider both the interaction of the numerical scheme with the particular mesh topology employed. The optimal mesh for most numerical schemes will be hexahedral or even Voronoi. Both will ensure that control volume faces are orthogonal to the line connecting the nodes that straddle these faces. However, the hexahedral mesh is better suited for resolving boundary layer flows than the Voronoi. For industry, the *automatic* generation of such meshes is of considerable importance. What is more, structured flow solvers generally have a substantially lower computational overhead than unstructured. Currently, to the authors' knowledge, there is always some level of manual interaction required to generate high quality structured topologies. There are a range of approaches for automatically breaking down a complex geometry domain so that it can be readily tessellated by structured hexahedral cells. Examples of different approaches are given in Fig. 10. Descriptions of the underlying logical arguments necessary to generate these meshes can be found in [27].

The use of Chimera or overset meshes allows the structured meshing of extremely complex geometries. For more bluff body, wake type flows, octree meshes can be highly suitable for ERS – their isotropic cells ensuring the wide range of filter choices available have a consistent solution impact. For high *Re* flows, due to lack of cell anisotropy near walls, grid count can unfortunately become excessive. A range of potential filters is given in Table 2. The wide range of available filters in the table can be found in [10]. Saving space, they are not outlined here. The key point is that the filter selection, potentially, has more impact than the chosen LES model. The filter scales in the table can vary by orders of magnitude depending on the grid.

Gridless methods such as Lattice Boltzmann Methods see some use in ERS. Again, this is an area where a deeper understanding of how numerical dissipation and dispersion traits interact with subgrid scale models is needed.

5. Best practices

Obviously the ultimate goal is that ERS be used by engineers engaged in design, i.e. non-ERS specialists. However, for ERS, careful grid design is needed – the grid density must satisfy basic heuristics largely based on practical experience. As

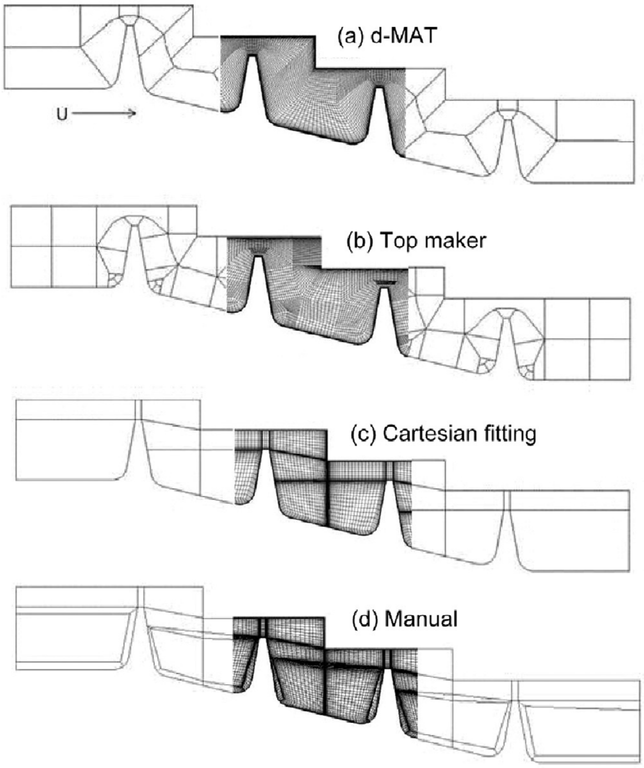

Fig. 10. Mesh topologies for a labyrinth seal using various approaches.

Table 2
Potential filter options for ERS.

Filter identification	Filter definition
Quasi-isotropic Cartesian grids	$(\Delta x\ \Delta y\ \Delta z)^{1/3}$
Anisotropic grids	$\surd((\Delta x^2 + \Delta y^2 + \Delta z^2)/3)$
Anisotropic grids	$max(\Delta x, \Delta y, \Delta z)$
Anisotropic grids, Andersson et al. [30]	$min(\Delta x, \Delta y, \Delta z)$
Anisotropic grids, Zahrai et al. [31]	$(\Delta x\Delta y\Delta z)^{1/9}\Delta x_j^{2/3}$
Anisotropic grids, Scotti et al. [32]	$(\Delta x\Delta y\Delta z)^{1/3}cosh(4[(lnc_1)^2 + (lnc_2)^2 - lnc_1 lnc_2]/27)$
Hybrid RANS-LES, Batten et al. [33]	$2max(\Delta x, \Delta y, \Delta z, \lvert\lambda\rvert\ \Delta t, L)$
Batten et al. [34]	$2max(\Delta x, \Delta y, \Delta z, \lvert u_i\rvert\ \Delta t, L_{\nu,K})$
Hybrid RANS-LES, Mani [35]	$2max(\Delta x, \Delta y, \Delta z, \lvert u_i\rvert\ \Delta t, k\ \Delta t)$
Hybrid RANS–LES, Batten et al. [33]	$2max(\Delta x, \Delta y, \Delta z, L_{\nu,K})$
Hybrid RANS-LES, Batten et al. [33]	$2max(\Delta x, \Delta y, \Delta z, L_{min})$
Vorticity aligned with a grid line, Chauvet et al. [36]	$\surd(n_x{}^2\Delta y\Delta z + n_y{}^2\Delta x\Delta z + n_z{}^2\Delta x\Delta y)$
General definition of Chauvet et al.'s – Deck [37]	$\overline{A_\omega}$
Curvilinear finite difference	$(J\Delta\xi\Delta\eta\Delta\zeta)^{1/3}$
Finite volume	$\mathrm{Vol}^{1/3}$
Unstructured control volume, Batten et al. [33]	$4max_{k=0,\ldots,n}[\lvert x_c - x_k\rvert]$
Unstructured control volume, Spalart	Maximal circle or sphere encompassing a cell
Farge and Schneider [38]	Wavelet based
NLES, ILES	$\Delta \to 0$[a]

[a] As input to the modeled scales.

noted above, the numerical scheme, grid and any chosen ERS subgrid scale model need to be compatible. Inflow can be challenging and the nature of the chosen synthesization method used is largely problem dependent. Although ERS is intrinsically simple and needs much less understanding of turbulence modeling traits, it is still an area where niche expertise is needed. For example, instances of under-resolved simulations can be readily found [28]. For example, in Fig. 11 the symbols represent ERS performed by other workers. The blue line labeled 'Turbo. LES' indicates the trend of the data. The red line labeled 'Realistic scaling' is adjusted [28] to take into account that many simulations are considerably more extensive than just chord-wise sections. The key point to see is that for turbomachinery, the red line has a negative gradient showing that the meshes used are not fine enough. Hence best practices are needed to help with grid design. The green horizontal line

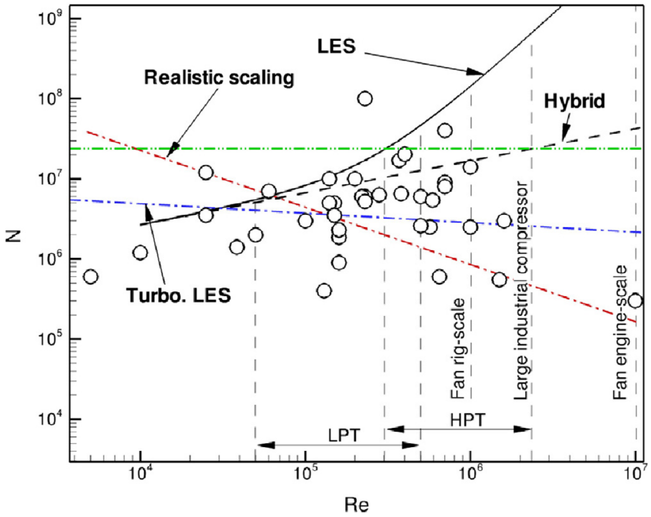

Fig. 11. Grid resolution requirements plotted along with numerous ERS found in literature showing the incorrect scaling of *N*.

indicates the level of simulation that can be comfortably tackled using either LES or hybrid RANS-LES in industry. Clearly many flows are now within practical reach using ERS.

6. Coupled modeling and future uses of ERS

As noted above, it is well established nowadays that many turbomachinery components interact in a coupled fashion. Also, future aircraft need increased coupling between the engine and airframe. As noted by Spalart, pilot–engine–aircraft interaction modeling is also a future simulation objective. This limits the applicability of computationally expensive ERS. Hence, for such systems it appears that ERS would be used to inform low order models. Then, the latter would be used as part of larger system level calculations or the ERS sandwiched within such calculations (see [29]). The low order models could be for example refined RANS models or POD (Proper Orthogonal Decomposition).

7. Data analysis

To deal with the massive data sets generated by ERS new data analysis techniques are needed including data mining. Also fault tolerant computing is needed to avoid data loss when one of many thousands of processors fail. Energy efficient computing is also needed. The energy consumption of ERS can exceed that of large-scale powerful rig tests. Ultimately, the way simulations and experiments interact is likely to radically change, still being complimentary but in very different ways.

8. Conclusions

In the future, ERS is likely to strongly impact on the way CFD is currently being used and the way experiments and CFD work together. There are, as ever, many areas of numerical algorithm development, computer science and computer architecture understanding that need to be explored. There are also many related pre- and post-processing challenges. However, steady progress is being made in performing simulations of ever increasing scale and fidelity. These are making good impact on our understanding of engineering problems that are of importance to society.

Acknowledgments

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