Large eddy simulation applications in gas turbines

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The gas turbine presents significant challenges to any computational fluid dynamics techniques. The combination of a wide range of flow phenomena with complex geometry is difficult to model in the context of Reynolds-averaged Navier–Stokes (RANS) solvers. We review the potential for large eddy simulation (LES) in modelling the flow in the different components of the gas turbine during a practical engineering design cycle. We show that while LES has demonstrated considerable promise for reliable prediction of many flows in the engine that are difficult for RANS it is not a panacea and considerable application challenges remain. However, for many flows, especially those dominated by shear layer mixing such as in combustion chambers and exhausts, LES has demonstrated a clear superiority over RANS for moderately complex geometries although at significantly higher cost which will remain an issue in making the calculations relevant within the design cycle.

Keywords: gas turbine; large eddy simulation; computational fluid dynamics; turbomachinery

1. Introduction

The gas turbine presents a significant challenge to the application of computational fluid dynamics (CFD) methods. The combination of flow physics and geometric complexities means that there are compromises in any computational method applied. With a desire for increasingly accurate solutions there is currently much emphasis on the application of advanced methods including large eddy simulation (LES). In this paper, we shall review the pertinent flow physics in the different components of the gas turbine and the current status of LES application.

2. Gas turbine architecture

The architecture of a typical modern gas turbine aero-engine is shown in figure 1. Air enters through the fan before splitting so that some air travels into the core of the engine while the remainder bypasses the core in order to mix with the downstream exhaust. The core flow is compressed before entering the combustion

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One contribution of 16 to a Discussion Meeting Issue ‘Applied large eddy simulation’.
chamber where liquid fuel is injected and burnt. The hot gas from the combustion chamber moves through the turbine, providing the power to drive the compressor. After the turbine the flow exhausts to the atmosphere. The secondary air system is fed with air bled from the main gas path and provides cooling of the discs holding the rotating compressor and turbine blades while the combustor and turbine main gas path surfaces are cooled in order to improve component life.

Flow enters the gas turbine through an intake that must be designed to deliver flow to the fan with minimum pressure loss and flow distortion. The flow leaves the engine via the exhaust where the core and bypass flows may mix; the exhaust must mix the flows with minimum loss in thrust while also minimizing radiated noise.

3. Technology drivers

Important considerations for gas turbine manufacturers include reduction of life cycle costs for the operator and reduced environmental impact in both manufacture and operation of the engines. Reducing life cycle costs places emphasis on improved component life, which demands an accurate prediction of the pressure and thermal environment of components during the design, as well as reduced fuel burn achieved through engine cycle and combustor performance. Environmental impact of engine operation can be mitigated by design of low emissions combustion systems as well as by reduced engine noise—both of which are subject to legislation.

These design improvements must be considered within an environment that requires shorter development times for each new engine, therefore placing an increasing emphasis on the use of computational tools that are able to deliver a reliable prediction within short time scales. The accuracy required from the models and the ranges of validity are continually increasing as novel concepts are explored.
4. Flow regimes

The gas turbine encompasses a wide variety of flow regimes. Many of the flows are at high Reynolds numbers and so fully turbulent, although the flow in some areas of turbomachinery and the engine intake undergo laminar to turbulent transition. The flow in the intake and turbomachinery is dominated by the presence and shape of the wall with the behaviour of the turbulent boundary layer governing performance for the attached flow at the design point. In regions such as the combustion system and secondary air system (as well as turbomachinery blading at off-design conditions) the flow contains large separated regions while the combustion system and exhaust contain free shear layers which promote mixing.

The flow experiences a wide range of Mach numbers, from subsonic through transonic in the fan to supersonic in high pressure ratio exhaust nozzles. It is also subject to rotation (in the turbomachinery stages) and swirl (from the fuel injector in the combustion system).

The combustion system has two-phase flow with the injection of liquid fuel as well as large density and temperature variations through the combustion process. In modelling different components of the gas turbine many of these features have to be considered simultaneously which is a significant challenge for the computational methods.

5. Current Reynolds-averaged Navier–Stokes modelling approaches

The CFD methods employed for routine analysis of gas turbine components are predominantly based around Reynolds-averaged Navier–Stokes (RANS) approaches. These RANS methods use single point closure turbulence models, mainly the one equation model of Spalart & Allmaras (1992) or two equation models either of the $k$–$\varepsilon$ family (Jones & Launder 1972) or of the $k$–$\omega$ family (Wilcox 1993; Menter 1994). The Spalart–Allmaras model is most often used for attached or mildly separated flows in turbomachinery while the two equation models are used for separated flows and flows with significant mixing.

A steady RANS approach is adopted for many of the gas turbine components although in the case of turbomachinery rotor–stator interaction we often use unsteady RANS (URANS), where the governing flow equations are phase averaged assuming a constant rotational speed. A steady method can still be used here but this implies that only averaged properties are transferred between blade rows and so the local effects of, for example, circumferentially discrete wakes are neglected.

The use of RANS modelling imposes some limitations on the accuracy with which we may represent many of the flows in the engine. In particular the representations of transition, mixing and separation are all limited by the RANS approach.

Transition remains a weak area for RANS modelling with most methods in routine design use employing a specified (not computed) transition location, although transport equation-based methods that attempt to predict the transition location (such as the methods of Menter et al. (2006) or Walters & Leylek (2004)) show promise. This particularly affects turbomachinery calculations where the boundary layer growth and heat transfer are compromised.
Separation itself is also a weak area for many of the RANS models used for design. While separation from a sharp corner is predicted, the extent of the separated zone and the post-reattachment recovery is often poorly captured by linear eddy viscosity turbulence models. Separation from smoothly curved surfaces is a particular weakness of most RANS models, which limits the prediction of turbomachinery performance off design and the behaviour of complex intakes.

In the RANS framework sketched above, scalar mixing is described by a gradient transport hypothesis requiring the prescription of a turbulent Schmidt number. The Schmidt number has a significant effect on the predicted mixing rate which renders the final solutions sensitive to the assumed value. Unfortunately, the correct value is hard to determine especially in the context of reacting flows in the combustion system and a single value is often not appropriate for the entire flow due to the weakness of the gradient transport hypothesis. This limits the predictive fidelity of combustion system calculations where fuel–air mixing is important and the prediction of exhaust plume development.

The application of turbulence modelling in the gas turbine combustor, as an example of the different approaches for complex flows, is described in Menzies (2001) while the limitations of RANS approaches for complex flows is described in more detail in, for example, Leschziner (2001).

6. The potential for LES application

Given the limitations of RANS modelling strategies for the complex flows in the gas turbine, as surveyed in §5, both LES and hybrid RANS–LES methods such as detached eddy simulation (DES) are increasingly applied to improve predictive accuracy; a recent review of LES is given by Fröhlich & Rodi (2002) while DES is described in Spalart et al. (1997). Here we survey the state of application of these methods through the gas turbine. We also highlight specific difficulties in each area while more general limitations with current LES and hybrid approaches are described in §7.

(a) Intake

Application of LES or hybrid methods to intakes has so far been limited, although one significant exception is the use of DES to calculate acoustic instability in a supersonic intake by Trapier et al. (2008), using the approach of Spalart et al. (2006). LES (or hybrid methods) would appear well suited to capture the dominant flow physics in complex intakes where flow separation from smooth curved surfaces must be controlled and the pressure distortion into the turbomachinery must be predicted. However, if we wish to include the effect of the turbomachinery on the intake flow then the computational requirements become very large, currently prohibitive for design methods.

(b) Turbomachinery

The simulation of turbomachinery with LES or hybrid RANS–LES methods is an extremely active research area. A recent review of LES methods for turbomachinery flows is given by Sagaut (2002).
The flow through turbomachinery blade passages is dominated by the presence and shape of the blade and the incoming wakes from the upstream blade row. The importance of the solid wall means that an extremely fine mesh is required in the near-wall region for LES calculations to capture all of the dynamic behaviour. This fine mesh is required in all three coordinates: wall-normal, streamwise and spanwise mesh spacings must all be sufficiently small to resolve the boundary layer structures governing the flow behaviour. This results in an unfeasibly large mesh requirement even for a single blade passage and so the hybrid RANS–LES methods appear more promising for predicting the flow around the blade aerodynamic surfaces especially if multi-passage or multi-bladerow calculations are desired. The incoming wake from the upstream blade row is also important in the development of turbomachinery flow, so this must be included in any calculation which usually requires a multi-bladerow model that increases mesh size and solution time.

The flow in the low pressure compressor and turbine is often at sufficiently low Reynolds numbers to be transitional. This poses severe problems for hybrid RANS–LES methods since the RANS layer is then responsible for the transition of the boundary layer to turbulence. In this instance a hybrid RANS–LES approach is unlikely to suffice and a pure LES method is required, with a very fine mesh to capture the near-wall features that grow during the transition process. The calculation of transitional boundary layers relevant to turbomachinery using LES is presented in, for example, Voke & Yang (1999) and Lardeau et al. (2005).

LES is also being used to explore and elucidate other aspects of turbomachinery performance. You et al. (2007) report an investigation of the tip leakage flow of a blade in a cascade which is a difficult problem for RANS methods; it may be in treating problems of this nature that the use of LES or hybrid methods in turbomachinery becomes apparent.

(c) Combustion

The application of LES to the flows in the gas turbine combustion system has shown significant promise, despite the complexity of the flow to be captured. Reacting flows place additional unique demands on LES since the reaction results in large changes in density and temperature and we must solve additional transport equations for the fuel distribution. In aeronautical gas turbines, the fuel is injected as a liquid and so the calculation must also represent the spray behaviour and its interaction with the gas phase including droplet break-up, evaporation and the interaction of the droplets with the turbulent eddies. Since combustion occurs at the fine (unresolved) scales we also require a subgrid scale (SGS) description of the two way interaction between turbulence and combustion, which is often achieved (for non-premixed combustion) by using a SGS probability density function for the unresolved fluctuations in chemical composition analogous to the approach used in RANS calculations of reacting flows. A brief overview of some of these issues is given by Jones (2002).

Despite these additional modelling assumptions required and the complexity of the flow to be represented, LES has already been demonstrated to give good representations of the flow in real combustion systems as shown by, for example,
Kim et al. (1999), di Mare et al. (2004), Kim & Syed (2004), Mahesh et al. (2006) and Gicquel et al. (2008). In all of these cases LES was shown to capture the dominant flow features well.

The success of LES in modelling the flow in non-premixed combustion systems is a result of the dominance of momentum and scalar mixing on the overall flowfield. This mixing is driven by interacting jets and shear layers along with the swirling flow from the fuel injector. In these cases we have large-scale structures responsible for the majority of momentum transport and scalar mixing. These structures are captured explicitly in LES whereas their effect must be modelled in RANS. In addition the jet–jet interaction is often unsteady which again is captured naturally by LES instead of RANS.

With the success of LES in representing the flow in the combustion system it is now possible to consider its use in more complex situations such as the prediction of thermo-acoustic instability (where the unsteady heat release from the chemical reactions couples to the unsteady pressure field to give self-sustaining oscillations). This will require significant computational power and potentially long run times but does offer the prospect of a more accurate description of this important phenomenon.

(d) Secondary air system

The secondary air system includes all of the air flows within the engine that are outside of the main gas path. In particular, it includes those flows used to feed the turbine blade cooling. These flows are characterized by complex physics including flow features driven by rotating walls as well as complex geometry. These flows exhibit large regions of recirculation and complex strains which make them appear well suited to LES application. Indeed there are similarities between the physics of these complex rotating flows and meteorological flows where LES originated.

Many of these flows are dominated by the near-wall physics, with the cavity flow being driven by diffusion of momentum from the boundary layer on the rotating surface. This means that capturing the near-wall region is critical and so a grid that resolves this region is essential whether a standard LES or hybrid RANS–LES method is used. As a result there may not be any advantage to using hybrid methods for these flows especially as the performance of the RANS layer has not so far been clearly demonstrated.

A second area of application of LES in the secondary air system is predicting the interaction with the main gas path and potential ingestion of hot gas through seals. This is an inherently unsteady phenomenon and preliminary application of LES shows more promise than URANS, as demonstrated by Sun et al. (2007).

More details on the flow physics of the secondary air system and modern prediction methods can be found in Chew & Hills (2007).

(e) Exhaust and plume

The flow in the gas turbine exhaust and the subsequent propulsive jet and plume are good candidates for LES and hybrid methods. The flow through the exhaust system undergoes acceleration and experiences complex straining especially due to gas path convolution to enhance mixing. After leaving the nozzle a free shear layer develops around the jet as it mixes with the surrounding atmosphere. The quality of prediction of plume characteristics such as mixing rate is seen to be strongly dependent on the chosen turbulence model and
constants in a RANS framework due to the influence of large-scale vortical structures on the mixing process. It is for this reason that we expect that LES should deliver better predictions without tuning.

In order to capture the correct behaviour at the exit to the exhaust nozzle it is necessary to include the flow in the upstream feed where the presence of walls and duct obstructions will modify the flow behaviour; furthermore, many nozzle flows show sensitivity to the boundary layer development on the internal and external surfaces. For this reason a hybrid RANS–LES approach may be necessary for plume prediction even though the plume itself is controlled by free shear layers (Georgiadis 2001; Chauvet et al. 2007). In a supersonic jet we also have significant shock affected regions in the jet near to the nozzle which requires some form of numerical smoothing in the discretization, such as an upwind-biased scheme, in order to eliminate numerical oscillations. However, the numerical dissipation introduced by an upwind discretization is undesirable in predicting the initiation of turbulence in the shear layer and subsequent plume mixing and decay of the potential core where we want the only source of energy dissipation to be the SGS model. This demands the use of either a self-adjusting scheme that adaptively adds dissipation only around shocks such as that described by Tristanto & Page (2004) or a high order upwind scheme such as the fifth order scheme demonstrated for jet flows by Shur et al. (2005).

A good review of the status of LES for nozzle flows is given by DeBonis (2006), where emphasis is placed on applications to practical exhaust systems. Applications of LES and hybrid methods to gas turbine exhausts and jets include Arunajatesan et al. (2002), Li et al. (2006), Tristanto et al. (2006), Chauvet et al. (2007) and Page et al. (2007). All of these examples consider realistic engine geometries. The work of Li et al. (2006) and Page et al. (2007) examines the particular case of twin exhaust jets impinging on the ground and the potential for hot gas reingestion into the engine, a situation found in the vertical descent phase of short take-off and vertical landing aircraft. This flow generates an unsteady upwash fountain from the interaction of the twin impinging jets as well as a slow unsteady ground vortex. LES has been shown in this work to deliver superior results to RANS where experimental data on simplified configurations are available. The method is applied in Page et al. (2007) to the flow around a complete aircraft model in ground descent, showing promise in such a geometrically complex case. The effects of the numerical method and SGS model on jet predictions for both the flowfield and noise are considered by Tucker et al. (2005, 2006, 2008) where the use of numerical LES coupled with RANS is shown to produce good results even for as complex a case as a civil engine exhaust with chevron mixer.

The capability of LES to accurately predict mixing rates is important in assessing plume decay and so this will become a key area for LES application. As more novel exhaust nozzle geometries are employed it will no longer be possible to rely on heavily calibrated RANS models and LES appears the only alternative approach.

(f) Noise

Noise prediction is an established field for LES application. In the context of the gas turbine we are interested in the prediction of noise from both the fan and the exhaust jet. In both cases LES is able to provide unsteady pressure levels

Phil. Trans. R. Soc. A (2009)
although integration to the farfield is impractical. A more common approach is to use the unsteady information as input to an acoustic model, such as the Lighthill (1962) acoustic analogy or integration over a Ffowcs-Williams–Hawkings surface (Ffowcs-Williams & Hawkings 1969). The application of LES to practical exhaust jets for calculation of noise levels is given in, for example, Andersson (2003) and Secundov et al. (2007) while the influence of numerical methods, SGS model and grid structure for noise calculations is considered by Tucker et al. (2008). An application of LES to the prediction of noise levels from chevron exhaust nozzles is given by Xia et al. (2008). The results for first and second moments of the velocity field agree well with measurements and the predicted farfield sound pressure levels reproduce the data too, including the effect of the different chevron geometries on the sound distribution.

With the demonstrated ability of LES to contribute to the understanding and reduction of noise this will remain an important application area in the context of the gas turbine. It is likely that mesh requirements will continue to increase to provide improved spatial resolution and this will drive application on larger numbers of processors in order to keep calculations within time scales relevant to product design.

7. Issues in LES application

In \S 6 we have illustrated the applicability of LES to the flows found in the gas turbine. While we have identified that LES has demonstrated an ability to better represent some of the complex flows and shows promise for others there are still important areas of development required for routine industrial calculations.

(a) Geometry representation and numerical methods

While not specifically a shortcoming in LES, the issue of accurate representation of complex geometry must be addressed for application to real engine components. The complexity of the geometry of typical gas turbine parts necessitates the use of unstructured meshes, often using tetrahedral or mixed tetrahedral and hexahedral cells. While much progress has been made in the development and application of LES methods using these mesh types (e.g. Tristani & Page 2004; Li et al. 2006; Mahesh et al. 2006; Page et al. 2007) there is still significant work required to improve the tolerance of the numerical methods to relatively poor meshes and reduce numerical dissipation on tetrahedral cells.

Since practical meshes often involve significant mesh anisotropy then this is another area of concern for application. With mesh anisotropy we resolve different ranges of the turbulence spectrum in different directions and locations. The effects of these differences must be assessed for complex flows.

The issue of the numerical discretization remains problematic for compressible flows. For most industrial applications it is impractical to use discretizations of order higher than two or three which suggests that second order central differencing is the best approach for discretization of the convection terms. However, this is not appropriate for regions involving shocks where some upwinding is desirable. This introduces additional dissipation that may overwhelm the dissipation from the SGS model so a careful assessment and tuning of adaptive
schemes is necessary to ensure that the dissipation required to maintain stability
and prevent decoupling of variables in colocated meshes does not dominate the
physical dissipation of turbulence.

The time required to achieve a solution with LES remains an issue
for application within a design environment. While this can be addressed with
larger parallel computers it also demands high parallel efficiency in the code
especially when including additional complex physics such as two phase flow and
spray tracking.

(b) Physical modelling

As well as the numerical issues outlined above there are a number of physical
modelling issues to be addressed to improve the applicability of LES to gas
turbine flows.

It seems likely that in many of the complex flows in the gas turbine the choice
of SGS model will have little significant impact on the results if a suitably fine
mesh is used. Since this places a large mesh requirement on many practical cases
then the evaluation of different SGS models in three-dimensional inhomogeneous
flows with complex strains is valuable.

One situation where the SGS model will have an impact is in the prediction of
transition. This remains a difficult area for LES, although the situation is
perhaps better than that in the RANS framework where heavy modelling and a
reliance on empiricism is essential. Further development of transition models,
capable of predicting transition location, is essential for application to
turbomachinery. It seems likely that this work will lean heavily on direct
numerical simulation to elucidate the important mechanisms to be captured.

An essential development to permit routine application of LES is in the
specification and generation of turbulent inflow conditions. For practical
industrial computations it is impractical to use precursor calculations to
generate correlated unsteady inflow data, while the use of uncorrelated white
noise is little better than using no turbulent fluctuations at all. A scheme for
defining the velocity signal at all inflows that reproduces measured or assumed
first and second moments is required, especially since the flows under
consideration display some sensitivity to the inlet turbulence prescription.
A number of methods have been proposed for generating inflow data, the method
of Klein et al. (2003) and di Mare et al. (2006) using digital filters appears the
most useful and applicable. At present this has been demonstrated in the context
of pressure-based low Mach number codes so must be extended to the density-
based compressible flow solvers used for many gas turbine calculations.

Finally an essential aspect of application of methods such as LES and hybrid
RANS–LES techniques to complex flows is validation. As the complexity of the
flows to be addressed increases so too must the complexity of the validation. In
particular it is necessary to obtain unsteady flow information (using techniques
such as particle image velocimetry alongside laser Doppler anemometry) to
provide a more comprehensive validation of LES than simply comparing mean
(first moment) quantities. The work described in Midgley et al. (2005) is an
example of how advanced diagnostics can obtain benchmark quality data in a
complex flow as well as directly increasing understanding of the flowfield itself.

Phil. Trans. R. Soc. A (2009)
8. Conclusions

We have surveyed the current state of the art in application of LES and hybrid RANS–LES methods to the flows in the gas turbine. We can see that during recent years there have been significant successes in these applications, and for flows dominated by shear layer mixing LES has proven its applicability compared to RANS. However, LES is not a panacea for all of the turbulence modelling problems within gas turbine flows. The flows in turbomachinery remain problematic and there are several important areas to be addressed to extend the capability of current LES approaches. The issue of computational cost remains a problem for use in a design cycle but it is clear that over the coming years LES will become more firmly established as a key part of the aerodynamicist’s toolkit for solving complex problems in these flows contributing to new designs.

The author would like to thank Professor Paul Tucker for his invitation to participate in the ‘Applied large eddy simulation’ meeting and Rolls-Royce plc for permission to publish this paper.

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*Phil. Trans. R. Soc. A* (2009)


