Propulsive jets and their acoustics

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The complex flow physics challenges and asks questions regarding these challenges a wide range of jet flows found in aerospace engineering. Hence, the daunting task facing Reynolds-averaged Navier–Stokes (RANS) technology, for which the time average of the turbulent flow field is solved, is set out. Despite the clear potential of large eddy simulation (LES)-related methods and hybrid forms involving some RANS modelling, numerous current deficiencies, mostly related to the limitations of computational resources, are identified. It is concluded that currently, these limitations make LES and hybrids most useful for understanding flow physics and refining RANS technology. The use of LES in conjunction with a ray-tracing model to elucidate the physics of acoustic wave transmission in jets and thus improved RANS technology is described. It is argued that, as a stopgap measure, pure RANS simulations can be a valuable part of the design process and can now predict acoustics spectra and directivity diagrams with useful accuracy. Ultimately, hybrid RANS–LES-type methods, and then pure LES, will dominate, but the time-scales for this transition suggests that improvements to RANS technology should not be ignored.

Keywords: jets; noise; RANS; LES

1. Introduction

Jet-type flows can be found in numerous aerospace configurations. Examples include combustion systems, rocket plumes and the propulsive jets from the back of jet engines. With rocket plumes, modern bypass aeroengines and propulsive jets operating at ground level, complex shear layer interactions can occur. The geometries of the jets found in aerospace engineering can be wide ranging. This gives rise, when for example they are combined with Mach number effects, to substantially different large-scale turbulent features. These aspects are especially challenging for Reynolds-averaged Navier–Stokes (RANS) models. In the sections to follow, the flow features/physics of various jet configurations are outlined. First, axisymmetric jets are discussed followed by three-dimensional jets and then wall jets. The latter are relevant to aircraft engines operating in airport environments. Here, the blast from the engine can raise serious safety
issues. The capabilities and limitations of RANS models when predicting all of
the above flows are outlined. This discussion is followed by a section identifying
the serious practical limitations of LES-related methods.

With the projected dramatic increase in demand for air transport, it is
apparent that urgent steps must be taken to reduce noise from the propulsive jets
of commercial aeroengines. These are a major source noise at take-off. Indeed, it
is this acoustic problem that has driven forward RANS jet prediction technology
and led to extensive large eddy simulation (LES) research. Therefore, the final
part of this paper focuses on extracting acoustic data from RANS solutions. In
addition, the use of LES to refine RANS-based acoustic predictive approaches is
demonstrated in the very final section of the paper, presenting an encouraging
RANS-based noise-predicting procedure for complex jet nozzles.

2. Jet dynamics

(a) Axisymmetric jets

A basic problem in using RANS codes to model jets is that when any of the standard
RANS turbulence models are used, different constants are required for the near and
far fields. This problem has been well known for more than 30 years and no really
satisfactory solution has ever been found for it. It was first discussed in detail by Rodi
(1972) who also provided the first suggestion for how the problem might be overcome.
Over the years, there have been intermittent attempts to develop versions of existing
models that address the problem. Additional modifications for a number of two-
equation models are discussed in the work of Launder et al. (1972), McGuirk & Rodi
(1977), Morse (1977), Vollmers & Rotta (1977), Pope (1978), Hanjalić & Launder
(1980) and Robinson et al. (1995), but in recent years, the turbulence modelling
community has largely ignored jet-modelling problems. This might seem surprising
giving the almost ubiquitous presence of jets in engineering applications, particularly
the major problems such as aeroplane noise; yet the reader studying recent reviews of
turbulence modelling (Hanjalic 1994 or Launder & Sandham 2002) looking for
information on the modelling of turbulent jets, is going to be disappointed.

Some of the turbulence model modifications that have been proposed
specifically addressed axisymmetric jets (Launder et al. 1972; Rodi 1972;
McGuirk & Rodi 1977; Morse 1977) and are not easily extendable to general
three-dimensional flows. Most of the others have either never been tested for an
extended range of flows or have been shown to perform worse than standard
models in applications other than jets. The only exception to this appears to be
the model proposed by Gulyaev et al. (1993). This model, however, is a one-
equation model for turbulent viscosity and does not directly predict turbulence
quantities that are needed for applications such as the prediction of jet noise. The
only turbulence model modification that has remained popular over the years is
that proposed by Pope (1978). In 1978, Pope proposed that a vortex stretching
term be added to the standard $k-\varepsilon$ turbulence model. The term has little effect on
the turbulent mixing in the near field of a low-speed jet, but reduces the mixing
in the far field, giving results that were much closer to the experimental data.

Pope’s modification is fairly simple and easily extendable to general three-
dimensional flows, which is probably the reason for its popularity; but it is also,
unfortunately, the one that can most easily be shown to be wrong. (Birch 1980;
Rubel 1985). Unfortunately, the physics on which this model was based is not correct and, while the modification gives improved results in low-speed axisymmetric jet calculations, it gives distinctly worse results for many other flows where vortex stretching is present (Lebedev et al. 2002). The Wilcox (1998) $k-\omega$ turbulence model incorporates a vortex stretching term that was patterned after the Pope modification.

The difficulty of modelling both the near and the far fields of an axisymmetric jet, using the same set of constants, is part of a more general problem of modelling axisymmetric and planar flows and appears to be related to the different stability characteristics of planar and axisymmetric flows. This leads to the difference in the turbulence structure that cannot be naturally incorporated in a RANS turbulence model. For a more detailed discussion of this problem (see Birch 1997).

For heated jets, the problem is worse. The turbulent Prandtl number close to a wall is generally taken to be approximately 0.9. It is, however, much lower in jets and the value is different in the near and far fields (Lauder 1978; Wilcox 1998). It is approximately 0.4–0.5 in a mixing layer, or the near field of a jet, and increases to approximately 0.7–0.8 in the far field. At high temperatures that are encountered in many propulsion applications, for example, the low Prandtl number in the near field of a jet will lead to a significant increase in jet mixing and this, therefore, needs to be modelled correctly.

For supersonic flows, there are additional modelling problems. For Mach numbers less than 1, the turbulent mixing in the near field of a jet in still air is essentially independent of Mach number. As the flow becomes supersonic, however, the spreading rate starts to decrease. This decrease is initially fairly steep with the spreading rate decreasing by almost a factor of two as the Mach number is increased from 1.0 to 2.0, and by approximately a factor of three at Mach 4.0 (Birch et al. 1973). Most turbulence models, when initially applied to this flow, predicted little or no change in the spreading rate with Mach number. In the early 1990s, it was widely assumed that this decrease in mixing rate was due to an increase in the turbulence dissipation rate, and a number of attempts were made to model compressibility effects in mixing layers as a dilatational-based modification to the turbulence energy dissipation rate. The performance of three of these models, in combination with the $k-\varepsilon$ and the $k-\omega$ turbulence models, is discussed in some detail in the work by Barone et al. (2006). It is now generally believed that the lower mixing rate in supersonic mixing layers is due to a slower turbulence energy production rate, rather than an increased dissipation rate, and this again seems closely associated with the changing stability characteristics and turbulence structure of the mixing layer, as the Mach number is increased.

This is a more bad news for Reynolds-averaged turbulence models. It may not be all that difficult to modify an existing turbulence model to mimic the reduced mixing rates in supersonic mixing layers; but it appears to be very difficult to do this in a way that correctly models the physical processes present in such flows, as we understand them at present, and the situation is obviously more complicated for the multistream mixing layers that are often encountered in propulsion applications.

(b) Three-dimensional jets

So far, we have just been discussing axisymmetric jets, while most of the jets encountered in practical applications are, to some degree, three-dimensional. One of the interesting properties of three-dimensional jets is that they tend to become
axisymmetric at large downstream distances, and for large aspect ratio jets like those shown in figure 1, based on experimental work by Sfeir (1976), the major and minor axes of the jet can interchange a number of times during this process. Note also that the jet development depends on the geometry upstream of the nozzle exit. In this case, both the nozzles had an aspect ratio of 10, but one of the nozzles was a sharp-edged slot while the other was a rectangular channel that was 50 nozzle heights long. The effects are due to a combination of pressure- and turbulence-driven secondary flows and the later effects will not, of course, be predicted by an eddy viscosity-based turbulence model.

While this is admittedly an extreme example of a three-dimensional nozzle geometry, it is useful as it clearly illustrates the added complexity of three-dimensional jet flows. It should also be noted that eddy viscosity-based models can also lead to large errors for nozzle geometries that are less extreme. One example of such a flow is the plume from a rocket with twin nozzles. At high altitudes, the two jets will interact strongly a short distance downstream of the nozzle exits. This interaction can lead to high static pressures between the jets that, in turn, lead to strong lateral outflows. Physically, we know that after some distance this outflow will be reversed and the plume will head back to a more axisymmetric shape. An eddy viscosity-based model, however, has no way of predicting these effects and, as can be seen in the work by Venkatapathy et al. (1989), such a model will tend to predict a very large aspect ratio plume at large downstream distances. Obviously, this is not physically correct.

(c) Wall jets

The two-dimensional wall jet follows the same scaling laws as a planar jet and, apart from the thin layer close to the wall, looks very like half a planar free jet.
Experimentally, however, the measured spreading rate of the wall jet is only approximately 70% of that of a free jet. While a casual examination of the wall jet appears to show that the effect of the wall is restricted to a thin region close to the wall, in reality, the presence of a wall has a major effect on the turbulent mixing rate over the whole width of the wall jet. For example, a standard $k-\varepsilon$ turbulence model that correctly predicts the spreading rate of a two-dimensional free jet, predicts a spreading rate for the wall jet that is approximately 30% larger than the measured value.

Early attempts using full Reynolds stress transport models also over-predicted the spreading rate for two-dimensional wall jets and gave results only slightly better than those obtained using a standard $k-\varepsilon$ turbulence model. The development of pressure-reflection models that provide strong damping of the turbulent fluctuations normal to a wall have led to improved predictions for the two-dimensional jet, but fail badly for the more complex three-dimensional wall jets that are generally encountered in practical applications.

(d) Three-dimensional wall jets

Given the difficulty of modelling even a simple axisymmetric jet, the reader will probably not be surprised to learn that the three-dimensional wall jet represents a very formidable challenge to the modeller (Craft & Launder 1999, 2001). One of the best-known characteristics of a three-dimensional wall jet is that lateral spreading rate of the fully developed jet is five or six times larger than the spreading rate normal to the wall. In other words, a wall jet that starts out being axisymmetric becomes strongly three-dimensional farther downstream. As described previously, in the absence of the wall, an initially three-dimensional free jet tends to become axisymmetric at large downstream distances, a behaviour totally opposite to that of the three-dimensional wall jets. Both of these effects are due to fairly subtle deviations of the turbulence from isotropy and it seems reasonable to require that any model that purports to model three-dimensional wall jets to also correctly model the apparently simpler three-dimensional free jet flows.

No generally applicable turbulence model appears to have been developed that correctly predicts the mixing of both three-dimensional free jets and three-dimensional wall jets. Certainly, models developed specifically to model two-dimensional wall jets failed badly when applied to three-dimensional wall jets. To the present authors’ knowledge, the only model that has been demonstrated to correctly predict the mixing in three-dimensional wall jets and three-dimensional free jet is the model described in Khritov et al. (2002). This model uses a non-isotropic constitutive relation for the Reynolds stress tensor and, while it has been shown to correctly predict the mixing in a variety of jet flows, it is obviously strongly empirical and has not been widely tested for other flows.

(e) Large eddy simulation

Many of the modelling problems discussed here appear to be due to changes in the large turbulence structure, owing to the changes in geometry, Mach number effects, or interactions with a wall. There seems to be no way to incorporate such effects into a RANS turbulence model that correctly reflects the real physics involved. By contrast, LES, even on quite coarse grids, seem to
predict the correct trends. To model these complex flows with sufficient accuracy to allow detailed comparisons with experimental data, however, requires very large grids and this makes such LES calculations impractical at present. The results presented in figures 2 and 3, Khritov et al. (2002) and

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Lyubimov (2003), support the suggestion that the problems discussed here are mainly due to an incorrect modelling of the large turbulence structure. The LES methods, which actually calculate these structures, do offer the prospect of improved modelling of jet flows, with minimal empiricism. The use of LES in the prediction of jets and their noise is discussed in more detail later in this paper.

3. RANS modelling of propulsive jets

In spite of all the difficulties of modelling general three-dimensional jets, discussed previously, the accurate modelling of propulsive jets is not as hopeless as it might seem. This is mainly because many propulsive jets are approximately axisymmetric, so the most difficult modelling problem can often be avoided and predictions with useful accuracy can be achieved with only modest modifications of standard turbulence models. Even when the flows of interest are locally three-dimensional, pressure-driven secondary flow effects often dominate, so uncertainties associated with modelling have little effect on the predicted flow field. This is fortunate, since RANS model are, at present, the only practical way to model such flows. Nevertheless, it is important to understand the limitations of current models so that situations where these models may not be reliable can be readily recognized.

Although the difficulty of modelling even the simplest axisymmetric jets has been known for more than 30 years, these problems, as discussed previously, have been largely ignored in recent general discussions of turbulence modelling. Owing to this, most of the recent work of finding a practical way to model jets has been done by those interested in improving the modelling of propulsive jets, for noise applications in particular. Some of these proposals are discussed in Thies & Tam (1996), Abdol-Hamid et al. (2003), Birch et al. (2003), Massey et al. (2003), Birch (2004) and Tam & Ganesan (2004). The model described in Birch et al. (2003, 2004) is a zonal model, based on a standard k-ε model, which uses different constants for the near- and far-field regions of a jet. Predictions using this model for flows ranging from single axisymmetric jets to jets from a coaxial nozzle/pylon (essentially this can be viewed as a radially emanating plate that allows one to mount the engine on the wing) combinations, with and without chevrons, are described in Birch et al. (2003, 2004, 2005a,b) and Khritov et al. (2005). These calculations will not be discussed in detail here. Suffice it to say, the predictions were generally in good agreement with experimental data. Indeed, it was the predictions obtained using this model that led to the discovery that jets from nominally axisymmetric, coaxial nozzle configurations are often strongly asymmetric. This appears to be because of the sensitivity of these jets to very small distortions in the nozzle geometry, which are difficult to eliminate totally when the primary jet is heated to a high temperature. If a pylon is added to the nozzle configuration, the resulting flow is much less sensitive to small distortions in the nozzle geometry. For these configurations, numerical prediction of the jet flow agrees quite well with the experimental data. This is discussed in more detail in Birch et al. (2005b).

RANS models also give surprisingly good predictions for the complex jet wakes behind aeroplanes taxiing on a runway.
Aeroplane jet wakes

At crowded airports, the danger of jet blast from aeroplanes during ground operations is a concern owing to the potential damage to ground crews, cargo equipment, terminal buildings and small aeroplanes nearby. Owing to these potential problems, it is important to be able to predict the jet plume behind an aeroplane accurately, hence the interest in complex three-dimensional wall jets.

It seems fair to say that the jet wake of an aeroplane is a very complex flow, whose detailed description appears to be well beyond the capabilities of any standard turbulence model. Nevertheless, it appears that it may often be possible to calculate the extent of the danger zone behind an aeroplane, with reasonable accuracy, using a relatively simple turbulence model.

One of the earliest attempts to predict the jet wake of an aeroplane was reported by Tjonneland & Birch (1980). This shows a comparison of a numerical prediction of a jet wake with full-scale data for a Boeing 727. For this calculation, a standard k-ε model was used and buoyancy effects were ignored. In spite of this, the predicted results were found to be in good agreement with the experimental data. While, at the time, the reason for the success of this calculation was not fully understood, a more detailed study by Khritov et al. (2002) was conducted later with some rather interesting results.

It appears that in spite of the complexity of this flow, the extent of the danger zone behind an aeroplane can probably be found with sufficient accuracy, for many practical applications, using a standard k-ε turbulence model (Khritov et al. 2002). This is not because this model accurately models the detailed flow physics in this complex flow, but is the result of a largely fortuitous and interesting cancellation of effects that, sadly, there is no space to discuss in detail here.

4. Eddy resolving approaches

Although LES-related methods are obviously more accurate than RANS, there are still problems to overcome. These are mostly related to computer resource limitations. For example, there is much open debate on the most appropriate LES model and the ability of numerical influences to replace the LES model. Realization of the latter is most frequently described as Monotone-Integrated LES (MILES), see Boris et al. (1992) or Implicit LES (ILES). In this section, in a jet noise context, it is hoped the reader will see the LES model’s importance and hence the strength of the MILES versus LES debate, in relation to other modelling elements such as: numerical influences; problem definition (especially inflow boundary condition modelling); solution uniqueness; transition; near-wall modelling; and grid quality. The numerical influences will be discussed first.

(a) Numerical influences

With LES, numerical influences must be insignificant relative to contributions from the LES model. When moving towards realistic engine conditions, if solutions are not to have significant ‘MILES/ILES’ character, this poses a serious solution constraint. As noted by Chow & Moin (2003), the numerous forms of the Navier–Stokes equations when discretized using the same numerical scheme will give different numerical influences. In addition, there is a wide range of temporal and
spatial discretizations and even nominally the ‘same scheme’ can be discretized differently, for example, one- and two-legged discretization forms. As noted by Tucker (2006a), different implementations of the Crank–Nicolson scheme (even with a maximum Courant number well below 1) can make substantial (20%) differences to jet turbulence statistics. In addition, discretizations that tend to migrate to having dissipative elements must ultimately be represented on grids. The non-alignment to the flow and skewing of different cell types also tends to produce further dissipation (Tucker 2006a). These aspects when combined with an LES model then tend to frequently (with more typical engineering codes) produce an excess of dissipation (Tucker 2006b). Furthermore, with jets, far-field numerical boundary conditions can play a strong role. The potentially significant, non-vanishing with grid, spatial numerical influence is well illustrated by Vreman et al. (1996), Ghosal (1996) and Chow & Moin (2003). From these works, it is clear that the ability to disentangle numerical influences from those of the LES model is not a trivial task that can be taken for granted.

Hence, it might seem pragmatic with dissipative codes, following Shur et al. (2003), Tucker (2004) and Uzun & Hussaini (2006), to omit the LES model, acknowledging that the contribution of the numerics when combined with those of the LES model is likely to cause an excess of dissipation. For example, with a Ma = 0.6 jet, Uzun and Hussaini use a 50 million cell grid, heavily focused in the near-field jet region. A sixth-order smoother is used (with no LES model) and still there is evidence of near-field turbulence suppression. In the literature, simulations using no explicit LES model have been given a wide range of names. These include: quasi-DNS (Shur et al. 2003); no model simulations; the no model–model; Alternative LES (ALES); Implicit LES (ILES); or MILES. As noted by Pope (2004), since modelling certainly takes place, the handle ‘no model’ is misleading. Hence, Pope recommends the term numerical LES (NLES) and this is used here. Ideally, with NLES, numerical diffusion is used to drain energy from small scales and is reminiscent of more advanced LES models, NLES can also introduce some backscatter (Rider & Margolin 2003).

Grinstein & Fureby (2002) show NLES can adequately capture some complex jet noise vortex dynamics. Hence in order to test the sensitivity of NLES to numerical discretization, the case of Shur et al. (2003) was repeated by Tucker (2006a) and Tucker et al. (2006) for five different, structured and unstructured, flow solvers using essentially the same grid and also for most of the solvers with a doubling of the number of grid cells in all directions. All codes, with the exception of a neutrally dissipative NEAT code (Tucker 2001), gave encouraging (similar to Shur et al. 2003) NLES statistics in the self-similar region. However, with the addition of LES modelling, results for the dissipative codes deteriorated due to an excess of total dissipation. It seems worth noting here that, as shown by Shur et al. (2003), the fourth-order NTS code would not even predict transition to turbulent flow with an LES model. This is in stark contrast to the other five second-order codes tested, which all managed to predict transition satisfactorily. Hence, clearly, code numerical traits can play a complex role with LES. Since NEAT is neutrally dissipative, its NLES results were worse than these for all the other codes and an LES model was very helpful. However, when studying lateral and longitudinal correlation coefficients and shear layer statistics, agreement for the different codes becomes less encouraging. This is probably not totally related to numerics since inflow conditions and measurement uncertainties will play a role.

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As noted earlier, the cell shape can potentially strongly influence results (Tucker 2006a)—even ignoring dependencies on filter definition and commutation errors for the different grids. To give an indication of the importance of grid quality, figure 4 contrasts predictions for the geometry (Bridges & Brown 2004) for ‘O’ and ‘H’ type near-axis grids. The former configuration results in an extreme number of radial grid lines converging on the jet axis (a large number of circumferential nodes is needed to resolve the chevrons). As can be seen from frame (a), this has caused extreme near-axis numerical stiffness with the flow appearing as if there is a fine wire at the axis. However, clearly the ‘H’ grid is satisfactory.

Continuing the theme of numerical quirks, when replicating the results of Shur et al. (2003), the predicted acoustic waves for the different codes, noted above, showed, unlike the turbulence statistics, substantially different traits. In addition, ultimately, to getting far-field sound, this acoustic information is fed into an acoustic post processor. This will also give further numerical influence/modelling uncertainties. For example, with the integral surface approach of Ffowcs Williams & Hawkings (1969), the placement and configuration of the integral surface is a key-modelling decision. When surveying the literature, opinions on the surface configuration are diverse but have an extreme impact on the predicted far-field sound levels. Hence, with jet LES, there is a wide range of numerical uncertainties that cloud judgement of the performance of an LES model. Uncertainties in the latter will be discussed next.

(b) LES model uncertainties

Most LES models assume isotropy of the modelled scales. However, with evidence for the existence of worm-vortices characterizing the smallest coherent turbulent structures, this assumption is open to question. Hence, the
applicability of LES models is an important question. Although the Smagorinsky LES model is popular, it is well known that it drains energy from all scales and not, as it should, just the smallest resolved scales. In addition, it does not provide backscatter and the strain rate term does not vanish at the wall. The latter gives rise to *ad hoc* modifications. Furthermore, elongated intricate vortices occur at the walls, the resolution of which creates serious problems. This latter aspect has been a strong driving force behind the development of hybrid LES–RANS methods pioneered by Spalart (1999). These use near-wall RANS modelling to cover over the fine near-wall structures (see later). It is important to note that eddy viscosity-based models, like the Smagorinsky, alter the effective Reynolds number of the flow. Consequently, as demonstrated by Bogey & Bailley (2005), for jets they exert an erroneous modelling influence on the more shear-governed noise components. In addition, with jets, for the flow to become independent of initial conditions, a Reynolds number of at least $4 \times 10^5$ is required (Birch 1983). This raises questions regarding the role of the effective Reynolds number arising from the use of eddy viscosity-based LES models on jet evolution and transition.

Most RANS models are based around Boussinesq’s 1877 approximation. This crude approximation spawned nonlinear quadratic and cubic RANS corrections. In a sense, LES appears to be following a similar path. For example, Lund & Novikov (1992), Wong (1992) and Kosovic (1997) produced quadratic and cubic LES extensions to the Boussinesq approximation. The so-called ‘mixed models’ also can be viewed in the same nonlinear model framework. For example, in Clark/Leonard’s original model, nonlinear terms are added to the usual linear terms. Meneveau & Katz (2000) note that *a priori* tests for a range of flows suggest nonlinear models are, on the whole, superior to linear. Nonlinear models make less use of the eddy viscosity. Hence, they might be more resilient to the above-noted effective Reynolds number influences. However, this remains to be tested and for jets the performance of nonlinear models remains unclear. For example, Liu et al. (in press) contrasted three nonlinear and two linear LES models for plane jets. In relation to the scatter in the benchmark data, it was difficult to conclude which model was better. There is a wide range of parameters to compare with when assessing each model’s performance and one model was found to be better for one parameter but worse for the next and so on. A part conclusion of this study, which follows the line of thought of Grinstein (2006), is that the supergrid scale influences, like boundary condition specifications, were more important than the LES (subgrid) modelling. However, for these plane jet tests, just a second-order central difference scheme was used with a small filter. This is also likely to cloud LES model assessment since numerical influences will be significant.

(c) Hybrid (N)LES–RANS

A key (N)LES problem is that at realistic Reynolds numbers, with current computers, the scales of the intricate near-wall turbulence structures will be impossible to resolve adequately. This motivated the development of hybrid LES–RANS methods. Of course, with hybrid LES–RANS, the issue of excessive dissipative numerical contamination in the LES zone remains. Hence, for a round jet with co-flow, Tucker (2004) combines (through a Hamilton–Jacobi equation)
near-wall RANS modelling with NLES. This approach is also adopted by Shur & Spalart (2006). The near-wall RANS model will ensure that a reasonable mean velocity boundary layer profile enters the free shear layers and also prevents separation on convex surfaces. However, clearly, this approach results in negligibly resolved scales in shear layers and this is an undesirable situation. Nonetheless, Georgiadis et al. (2003) gain encouraging results with a similar approach. With chevron (serrated) nozzles, essentially the chevron tip could be considered as a sharp convex geometrical feature. As shown by Tucker & Liu (2006), RANS models can exhibit anomalous behaviour around such regions giving dramatically different predicted eddy viscosity levels. Hence, there is a question mark regarding how well hybrid (N)LES–RANS will perform for such problems. Indeed, there are many unresolved theoretical questions with hybrid (N)LES–RANS methods and they should be used with thought and care.

\[(d)\  \text{Boundary condition influences}\]

The typical momentum thickness used in LES is around an order of magnitude larger than that from experiments (Bodony & Lele 2006). Bogey & Bailly (2004) show that this difference gives excessive reduction in predicted turbulence and hence sound levels.

In addition, to accurately model full-scale jets, the initial boundary layer needs to be turbulent. It is difficult to achieve a fully turbulent boundary layer for \(Re < 10^4\), and the added requirement of being thin pushes the nozzle Reynolds number requirement closer to \(Re \approx 10^6\). This is what makes LES calculations of complete jets so difficult at present.

Inflow turbulence can be synthetically generated in a range of ways. However, Barré et al. (2006) and Uzun & Hussaini (2006) strongly suggest that resolution of the upstream nozzle boundary layers is necessary to gain relevant results with turbulence synthesis best being avoided. As noted by DeBonis (2006), upstream boundary layer resolution removes the substantial level of empiricism used to direct solutions to desired answers. Hence, boundary layer resolution makes CFD technology more predictive. Having said this, the high-grid resolution simulations of Uzun & Hussaini (2006), which resolve the upstream nozzle boundary layers, are not that convincing. This could be because the boundary layer Reynolds number in these simulations is only approximately 300 and so the boundary layers are likely to have a laminar nature. Of course at higher Reynolds numbers the grid demands become too severe. This leads back to the need for hybrid LES–RANS methods with perhaps, at the jet outlet, forcing of resolved scales based on upstream RANS zone information (Batten et al. 2004).

For jet LES simulation, non-reflecting inflow and outflow boundary conditions are necessary and in the literature a wide range of strategies can be found. As noted by Klein et al., jets are sensitive to far-field boundary conditions and so their modelling is an important uncertainty that can explain anomalies between various datasets. It is also worth noting that inflow region metastability issues are observed for jets with co-flow. These could manifest themselves in some numerical form giving rise to solution non-uniqueness. This is not such an uncommon problem in other engineering systems. However, currently with regards to jets this remains an open question.
5. RANS-based noise prediction procedure

(a) Introduction

While the prospect of calculating noise directly makes LES attractive, it also makes it very difficult and seems probable that noise calculations for practical nozzle configurations will be forced to rely on RANS approaches for some time yet. Many publications are devoted to the jet noise problem using this approach, including the well-known classic work of Blokhintsev (1946), Lighthill (1952), Ffowcs Williams (1963), Ffowcs Williams & Hawkings (1969), Lilley (1974), Goldstein (1984), Ribner (1996) and others. All these approaches are based on several common ideas of classical aeroacoustic theory.

This theory contains the following main elements; namely, a RANS calculation is first performed to obtain time-averaged mean flow and turbulence quantities. A second step involves obtaining the explicit solution of linearized Euler equations for pressure $p_{ac}'(t)$ (or density) fluctuations, using a Green’s function and noise source term as an integral over the whole volume containing the turbulent jet. The third step is obtaining a spectrum and a directivity diagram, using a Fourier transformation and an averaging procedure for $p_{ac}'(t)$.

Let us consider some features of this traditional aeroacoustic theory in more detail. The typical structure of modern aeroacoustic equations is as follows:

$$L(U, p_{ac}') = Q(x, y, z, t).$$  \hspace{1cm} (4.1)

Here, $L$ is a linear wave operator, $U = \{U_1, U_2, U_3\}$ is the velocity vector and $Q$ is a source term, which is connected with turbulence and varies randomly along space and time. The main physical problem in equation (4.1) is correct pressure decomposition in the sum of averaged, $\langle p \rangle$, vortical, entropic and acoustic terms

$$p = \langle p \rangle + p_{vor}' + p_{ent}' + p_{ac}'.$$  \hspace{1cm} (4.2)

This problem is currently unsolved and this is the main weakness of the current traditional acoustic theory.

Using Fourier transformation, it is possible to eliminate time from the equation and get an equation with the frequency parameter $\omega$

$$L(\omega, U, p_{ac}) = Q(x, y, z, \omega).$$  \hspace{1cm} (4.3)

The Green function for equation (4.3) is necessary in order to find the explicit acoustic density fluctuation $p_{ac}$ (Fourier transformed) as an integral for turbulent volume

$$p_{ac}(x_0, \omega) = \iiint G(x, x_0, \omega)Q(x, \omega)dx^3.$$  \hspace{1cm} (4.4)

Then it is possible to obtain some averaged values for noise characteristics, for example, for noise spectrum

$$\Phi(x_0, \omega) \equiv \langle p_{ac}(x_0, \omega)p_{ac}(x_0, \omega) \rangle = \iiint \iint G(x\prime, x_0, \omega)G(x\prime\prime, x_0, \omega) \times \langle Q(x\prime, \omega)Q(x\prime\prime, \omega) \rangle dx^3dx^3.$$  \hspace{1cm} (4.5)

Here, $\langle Q(x\prime, \omega)Q(x\prime\prime, \omega) \rangle$ is the space correlation function for source terms in equation (4.3). In this step, different scientists use different relations for the source
term and the correlation function. Such uncertainty about a concrete choice for $Q$
reflects the above-mentioned principal difficulty for the pressure decomposition (equation (4.2)).

The other purely formal mathematical weakness of the theory is connected with the Green function. The equation for Green function is

$$A\{\omega, U, G\} = \delta(x - x_o)\delta(y, y_o)\delta(z - z_o).$$

Hence, its solution is a function of seven arguments,

$$G = G(x, x_o, y, y_o, z, z_o, \omega).$$

Here, $x = \{x, y, z\}$ gives the coordinates of the noise source for integration in equation (4.5) and $x_o = \{x_o, y_o, z_o\}$ the ‘observer’ coordinates (microphone position). In addition, the function $G$ has a rather fast oscillation along the space coordinate. In principle, it is possible to perform integrations of equation (4.6) to get a large file with all the information for equation (4.7). However, such a procedure is impossible with modern computers. Generally, the use of some analytical and very simplified solution of equation (4.6) is made. In particular, axial symmetry is assumed for the jet flow $U = \{U_1(r), 0, 0\}$ and for the acoustic field, only the high-frequency range is considered: $\omega D / U_1 \gg 1$ and so on. Similar analytical solutions for complex jet flows, for example, chevron nozzles with pylons, are absent.

Among the numerous traditional aeroacoustic equations such as equation (4.1), the Lilley equation (Lilley 1974) predicts the effects of refraction and convection of acoustic waves better than many other theories. Many approaches use this equation in order to get a Green function and calculate jet noise. This approach was used in the well-known MGBK codes (see Mani et al. 1978; Khavaran et al. 1994), and in the NASA Langley code Jet3D (Hunter 2002; Hunter & Thomas 2003) for jet noise prediction.

In spite of attempts to use a rather strict aeroacoustic Lilley equation, the main considerations are traditionally inaccurate. In particular, the Green function is obtained for a simple velocity profile and for short-wave approximations only. Similarly, the Green function is not able to describe real jet velocity fields and large-scale turbulence fields. Hence, such an approach cannot give an accurate prediction of chevron nozzle jet noise. The time–space correlations are separated into space and time correlations in this method and both correlations have an exponential shape, although all experiments show that the correlations really have a power decay. As a consequence, noise spectra shapes in these approaches have an exponential factor

$$S(\omega) \propto \omega^m \exp\{-A\omega^2\},$$

while the known experiments show that the spectrum at high frequencies has power decay law $\omega - m$, were $m \approx 2 - 3$.

A directivity diagram could be obtained from the Green function, in principle; however, due to the above-mentioned approximations for this function, it is impossible. Usually, the directivity diagram is obtained from approximate semi-intuitive considerations that are similar to the work of Ribner (1996) or others.

Consideration of the above difficulties and defects of traditional aeroacoustic theory results in attempts to develop other more practical methods of jet noise prediction. The approaches of Munin et al. (1981), Kopiev & Chervyshev (1997),

The latter approaches use approximate or even empirical approximations for the Green and source term functions, instead of ‘exact’ solution of any aeroacoustic equation. Such a method is less universal, but at the same time, such a simplified approach makes it possible to take into account several important features of ‘real’ jets and to get more accurate noise prediction for a class of jet flows with a relatively narrow parameter range. The word real implies turbulent jets that have Mach numbers $M_{aj} = 0.5–0.9$, temperature ratio $T_j/T_e = 1–3$ (ratio of the jet outlet to ambient temperature), and coaxial jets having a bypass ratio of 5–8. Some important features of this approach will be considered below.

6. Some specific acoustic features of real turbulent jets

(a) Temperature influence

The effect of temperature on the jet noise was considered in several experimental studies (Tanna 1977; Bridges & Brown 2004; Viswanathan 2004). The results common to all these studies are briefly as follows. At high-acoustic Mach numbers ($M_a = U_j/c_o = 0.9–1.2$, where $c_o$ is the ambient speed of sound), jet heating causes a decrease in the noise level at all frequencies. In contrast, at low Mach numbers ($M_a = 0.5–0.62$), jet heating leads to an increase in the noise level, at least at the lower frequencies. Differences in the measured noise between the different experiments, however, were as high as 5 dB. A possible explanation for this data scatter is connected with low values of Reynolds number used in most
of these experiments. The Reynolds number drops fast when a jet is heated and for many of these studies, particularly with the lower Mach number flows, the Reynolds numbers used were quite low.

As noted previously, the modified zonal $k-\varepsilon$ model of Birch et al. (2006) does a relatively good job of predicting jet flows. Mean flow and turbulence for a hot jet are correctly predicted using such a model without the need for any additional assumptions about the turbulence. Heating typically leads to a faster mixing of the jet. Since this faster mixing occurs with little or no change in the turbulence level, the mean flow and turbulence for the hot jet, as predicted by a RANS model, can be approximated by simply scaling the $x$-axis for the cold jet data to reduce the length of the jet potential core.

What is perhaps even more surprising is that this scaling also seems to accurately predict the associated noise reduction for the hot jet (Birch et al. 2006). This seems to suggest that the physics of hot jets, at least at the higher subsonic Mach numbers, may not be as different from that of cold jets as is sometimes supposed and that most of the differences, other than refraction effects, may simply be due to the shorter length of the jet potential core.

(b) Refraction due to turbulence fluctuations

It is known that the aviation noise standard considers only noise in the frequency range from 50 to 10 000 Hz. The human ear is most sensitive to frequencies in the range 2000–4000 Hz. Such frequencies correspond to acoustic wavelengths of $\lambda \approx 0.1–0.2$ m. The exhaust jet diameter of a real commercial aviation engine is rather large: $D = 2–3$ m, so $\lambda \ll D$. In this case, it is shown that the main features of acoustic waves are described by a relatively simple version of the acoustics (short-wave approximation), namely, by geometric acoustics. Acoustic waves can be considered as rays, the direction of which can be changed during their penetration through a non-uniform medium (refraction).

Owing to velocity and temperature gradients, short acoustic waves deflect from a linear path within jets. The deflection is towards the side of less velocity and less temperature (or less sonic speed). These effects were known long ago and were considered, for example, in the works by Blokhinstev (1946), Avila & Keller (1963) and Cervino et al. (2002). Owing to refraction and convection, the peak noise radiates at polar (relative to the jet axis) angle $\theta_{\text{m}} \approx 30$° and decreases as the difference $|\theta_{\text{m}} - \theta|$ increases. The plot of noise level with respect to angle is called the directivity diagram, $D(\theta, M)$, and it depends, of course, not only on $\theta$, but also on the jet Mach number.

Turbulent jets are distinguished by large-scale and large amplitude velocity and temperature fluctuations. Instantaneous gradients in turbulent jets are larger than average. The necessity of taking into account the scattering of acoustic waves by turbulence is mentioned in Blokhinstev (1946), Avila & Keller (1963), Cervino et al. (2002) and Khritov et al. (2005). Direct numerical simulation of interactions between acoustic waves and the instantaneous velocity field in the turbulent jet are discussed by Cervino et al. (2002) and Khritov et al. (2005).

Some examples of acoustic ray tracing are shown in figure 5 for a round coaxial jet from the NASA Glenn 3BB nozzle. Here, results were obtained from the LES jet calculations of Lyubimov (2003), using the method described in Landau & Lifshits (1987). A schematic of the nozzle geometry is shown in the figure 5a. An
acoustic source is placed at a point \((X_0, Y_0, Z_0)\) inside the jet mixing layer and acoustic rays are released from the point source at 2° angular increments, from 0° up to 360° (figure 5b). A picture of the spread of these rays is shown in the figure 5b for a cross-section at, \(X/Dc = 8\), where \(Dc\) is the diameter of the core nozzle, for an acoustic source placed at a radial location \(Y_0/Dc = 0.7\), \(X/Dc = 8\). The acoustic source was then moved to another location inside the jet and the spread of the rays from this new location was calculated. This procedure was repeated for numerous locations of the noise source. This led to three main conclusions as follows.

(i) Acoustic rays are strongly curved by turbulence. It seems that refraction due to turbulence is larger than that due to the mean velocity and density fields. Similar conclusions can be found in the work by Avila & Keller (1963), Durbin (1983), Morris & Farassat (2002) and Suzuki & Lele (2002).

This phenomenon leads to a more uniform directivity diagram. Owing to this, we have to add the second additional term connected with turbulence in the known relation for directivity,

\[
D(\theta, M) = (1 - M_c \cos \theta)^2 + \left(\frac{k}{c_0}\right) \times M_c^2 \times F_D(\omega). \tag{6.9}
\]

Here, \(M_c = U/c_0\) is the ‘convective’ Mach number and is approximately equal to the ratio of the local velocity \(U\) to the ambient speed of sound. The first term in equation (6.9) describes refraction effects due to the averaged velocity field. The second term describes refraction effects due to the turbulence. A similar relation has been proposed by, for example, Ribner (1996).

(ii) It is clear that all acoustic rays after several distortions and refractions penetrate through the jet and escape from it. However, it is seen that (figure 5) if a ray source is placed in the upper side of the jet, then ray traces are practically absent in the lower part of the jet. This complex phenomenon shows that a real turbulent jet is practically opaque to short wavelength waves.

(iii) Finally, it should be noted that the wavevector \(k\) and frequency \(\omega\) of acoustic waves is changed rather strongly by the Doppler effect at acoustic wave–turbulence interactions. This effect can increase the high-frequency part of the noise spectrum.

It is not possible to discuss these results in detail here, but it is important to note that the jets from real nozzles are always three-dimensional, due to the presence of the pylon and wing interaction effects, and the associated radiated noise is always to some degree asymmetric. This makes noise prediction very difficult, but the ‘non-transparence’ results described here do seem to provide an opportunity to account for these effects at least approximately.

7. Mechanisms of chevron nozzle influence on the jet noise spectra

Many experiments show that chevrons decrease low-frequency noise and increase the high frequency (Bridges & Brown 2004). One of the most popular explanations for low-frequency noise reductions is that chevrons increase the
jet mixing rate and reduce the volume of the jet with high velocity and this is a reason for the low-frequency noise reduction. However, the experiment described in Bridges & Brown (2004) with a relatively small chevron (SMC003) does not show any mixing increase. The jet potential core is shorter for a nozzle with large (SMC006) chevrons (Bridges & Brown 2004). However, it is not obvious that this fully explains the observer change in the low-frequency noise. No mechanism has been proposed to explain the high-frequency noise increase.

In figure 6, cross-sections of the flow from the large chevron nozzle (SMC006) are shown at two axial stations. At an $X/D$ of 1.0, the chevrons strongly distort the mixing layer to form a star-shaped cross-section that greatly increases the contact area between the jet and the external flow. This appears to be the main reason for the increased mixing downstream of chevron nozzle flows. Note, however, that the mixing layer itself remains quite thin. Farther downstream, at an $X/D$ of 2–3, the continuing mixing causes the flow in the arms of the star to merge to again form a quasi-round mixing layer. The width of the mixing layer now, however, is much larger than that of a round nozzle at the same axial station. This merging of the arms of the star, in effect, leads to a very rapid increase in the width of the mixing layer. This causes a local imbalance between the turbulence and the mean flow that leads to a reduction in the turbulence production, relative to its dissipation rate. As a consequence, the peak turbulence level is reduced, which reduces the noise at the lower frequencies.

Both the predicted and experimental data (Bridges & Brown 2004; Brich et al. 2006) show that with these chevrons, there is a small increase in the turbulence just downstream of the nozzle exit ($X/D < 1$), but that this was followed by a decrease in turbulence level ($1 < X/D < 7$), so that overall turbulence levels tended to be lower over most of the potential core for chevron nozzle flows. This interesting turbulence reduction turns out to have a rather simple explanation and is well predicted by even a relatively simple RANS model. It was therefore a surprise to find that there was a large discrepancy between the predicted (Birch et al. 2006) and the measured noise for these chevron nozzle flows at high frequencies.

Figure 6. Contours of turbulence levels for large chevron nozzle (SMC006) at (a) $X/D=1$ and (b) $X/D=3$. 

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After a careful study, it was concluded that the noise increase at high frequencies could not be explained as being due to any change in the turbulence kinetic energy or its dissipation rate. To explain the experimentally observed noise increase simply as a function of the turbulence energy would require an increase in the turbulence energy of approximately 70% over the first two nozzle diameters, but the RANS predicted turbulence energy is not in error by anything close to this. As best, we could determine that this additional noise appeared to be produced by the interaction of the axial vortices with the turbulence and scales with the strength of the axial vortices themselves. In other words, it does not appear that the effect of chevrons can be correctly predicted using any of the current noise prediction methods and this is the reason why Birch et al. (2006) were forced to develop a new empirical noise model for these flows. This model is briefly described below.

8. RANS chevron jet noise model JNPM-05

Considering the complex effects involved and the limitations of traditional aeroacoustic theory, it seems reasonable to try more approximate methods. These may involve less rigorous approximations for the Green function, or the spectrum shape, or even purely empirical models based on experimental jet noise data. Similar jet noise prediction methods are described in Stone (1977) and Stone et al. (2003). In the present model, functions for refraction and convection effects in complex coaxial jets were obtained with the help of elementary ray-tracing predictions. The main feature of this model that differs from other simplified jet noise models is the use of a term that is designed to better describe the influence of chevrons on jet noise. There is also a strong connection with the zonal turbulence model discussed previously. This jet noise prediction model JNPM-05 is not intended to represent a new noise theory. It is simply a tool to try to obtain a better understanding of the noise from chevron nozzles.

The definition of the jet noise spectrum at a point with distance $r$ from the nozzle exit and with polar angle $\theta$ is

$$S(r, \theta, \omega) = \frac{1}{(2\pi \rho_0 c_0)} \int \langle pt(x, t) pt(x, t + \tau) \rangle e^{i\omega \tau} d\tau. \quad (8.10)$$

In our noise model JNPM, the spectrum is an integral for jet volume for the noise source $Q$

$$S(r, \theta, \omega) \approx \frac{1}{\rho_0 r^2} \iiint \rho^2 k \frac{Q \cdot F(\omega/\omega_s)}{D(\theta, M)} d\omega d\theta d\phi. \quad (8.11)$$

The main terms in this noise source relation are

$$Q = A \frac{k^{5/2}}{c_o^2} F(\Omega) + \cos^2 \theta \frac{L^2 (dU/dr)^2 k^{3/2}}{c_o^3}, \quad (8.12)$$

$$\phi \left( \frac{\omega}{\omega_c} \right) = \frac{a_1 (\omega/\omega_s)^{3/2}}{1 + a_1 (\omega/\omega_s)^{3/2}} \times \frac{1}{1 + a_2 (\omega/\omega_s) + a_3 [\omega c_o^2 / (1 + k c_o^2)]^{3/2}. \quad (8.13)$$

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Here, $D(\theta, M)$ is the directivity function, $k$ is the turbulence energy, $\rho$, $\rho_0$ are the density inside and outside the jet, respectively, $F(\Omega)$ is the function from longitudinal vorticity $L = k^{3/2}/\varepsilon$, and $U$ is the averaged longitudinal velocity. The characteristic frequency $\omega_1 = 2\pi f_1 \approx \varepsilon/k$. The coefficients $a_1$, $a_2$ and $a_3$ are functions of the local turbulence level, directivity angle $\theta$ and density variation, respectively. The whole structure of these relations is rather typical and based on numerous previous publications.

The vortex term $F(\Omega)$ requires additional foundations. Bridges & Brown (2004) showed that if the chevron edge projection onto the axial plane is given by radius $r$ as a function of arclength $s$ at a midpoint of a chevron, then the local deflection is proportional to $\Gamma = |\partial r/\partial s|$. This parameter $\Gamma$ can be useful in characterizing a variety of different chevron nozzle shapes. It is possible to write this parameter using chevron geometric values, namely

$$\Gamma = \frac{L_{im}}{\Delta_{ch}}. \quad (8.14)$$

Here, $L_{im}$ is the depth of chevron immersion and $\Delta_{ch}$ is the distance between chevrons in the circumferential direction. A similar idea was suggested by Krasheninnikov and discussed in Khritov et al. (2005). For numerical calculations, however, it is more convenient to express geometric chevron parameters in terms of local flow parameters. In order to characterize the distance between chevrons ($\Delta_{ch}$) and the depth of chevron immersion $L_{im}$, the shortest distance to the nozzle wall surface $d$, longitudinal vorticity $\Omega$ and secondary velocity ($v$ and $w$) were used (Khritov et al. 2005). In this case function, $F(\Omega)$ is

$$F(\Omega) = \frac{\Gamma_1 \approx d|\Omega|}{\left\{k^{1/2} + (v^2 + w^2)^{1/2}\right\}}. \quad (8.15)$$

This concept is implemented in the jet noise prediction model Khritov et al. (2005) as an additional correction coefficient. It should be noted that this correction function takes into account only effects connected with high-frequency noise ($\omega > \omega_k \approx \varepsilon/k$) that could not be predicted with it. Unfortunately, no clear physical explanation for the mechanism of the interaction between the turbulence and the longitudinal vorticity is available at present.

The effect of this term on noise predictions for the chevron nozzle SMC006 nozzle flows, for both hot ($T_j/T_e = 2.7$) and cold ($T_j/T_e = 0.86$) flows, are shown in figure 7. As can be seen from these figures, the new vortex term gives noise predictions that are in good agreement with the experimental data from Bridges & Brown (2004). Similar tests were performed for numerous other single and coaxial round jets, nozzles with pylon and chevrons, for different bypass ratios (BPR) nozzles (STAN, this is not defined), temperatures and pressure ratios. Comparison with the available experimental data shows that the JNPM model gives prediction of spectra and directivity diagrams with errors of less 2–3 dB.

9. Concluding remarks

The geometries from which jets found in aerospace engineering can be wide ranging giving rise, when for example combined with Mach number effects, to substantially different large-scale turbulence features. These aspects are especially
challenging for RANS models and present them with a daunting task. Large Eddy Simulation, even on quite coarse grids, seems to predict the correct trends. However, to model complex jet flows with sufficient accuracy to allow detailed comparisons with experimental data requires very large grids and this makes such LES calculations impracticable at present. With respect to LES, problem definition uncertainties (such as nozzle geometry definition and its influence on inflow), near-wall modelling, transition issues, grid structure along with its implications on filter definition are of potentially greater importance for practical jet flows than the LES model itself, which can be theoretically questionable. When moving to realistic engine conditions, disentangling numerical influences from the LES models appears difficult and diminishes the LES models value with its omission frequently being beneficial. However, even with the above problems, the numerical study of the delicate turbulence interactions required to reduce noise is best carried out through LES-related techniques. These are generally not, as with the RANS approach, so dependent on calibration for different flow types and therefore offer the best prospects for improved noise prediction, with a minimum of empiricism. Complex jet geometries, however, pose specific problems that make it very difficult to model the complete flow field accurately with the computer resources at present available. It does seem possible, however, to conduct detailed LES studies of specific features of the flow. The results of these studies could then be used to improve RANS (or even LES) modelling, which, in turn, could be used to perform the complete flow-field calculations. One such study, which could yield very useful near-term results, is a detailed study of just the initial mixing region, just downstream of the nozzle exit. This is, arguably, the most complex and least well-understood region of the flow, particularly for chevron nozzle flows, and where the use of LES could be most beneficial. The use of LES in conjunction with a ray-tracing model to elucidate the physics of acoustic wave transmission in jets and thus improve RANS technology was illustrated. It was argued that, as a stopgap measure, pure RANS technology can be a valuable part of the design process and can now predict acoustics spectra and directivity diagrams with useful accuracy. Hence, it seems probable that near-term progress in the calculation of the complex flows of industrial interest will require a combination of RANS and LES, with an eventual transition to LES, as computer resources improve.

Figure 7. Noise predictions for the large chevron (SMC006) nozzle with cold and hot jets.
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