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Progress Toward Large-Eddy Simulations for Prediction of Realistic Nozzle Systems

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I. Introduction

THIS paper gives an overview of the current state of large-eddy simulation (LES) for nozzle flows and discusses the issues which currently limit its application to simulating realistic noise reducing nozzle systems. LES has been used extensively to compute the flowfield of simple turbulent round jets. Although results at this point are not better than Reynolds-averaged Navier–Stokes methods, it has shown the potential to significantly impact the design and analysis of future noise-suppressing nozzle systems through a promise of improved accuracy and physical insight. There are many issues that must be resolved before an accurate prediction can be made for a complex nozzle system. Foremost, the high-order schemes used in LES must be adapted to be used in flexible gridding systems which can handle complex geometries. Hybrid Reynolds-averaged Navier–Stokes/LES schemes with appropriate interfaces must be developed to model the region near the nozzle exit and initial shear layer. Also, improved accuracy without reliance on empirical adjustments of simulation parameters must be demonstrated.

Regulations on aircraft noise have become increasingly stringent throughout the world. A large contributor to aircraft noise at takeoff is the noise produced from the exhaust system jet noise. As a result, jet noise reduction has become a critical technology for the aerospace industry. Significant noise reductions for turbofan engines on subsonic transports have resulted from increasing the engine's bypass ratio. This increase in bypass ratio lowers the overall jet velocity, reducing the noise. However, future stricter noise regulations will require additional noise reduction strategies. Engines for proposed supersonic aircraft, business jets, and large transports typically use lower bypass ratios. Here, noise reduction technologies are critical for the viability of such an aircraft. NASA's High-Speed Research program developed a mixer/ejector nozzle which met the program's noise and performance goals [1]. However, this nozzle was very heavy and complex. It is hoped that a better solution will be found through current research.

The most successful noise reduction technology to date is the chevron nozzle (Fig. 1). This nozzle has been flying on several commercial aircraft engines already. The serrated edge of the chevron nozzle increases the mixing of the exhaust streams and modifies the turbulent characteristics in the jet, reducing noise [2].

There are several other noise reduction concepts currently being studied. Most concepts, such as plasma actuators [3], fluidic injection [4], tabs [5,6], and lobed mixers (Fig. 2) [7] aim to increase mixing and modify the jet turbulence similar to the chevron nozzle. For the most part, these studies are fundamental in nature and realistic nozzle systems based on these technologies have not been developed.

Papamoschou has developed a series of concepts that are referred to as offset fan flow technology nozzles [8,9]. The idea is to divert or "offset" the fan flow below the core flow. This would create a thicker layer of low-speed fan flow below the high-speed core flow and change the noise directivity and intensity. The result would be lower noise levels directed toward the ground. Implementation of the offset fan flow idea would be through devices such as vanes or wedges (Fig. 3) that would redirect the fan flow at takeoff. The best results using this technology have been shown for low-bypass ratio nozzles. This system is promising both because of the large noise reductions demonstrated in benchmark experiments and because of the simplicity in implementation on a realistic system.

In all of the concepts discussed, the exact mechanism for noise reduction is not clearly understood. Detailed information on the turbulent structures and how they are affected by the noise reduction devices is needed. Design and analysis of these concepts would be greatly enhanced through the use of accurate computational fluid dynamics (CFD) simulations. CFD has been successfully used for years in the development of other aerospace components. To date, almost all CFD for design and development has been steady Reynolds-averaged Navier–Stokes (RANS) calculations. However, RANS turbulence models have not proved accurate for jet flows [10]. Much work has been done in the area of advanced RANS models, specifically for jets [11–13]. The results have been mixed, and generalizing these models to a wide range of flow conditions and geometries may not be possible. RANS is also limited in the information it can provide. For most jet applications, a two-equation k–ϵ or k–ω is used [14]. The models can only provide a simple statistical representation of the turbulence in the form of the turbulent kinetic energy and a local length scale.

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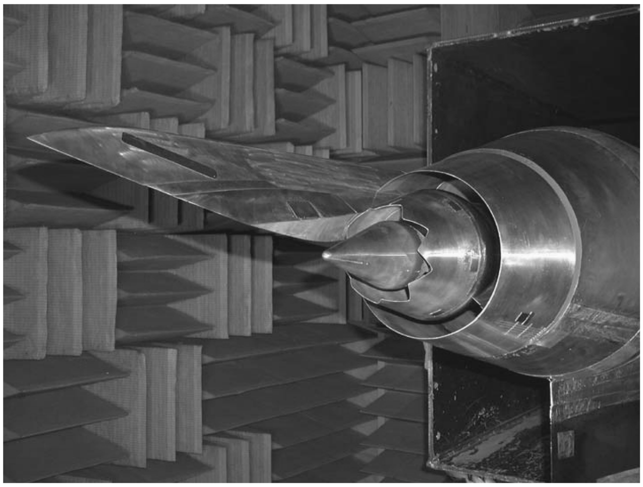


Fig. 1 Chevron nozzle with pylon, installed in the NASA Langley low-speed aeroacoustic wind tunnel (from Thomas and Kinzie [59]).

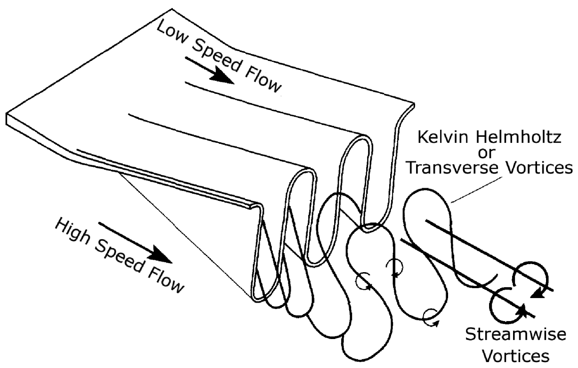
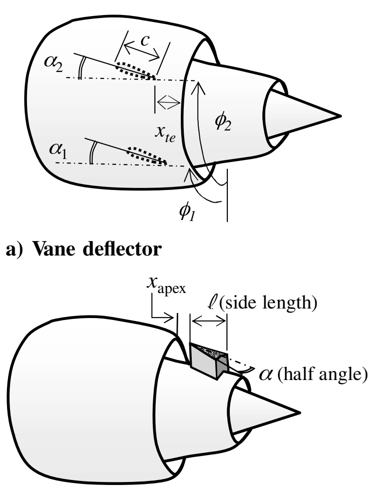


Fig. 2 Schematic of a lobed mixer (reprinted with permission by McCormick [7]).



a) Vane deflector

b) Wedge deflector

Fig. 3 Offset fan flow nozzle concepts (reprinted with permission by Papamouschou [9]).

Acoustic predictions based on RANS solutions are done using the acoustic analogy [15,16]. This acoustic modeling relies heavily on modeling the acoustic source based on the RANS solutions [17]. The results from this method are reasonable for cold round jets. Results are poor for heated jets and nonaxisymmetric geometries.

Large-eddy simulation is the next logical step toward improved jet predictions. Over the last decade, LES has been increasingly used due to the growth in computing power. LES is an unsteady method which directly computes the large-scale turbulent structures and reserves modeling for the small-scale turbulence. Because the large-scale turbulence carries most of the turbulent energy, very good predictions of the turbulent flowfield are possible. The direct simulation of large-scale structures can significantly enhance our understanding of the flow and lead to better noise reduction strategies and improved designs.

The large-eddy simulation of the jet near field captures the nonlinear sound generation process. It is possible, but not efficient, to carry the simulation to the acoustic far field to compute the noise directly. The propagation of the sound to the far field is a linear process and can instead be predicted by several simpler methods. Shih et al. give a good discussion and evaluation of these methods [18].

LES has the potential to vastly improve the prediction of jet flows and impact designs of noise suppressing nozzles. However, there is much work to be done before LES can be used reliably in this manner. Great strides in advancing LES have been made in the past decade, but the vast majority of this work has been done on simple benchmark problems. There is a danger in assuming that LES is ready for more applied work. Many widely used government and commercial CFD codes now include LES capabilities. But without a detailed understanding of LES and careful application, unpredictable and erroneous results will occur. The intent of this paper is twofold. For the application-oriented, it is to provide a brief overview of LES for jet flows, provide some insight into the various components of an LES code, and identify those issues which prevent LES from being used as a predictive tool. For the LES developer, it is to identify those areas where further work is needed to make this technique more valuable for the propulsion community.

II. Examples of LES of Jet Flows

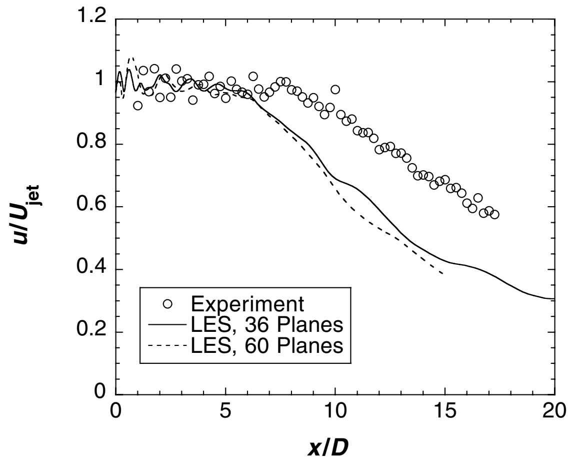
Jet flows have been a popular application of LES. This section summarizes a representative sample of the work to date. Much of the work has focused on unheated round jets; the exceptions to this are noted.

Lele and coworkers performed several simulations of hot and cold Mach 0.9 jet at low to moderate Reynolds number using a consistent approach [19–21]. They employ a sixth-order compact differencing in space [22] and an explicit low-dispersion Runge–Kutta (LDRK) differencing in time. They use a dynamic subgrid model and the solution is explicitly filtered. The inflow boundary condition consists of a velocity profile with sinusoidal forcing of the axial velocity component and random forcing of the azimuthal velocity component.

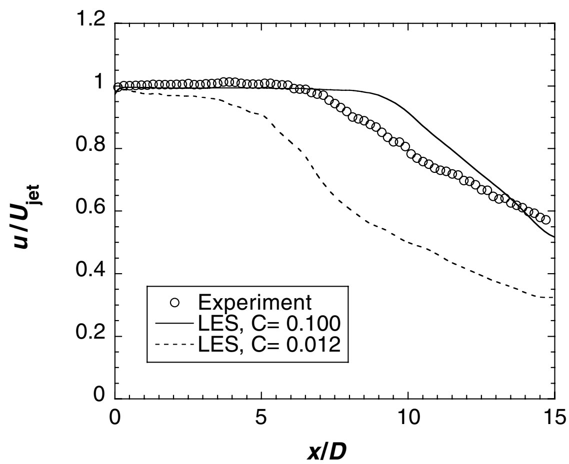
Bogey and Bailly [23,24] and Bogey et al. [25] have simulated several subsonic jets . Their method uses a 13 point finite differencing in space. The finite difference stencil is optimized to minimize the dispersion error and is based on Tam and Webb's dispersion relation preserving (DRP) scheme [26]. They also use an LDRK scheme for time advancement. Their earlier work employed explicit modeling of the subgrid scales. However, recent work has relied on filtering without subgrid models. They have also examined the influence of eddy viscosity on the effective Reynolds number of the flow.

Shur et al. have taken a different approach [27,28]. They have adapted a RANS code which uses a finite volume approach employing the Roe scheme. The fluxes are computed with hybrid fifth-order upwind/fourth-order central differences. Limiters are used in the presence of shocks. Time advancement is done using an implicit second-order scheme. This simulation does not use a subgrid scale model. They rely on the numerical dissipation of the scheme to remove energy that would be dissipated by the small scales. The authors have simulated a chevron nozzle by modifying the inflow boundary condition and altering the grid at the inflow plane.

These simulations all used an inflow boundary condition that specifies the jet velocity profile. The velocity profiles are typically represented using a hyperbolic tangent function. With the exception of Shur et al. [27,28], some type of unsteady perturbation is imposed. The development of the shear layer is dependent on the initial shear layer thickness as well as the type, frequency, and magnitude of the

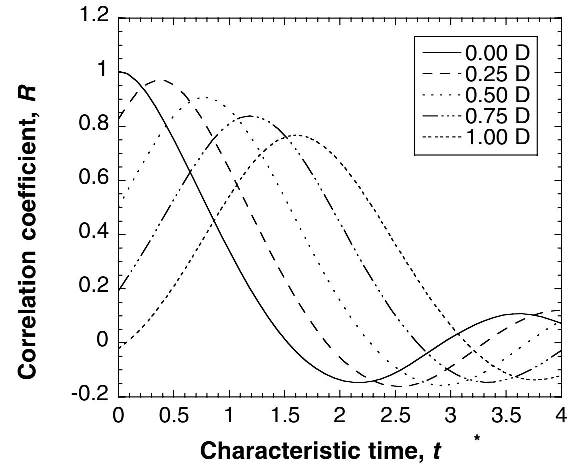


a) Supersonic, M=1.4

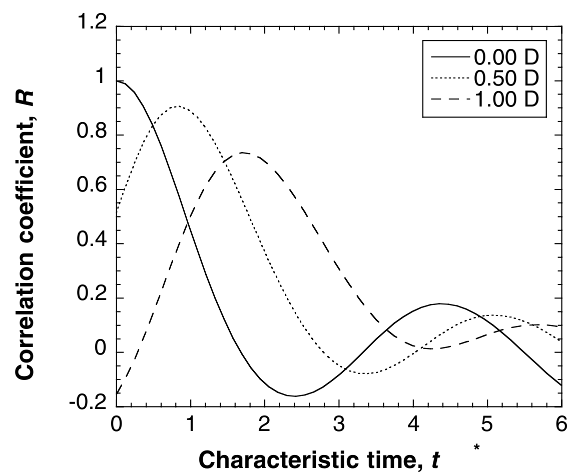


b) Subsonic, M=0.9

Fig. 4 Predictions of centerline velocity from simulations that include the nozzle geometry.



a) Mach 1.4 jet



b) Mach 0.9 jet

Fig. 5 Two-point space-time correlation coefficient.

imposed velocity perturbations. Because turbulence data near the nozzle exit are difficult to obtain, the inflow boundary is usually assumed to be at an unspecified location downstream of the nozzle exit. To compare with experimental data, the results of the analysis are usually shifted along the jet axis so that the end of the potential core in the experiment and LES match.

DeBonis and Scott have performed LES on a supersonic jet, Mach 1.4, and a subsonic jet, Mach 0.9, where the nozzle geometry was modeled [29,30]. This avoids the ad hoc specification of inflow conditions by directly solving the internal nozzle flow. However, the accuracy of this approach is compromised by the difficulty of resolving the small-scale structures in the nozzle boundary layer. It can be argued that the small-scale turbulence from the nozzle boundary layer does not play a significant role in the downstream development of the jet, and that it is most important to correctly model the bulk properties of the initial shear layer. This approach eliminates the uncertainty in the origin of the jet exit. Centerline velocity profiles for the supersonic and subsonic jets are shown in Fig. 4. For the supersonic case, a comparison is made of two solutions in which the number of azimuthal grid planes was varied. For the subsonic case, the effect of the coefficient in the Smagorinsky subgrid model was studied.

Paliath and Morris [31] performed a simulation which combined both approaches. The nozzle was included in the simulation to obtain the correct bulk properties of the boundary layer/initial shear layer. They also imposed small perturbations in the shear layer to simulate the small-scale turbulence that could not be modeled. Their analyses included both round and rectangular nozzle geometries.

DeBonis's results also demonstrated the ability of LES to produce more detailed turbulent information [29,30]. In this case, DeBonis reported two-point space and space-time correlations for both the supersonic and subsonic jets as shown in Fig. 5. These statistics are important for the construction of acoustic source models for jet aeroacoustic analysis. The correlations of u' and u'^2 are used to compute the shear and self-noise components, respectively. The figures show the correlation of u' in the jet mixing layer near the end of the potential core for several separation distances. For the supersonic case, two-point space correlations were used to estimate a turbulent length scale (Fig. 6) and the space-time correlations were used to estimate a convection velocity (Fig. 7).

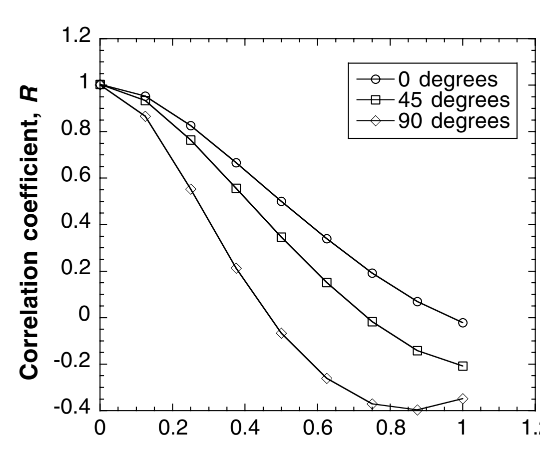


Fig. 6 Two-point space correlation coefficient from a Mach 1.4 jet.

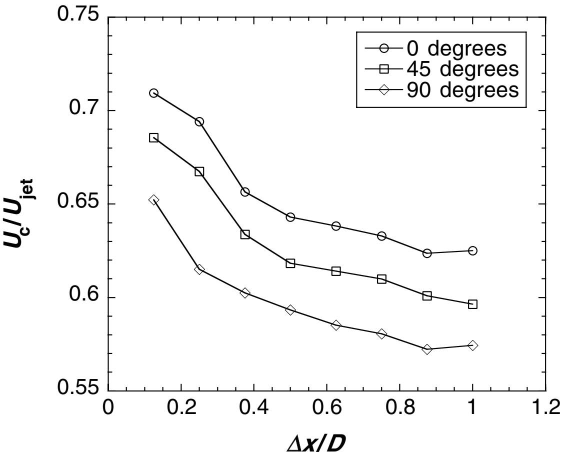
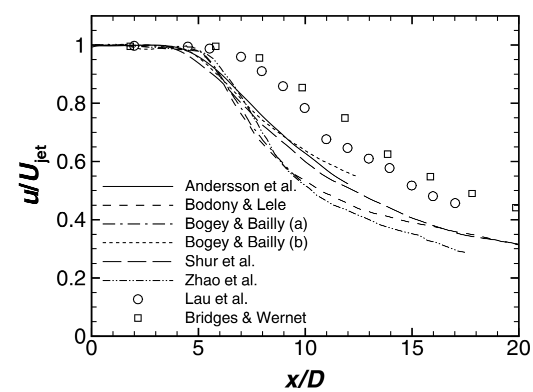
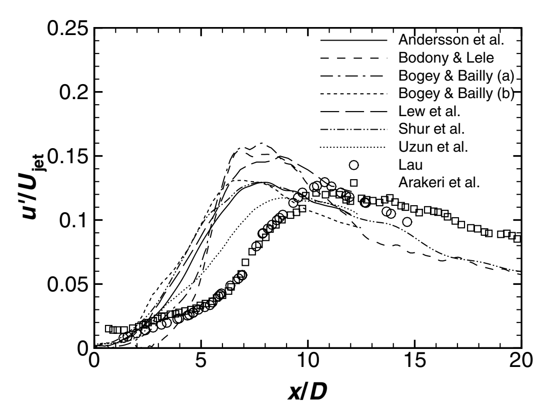


Fig. 7 Convection velocity from a Mach 1.4 jet.

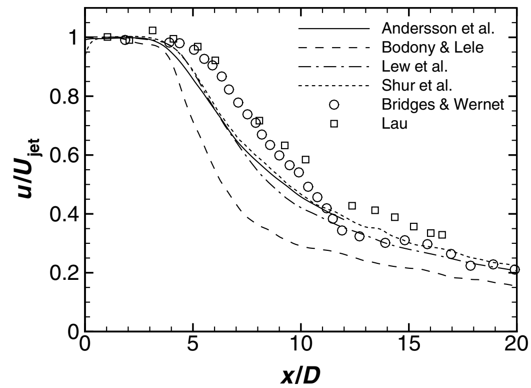


a) Mean velocity

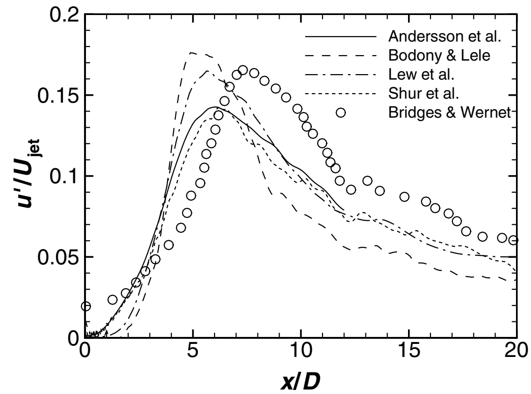


b) Root mean square velocity

Fig. 8 Comparison of LES predictions on the centerline of a cold Mach 0.9 jet (reprinted with permission by Bodony and Lele [32]).



a) Mean velocity



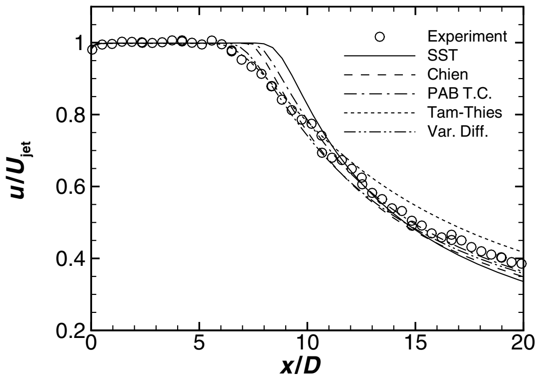
b) Root mean square velocity

Fig. 9 Comparison of LES predictions on the centerline of a hot Mach 0.9 jet (reprinted with permission by Bodony and Lele [32]).

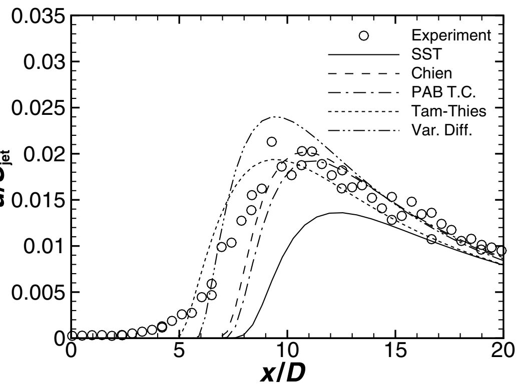
In their review paper, Bodony and Lele [32] presented a comparison of several predictions of axial velocity and axial velocity root mean square on the jet centerline for several different speed jets. A representative sample at Mach 0.9 for both cold and hot jets are shown in Figs. 8 and 9. The predictions were supplied by several leading researchers in jet LES. The authors were Andersson et al. [33], Bodony and Lele [19], Bogey et al. [25,34], Shur et al. [27,28], Zhao et al. [35], Uzun et al. [36], and Lew et al. [37]. These plots are representative of the type of agreement with experimental data that is obtained with the current state-of-the-art LES. In general, LES provides a good qualitative agreement with experimental data. However, there is much room for improvement in the details, including predictions of the end of the potential core, jet spreading rate, and turbulence intensities. The details of the methods vary greatly. Table 1 summarizes the temporal and spatial discretization schemes and subgrid model approach used. It is interesting to note that despite the wide range of approaches used, no one approach stands out as superior. This conclusion illustrates very clearly that LES is still not well understood and much work needs to be done before it becomes a reliable predictive tool. For comparison RANS

Table 1 Computational details of the analyses shown in Figs. 8 and 9

Authors	Time discretization	Spatial discretization	Subgrid model
Andersson et al. [33]	3 stage Runge–Kutta	third-order upwind	Smagorinsky
Bodony and Lele [19]	6 stage Runge–Kutta	sixth-order compact	dynamic
Bogey et al. [25]	4 stage Runge–Kutta	7 point DRP	Smagorinsky
Bogey and Bailly [34]	6 stage Runge–Kutta	13 point DRP	implicit (filtering)
Lew et al. [37]	4 stage Runge–Kutta	sixth-order compact	implicit (filtering)
Shur et al. [27]	second-order implicit	hybrid central/upwind	implicit (numerical scheme)
Uzun et al. [36]	fourth-order Runge–Kutta	sixth-order compact	dynamic
Zhao et al. [35]	fourth-order Runge–Kutta	sixth-order compact	dynamic

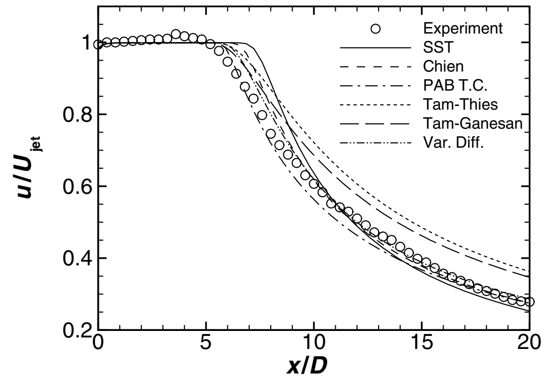


a) Mean velocity

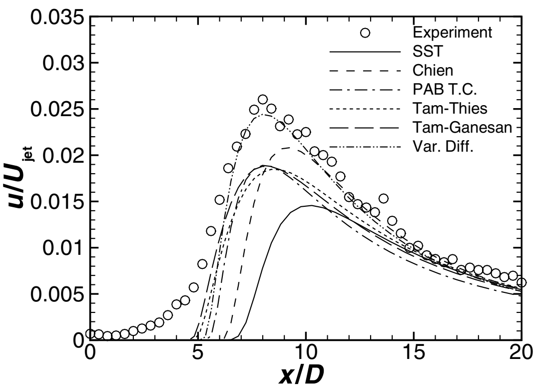


b) Turbulent kinetic energy

Fig. 10 Comparison of RANS predictions for a cold Mach 0.5 jet (reprinted with permission by Georgiadis et al. [10]).



a) Mean velocity



b) Turbulent kinetic energy

Fig. 11 Comparison of RANS predictions for a hot Mach 0.5 jet (reprinted with permission by Georgiadis et al. [10]).

solutions of a Mach 0.5 jet, both hot and cold are shown in Figs. 10 and 11. These solutions were obtained using a standard RANS solver and several different two-equation turbulence models [10]. Despite LES's potential, at this point in time both mean flow and turbulence is better predicted using RANS.

III. Approaches to LES of Jet Flows

There appears to be two general philosophical approaches to the application of LES to jet flows: the rigorous and the practical. Both approaches have yielded reasonable results in their targeted application.

A. Rigorous LES

The approach which will be called rigorous LES, involves careful attention to all aspects of the LES procedure. Each part of the LES solution is explicitly addressed: numerical error, filtering and subgrid modeling. Careful attention is paid to minimizing numerical error. High-order schemes which minimize dispersion and dissipation errors are used. Explicit filtering of the solution is typically performed. The filtering process removes the small unresolved scales from the solution in a mathematically consistent manner and has the added benefit of enhancing numerical stability. The subgrid scales are modeled using any one of a number of subgrid models. These calculations are typically performed for very low-Reynolds number round jets. In addition, these approaches have traditionally been used for simple geometries. A low-Reynolds number flow has a narrower range of turbulent scales and enables better resolution, decreasing the importance of the subgrid model. The benefit of this approach is the ability to evaluate and control the contributions of each solution component. The drawback is the cost and complexity of the system.

B. Practical LES

Practical LES takes a more pragmatic approach, attempting to get a reasonable answer with less regard to every detail of the analysis (this is not a statement on the quality of the work). Instead of separate components for filtering and subgrid modeling, one or both of these are usually combined with the numerical scheme. More dissipative schemes such as those found in most RANS codes are used. These analyses are usually performed for complex geometries and at high Reynolds number. More empiricism may be needed to achieve a good solution. Many simulations which fall into this category use codes that have been adopted from RANS. In these cases, the codes have more flexible grid requirements and complex geometries are easier to model.

IV. Issues

At the present time, LES is less accurate and much more costly than a RANS analysis. To advance LES toward its potential, much more work is needed. A large-eddy simulation code is a combination of many components: numerical scheme, boundary conditions, subgrid model, filters, etc. As the examples of Sec. II show, numerous approaches made up of various combinations of code components have all done a fair job of predicting jet flows. From these results, it is impossible to identify a preferred method, and it is certainly not possible to handpick the best components from several different works and expect them to work well together. To further complicate matters, a fair amount of empiricism is usually involved in obtaining these solutions. Examples of this include adjusting the coefficient of the subgrid model, changing the order of accuracy of the numerical scheme, adjusting the order or coefficient of the filter, selecting the proper grid resolution, and adjusting the incoming jet profile. LES cannot become a predictive tool until this empiricism is removed.

The sources of error in a simulation must be quantified to make improvements to the solution. This can best be done by applying rigorous methods to benchmark problems to compare approaches and identify needs. For example, various numerical schemes or subgrid models compared in a common framework could identify the best methods for more research. Finally, these methods must then be adapted to handle complex geometry. This can either be done by adapting and porting these methods into existing production CFD codes or by enhancing the research codes to handle complex analyses. Additional work specific to complex geometry, such as hybrid RANS/LES models and interfaces, must also be incorporated. The issues that must be addressed are outlined in this section.

A. Numerical Scheme

The numerical scheme used plays a major role in the simulation's accuracy and can have a significant effect on how the other components of the simulation work. A wide variety of numerical schemes have been employed for the LES of jet flows. A large majority of LES has been performed using schemes that have a high order of accuracy.

1. Explicit Finite Difference Schemes

Explicit finite difference methods include both the traditional finite difference stencils and the optimized dispersion relation preserving type schemes. For a traditional finite difference stencil, the coefficients are chosen to maximize the order of accuracy of the scheme. Newer optimized stencils are based on Tam and Webb's DRP scheme [26]. In this method, the order of accuracy does not determine the stencil coefficients. Instead, the coefficients are chosen to minimize the error of the scheme over a limited range of wave numbers. Optimized schemes are a good choice for large-eddy simulation. Because the range of scales that must be resolved is finite, it makes sense to minimize the error over this range. Furthermore, it must be pointed out that a numerical scheme's order of accuracy only indicates how the error will be reduced with grid refinement and does not indicate the magnitude of the error for a given grid size. Tam and Webb's original DRP scheme uses a seven-point stencil. Bogey and Bailly's scheme uses a 13 point stencil [38]. Such a wide stencil makes implementation of the scheme difficult near boundaries and block interfaces.

2. Compact Schemes

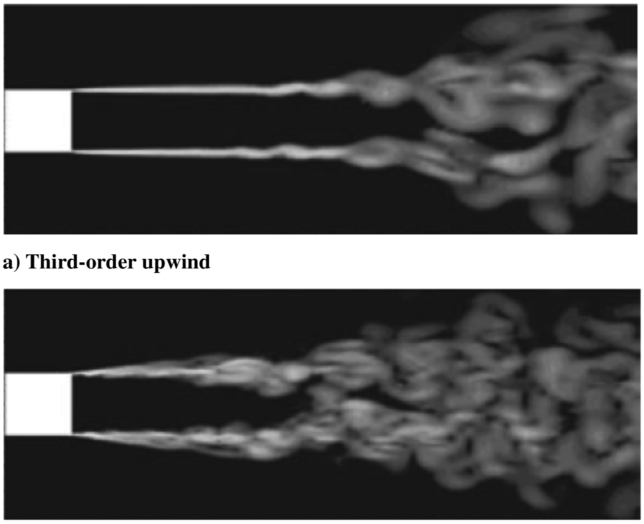
Compact schemes are probably the most popular high-order scheme used in large-eddy simulation. These schemes implicitly compute the derivative [22,39,40]. The most popular compact scheme is a sixth-order version that results in a tridiagonal system that must be solved. This enables more accurate schemes for a given size stencil. In addition, these schemes have excellent resolution in wave number space. Their implicit nature increases the complexity and computational cost of the scheme, but the narrow stencil aids in implementation near boundaries and block interfaces. Some codes using compact schemes for jet analyses have been developed by Lele [22], Visbal and Gaitonde [41], and Hixon [39].

3. Artificial Dissipation/Filtering

The schemes discussed so far are central difference. This is done to eliminate the dissipative error terms and preserve the turbulent structures. The lack of inherent dissipation in the scheme means that the solution will be unstable. Artificial dissipation, frequently in the form of a filter, is added to maintain stability. Compact filters have been developed by Lele [22], Gaitonde and Visbal [40], and Hixon [42]. Other filters by have been developed by Kennedy and Carpenter [43], Vasilyev et al. [44], and Bogey and Bailly [38]. These schemes do not capture shocks well and they have been applied primarily to subsonic jets. Some work has been done to improve shock capturing by combining filters; a switch, typically based pressure gradient, is used to apply the more dissipative shock-capturing filter near the shock and apply the less dissipative filter elsewhere [45,46].

4. Upwinded Schemes

The vast majority of modern CFD codes are finite volume RANS solvers using upwinded schemes such as the popular Roe scheme [47]. Upwinded schemes are dissipative and tend to damp turbulent structures that LES hopes to capture. Such general-purpose solvers may not be immediately appropriate for high-quality LES run in the same manner as RANS. However, by increasing the order of the schemes, and subsequently reducing the amount of dissipation, they have proven successful in some implementations [27,28]. They are particularly suited for the monotonically integrated large-eddy simulation (MILES) approach [48,49].



a) Third-order upwind

b) Fifth-order upwind

Fig. 12 Effect of numerical dissipation on resolution of turbulent scales (reprinted with permission by Shur et al. [27]).

The importance of the spatial discretization scheme in LES cannot be overstated. As illustration, Fig. 12 shows the difference between two numerical schemes with differing amounts of dissipation. The simulations, from Shur et al. [27], are identical except for the fact that the first uses a third-order upwinded scheme and the second uses a fifth-order upwinded scheme. The latter scheme has significantly less dissipation and therefore has better resolution of the turbulent structures.

5. Temporal Discretization

A lot of attention has been focused on the proper spatial discretization for LES. In contrast, relatively little effort has been given to the temporal scheme. Some work has been done examining the error due to the temporal discretization on numerical solutions in one dimension [50]. There, it was clearly shown that the order of the numerical scheme was determined by the lower-order discretization (temporal or spatial). A high-order spatial discretization can be compromised by the error of a lower-order temporal scheme. This has not been extended to multiple dimensions where additional error in the spatial discretization complicate matters. Explicit Runge–Kutta schemes are used for most analyses; typically combined with compact or explicit finite difference schemes. Both the standard four-stage fourth-order scheme [51] and optimized low-dissipation and low-dispersion schemes are used [52–54]. The optimized schemes add additional stages to reduce error. Regardless of the scheme, it is prudent to perform a simple check of the effect of the temporal discretization error by repeating a portion of the calculation using a smaller time step.

B. Grid

Grid requirements will obviously vary based on the numerical scheme used. Issues, such as the number of grid points required, grid skewness, and the allowable rate of grid stretching, are highly dependent on the individual numerical method. Some, but not all, researchers have attempted to quantify these requirements for their particular schemes. Ideally, isotropic grids would be used for these calculations. But computing limitations force the implementation of grid stretching to cluster points in the regions of interest.

Many analysis codes used for jet LES have limited geometric flexibility. Most written for jet analysis have used a cylindrical coordinate system, a natural choice for a round jet. Others have used a Cartesian system for simplicity in the numerical implementation [55,56]. As the technology begins to move beyond studies of simple round jets, it will be necessary to add geometric flexibility by adopting generalized curvilinear coordinates. This will enable a transition to studies of more realistic nozzle systems with complex geometries.

Generalized curvilinear coordinates may not be enough to tackle the most difficult nozzle systems. RANS analyses of complex nozzle systems use flexible multiblock grids with varying topologies [57–60]. LES simulations do use multiple grid blocks to enable parallel computation. But the grid blocks are subdivided from a single grid, which enables simple point matched interfaces through overlapping or ghost cells. Block interfaces that maintain a high order of accuracy must be developed. Nonpoint matched interfaces will be very useful for geometry modeling and to coarsen the grid away from regions of interest.

Unstructured grids offer a solution to the difficulties faced in multiblock structured grids. However, developing high-order schemes for unstructured grids is a difficult task. Some work has begun in this area [61–63]. However, there is a lot of work to be done before this technology can be implemented.

Pope advocates the use of solution adaptive gridding to eliminate the subjective specification of the resolved turbulent length scale [64]. This idea is an excellent way to insure proper resolution, but it will place a great dependence on increased grid flexibility in LES codes.

C. Boundary Conditions

1. Outflow Boundary

There have been two ongoing issues regarding boundary conditions for jet LES. The first is a nonreflecting outflow boundary condition. Waves that reflect from the outflow back into the computational domain can contaminate the solution. It is recognized that a nonreflecting boundary condition is critical to a successful solution. There are many self-contained boundary conditions written to eliminate these reflections using characteristic wave relations [65–68]. These methods have had moderate success but can be difficult to implement in a general way. Many researchers have had success with the more ad hoc approach of creating what is referred to as absorbing layers/sponge regions/exit zones near the boundary [69]. These are areas of gradually increasing grid spacing. The increased grid spacing combined with dissipation of the numerical scheme serves to damp waves as they near the boundary. Additional dissipation or source terms in the governing equations are sometimes added to increase the damping.

2. Specification of the Jet

The second boundary condition issue, the inflow boundary, is perhaps the most critical need for LES of complex nozzle systems. The method used to specify the jet is critical to the downstream development of flow structures. A common approach to specifying the inflow is through a velocity profile. The profile is frequently based on a hyperbolic tangent function and the initial mixing layer thickness is specified. An unsteady component can be added to simulate the initial turbulence levels. This artificial “forcing” of the shear flow can greatly influence the mixing of the jet. Great care must be taken to avoid biasing the solution and affecting the acoustic far field. Glaze and Frankel found that random fluctuations based on a Gaussian distribution dissipated quickly downstream [56]. Bogey and Bailly studied both the effects of forcing different modes and the effect of shear layer thickness, with significant differences in results [55].

The initial mixing layer thickness affects the stability of the flow and also has a great effect on the jet development. Shur et al. [27] argue that this is the primary mechanism in the transition from small-scale to large-scale turbulence in the jet and that the small-scale turbulence from the nozzle boundary layer has only a weak effect. They do not use forcing and have had good success. DeBonis and Scott [29,30] included the nozzle geometry in the grid. These simulations resulted in realistic boundary-layer thicknesses at the nozzle exit, but the grid spacing was not sufficient to capture the small-scale turbulence. These simulations also showed reasonable success without forcing.

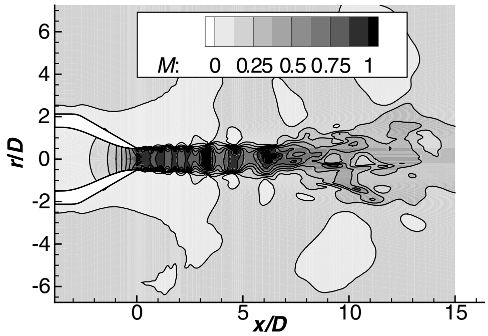
To accomplish the goal of producing predictions of nozzle systems with acoustic suppression devices, a hybrid RANS/LES approach is the most promising option. In this approach, the nozzle geometry is included in the simulation and the flow exiting the nozzle is directly computed, removing the assumptions involved in specifying a velocity profile. Correct modeling of the boundary layer on the internal nozzle surface is critical. LES of the small turbulent structures in the boundary layer is prohibitive due to the very fine grid necessary. A hybrid RANS/LES approach can accurately capture the bulk properties of the boundary layer. Unsteady information for the LES of the jet cannot be gotten directly from the RANS simulation of the boundary layer. There are several approaches to interface the RANS to LES regions. As with an inflow boundary condition, randomly generated turbulence, which is scaled to match the RANS turbulent kinetic energy, is quickly dissipated. Batten et al. [70] have developed a method which generates velocity fluctuations at the interface that satisfy a target set of time and length scales from the given RANS statistics. Others have used the concept of recycling, scaling the results of a previously run LES simulation of a boundary layer to match the RANS simulation and imposing them on the interface [71,72].

D. Subgrid Modeling

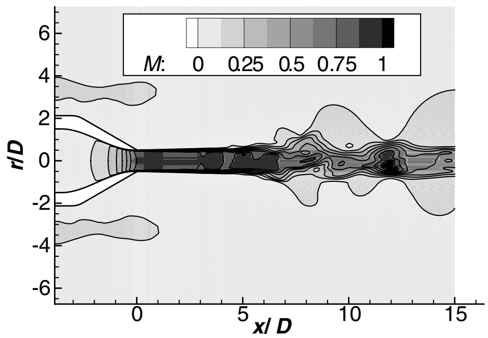
There are numerous approaches to subgrid modeling, many of which have been applied to jet flows with success. Piomelli has an excellent discussion of the types of subgrid scale models in his review paper [73]. This explicit modeling of the subgrid scales has been the traditional approach. Recently, there have been several works in which the subgrid dissipation has been represented implicitly by dissipation inherent in the filter or numerical scheme. Bogey and Bailly forego subgrid modeling and rely on the dissipative effect of an explicit filter to remove energy from the large scales [55]. Shur et al. also use no subgrid modeling, relying on the dissipation present in their hybrid upwinded scheme [27,28]. The success of the MILES approach also indicates that the details of the subgrid model are unimportant. In some circumstances, subgrid modeling may be detrimental. Bogey and Bailly found that the added viscosity from a subgrid model effectively decreases the Reynolds number of the flow, altering the mean axial velocity, turbulence intensity, and sound spectrum [74].

Explicit subgrid models are formulated with a physics-based approach. The dissipation they produce is based on the resolved motion in the simulation and the filter width (typically, the grid size). Implicit subgrid modeling relies on the dissipation from the numerical scheme and is not related to the resolved motion in any physical way. Explicit models should provide the proper amount of dissipation within a range of grid resolution where the flow is properly resolved. There is no basis to assume an implicit subgrid modeling approach will provide the proper dissipation at different levels of resolution. In other words, the results from a simulation using explicit subgrid modeling should be expected to improve with grid resolution. The results from a solution using an implicit approach should not have the same expectation.

The effect of the subgrid model can be seen in the solution of a high Reynolds number Mach 0.9 jet (Fig. 13) [30]. The method for both solutions was identical save for the coefficient in the Smagorinsky subgrid model [75]. The first solution uses the generally accepted “standard” value of 0.012 (Fig. 13a). This solution shows a very energetic flowfield with numerous small-scale eddies. The mean centerline velocity profile for this solution showed too much mixing, indicating that not enough energy was being dissipated from the large scales. The second solution uses an increased Smagorinsky coefficient of 0.10 (Fig. 13b). This solution shows only a few large-scale structures, the Reynolds number effect quantified by Bogey and



a)



b)

Fig. 13 Mach contours showing the effect of the subgrid model on resolution of turbulent scales: a) Smagorinsky coefficient, $C = 0.012$, and b) Smagorisnsky coefficient, $C = 0.10$.

Bailly [74]. But the centerline velocity profile is a close match with the experiment (Fig. 4b). It is critical that the correct amount of energy is dissipated from the large scales.

E. Filtering

The process of filtering the Navier–Stokes equations is fundamental to the development of LES. The practical need for and implementation of explicit filtering in large-eddy simulation is not clear. Many researchers use the implicit filtering approach. One can argue that the discretization process acts as a filter and no further filtering is necessary [14]. Others explicitly apply a filter to the solution at each time step. Explicitly filtering the solution is certainly the more rigorous approach. But in practical terms, the real benefit of filtering is to provide artificial dissipation for stability, because it removes the small unresolved waves. Successful simulations have been performed with both approaches.

Filtering is a conceptually simple process, however, the process becomes more difficult for nonuniform stretched grids. A key to the development of the LES equations is the fact that the filter commutes with the derivative. This is true for uniform grids. Ghosal and Moin defined a new filtering operation which is second-order accurate on nonuniform grids [76]. This error is relatively large compared with the error of high-order schemes. Vasilyev et al. developed a class of filters with arbitrary accuracy to enable higher-order solutions [44]. It should be pointed out that these same filters were previously derived by Kennedy and Carpenter without the issue of commutation error in mind [43].

F. Reynolds Number

The majority of jet LES has been done at low Reynolds number. This significantly reduces the range of turbulent scales and allows for more complete resolution in the analysis. For a given grid size, a low Reynolds number jet will have a greater majority of the turbulent energy directly computed. This means that for a high Reynolds number jet, the contribution of the subgrid model becomes more important, exacerbating any modeling errors. In some cases, at very high Reynolds number, it is not practical to resolve down to the inertial subrange. In these cases, the assumptions upon which most subgrid models are developed may not apply and the errors in the subgrid model are increased. Although most flows of interest are at high Reynolds number, exploring low Reynolds number jets aids in developing the numerical scheme by providing a resolvable flowfield.

G. Evaluation of Solutions

LES generates large amounts of information that can be evaluated, not only to gain information on the flow, but also to evaluate the accuracy of the solution. By their nature, the solutions provide great spatial resolution. However, due to the large computational costs involved, the temporal evolution of the flow is usually limited. The small time steps limit the total simulation time to fractions of a second. As computing power is increased, the natural inclination is to increase spatial resolution or increase the complexity of the simulation. It is very important that the simulation has been run "long enough." For all simulations there is transient period at startup where the turbulence is developing. During this period, especially near the end of this period, the solution may look realistic. However, the statistics obtained will vary in time. It is important to insure that the statistics are invariant with time. Rules of thumb such as two or three "flow-through" times have been cited. But these are ad hoc and are not a substitute for analysis to insure accurate statistics.

As previously mentioned, analysis of the temporal error should be carried out by repeating a portion of the calculation at a reduced time step.

For a RANS analysis, it is common practice to perform a grid resolution study to demonstrate the solution's grid independence. It is not clear that this is practical or even possible with LES. At the current time, most LES calculations push the limits of the available computing power. Grid refinement is not an option in these cases. Grid coarsening is possible but the results would most likely be unsatisfactory. When grid refinement is possible, it is unclear what will result. As the resolution increases in an LES solution, more and more turbulent structures will be revealed until the Kolmogorov scales are reached and the solution becomes a direct numerical simulation. When the grid is refined, the structures within will change and the solution will look "different." A time history of velocity at a point should show additional unsteady motion. This small-scale motion serves to dissipate the larger scales and was previously represented by eddy viscosity or numerical dissipation. But this motion will now directly contribute to the turbulence statistics of the flow. Further refinement will add additional small-scale motion. Its influence on the statistics and large-scale structures will decrease as the energy of these structures is small compared with the large scales. The limit where this influence becomes negligible is the ideal level of grid resolution. The question remains whether or not this level of resolution is practical for high Reynolds number jets and complex geometries. Also, are solutions at a lower resolution valid if they have an accurate mean but have compromised turbulent statistics, due to the effect of subgrid dissipation?

The high spatial resolution and short temporal resolution is typically opposite of experimental data sets. The limited time history can make it difficult to obtain accurate spectra. It is impractical to replicate the amount of data obtained in experiment, typically thousands of bins of 256 data points. Great care must be taken when comparing statistics between CFD and experiment.

H. Experimental Data

As mentioned previously, experiment data typically has limited spatial resolution. Many often-used data sets have only centerline and select radial profiles. Some new experimental techniques have improved greatly on this. Particle image velocimetry [77] and planar Doppler velocimetry [78] are two examples of new techniques with great spatial resolution. Rayleigh scattering, a density-based pointwise technique, is completely nonintrusive (no probes or particle seeding). This method was used by Panda and Seasholtz to experimentally evaluate the implications of Favre averaging [79] and to characterize the initial mixing layer of the jet [80].

To improve LES of complex nozzle systems, additional information is needed from experiments. Experimental studies typically do not report the nozzle geometry or characterize the flowfield right at the nozzle exit. Nozzle geometry, internal nozzle boundary-layer data, and turbulence data in the shear layer right at the nozzle exit are important for developing accurate hybrid RANS/LES interfaces.

V. Summary and Conclusions

There is a need in the aerospace community for accurate aerodynamic and acoustic prediction tools for noise-suppressing nozzle systems. Large-eddy simulation has the potential for improved accuracy over current RANS methods. In addition, LES provides additional important unsteady information for noise prediction. To date, LES has been used to simulate turbulent jets with moderate success, but RANS methods perform as well or better at a much lower cost. Many varied approaches have been used and, despite large differences in numerics and modeling, they have produced similar results.

These simulations have focused mainly on benchmark experiments of round jets for purposes of method and code development and to gain physical insight. Noise-suppressing nozzle systems contain complex geometry to modify the shear layer. Therefore, the nozzle geometry itself must be included in the calculation. Additional effort is required to adapt current LES methods to handle this complex geometry.

Current LES analyses fall into one of two general categories: the rigorous and the practical. The rigorous method pays careful attention to all details of the solution procedure and usually employs high-order numerical schemes, explicit filtering, and subgrid models. But these methods are typically limited to simple geometries at low Reynolds number. The practical method applies lower-order accurate codes, usually developed for RANS applications, and typically forgoes subgrid modeling. The practical approach can be more readily applied to complex geometries. Both approaches have much to offer the other and their capabilities must be merged to improve the handling of complex geometries and improve predictions.

A very important issue in current jet LES is the specification of the jet inflow. Many researchers use a prescribed velocity profile with imposed unsteady forcing, whereas others have specified the profile without forcing or have modeled the nozzle geometry. Correctly specifying the initial shear layer and understanding its effect on the calculation is key to a successful solution. A promising approach for complex geometries is a hybrid RANS/LES simulation that includes the geometry. But further work must be done to develop the proper interfaces between the RANS and LES regions.

Finally, to create a true predictive capability, the amount of empiricism currently used in LES must be significantly reduced. There are many aspects of the simulation that are currently tailored by the researcher to improve the prediction: grid resolution, inflow boundary profile and forcing, subgrid model coefficient, filter order and coefficient, numerical scheme, etc.

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