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

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This paper reviews 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 turbulent jets. It has shown the potential to significantly impact the design and analysis of future noise suppressing nozzle systems through 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.

I. Introduction

Regulations on aircraft noise have become increasingly more 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 have resulted from increasing the engine's bypass ratio. However, additional noise reduction technology is needed for low bypass engines and to meet future regulations for the high bypass ratio engines.

One such technology that is currently flying is the chevron nozzle (figure 1). The serrated edge of the chevron nozzle increases the mixing of the exhaust streams and modifies the turbulent characteristics in the jet, reducing noise [1]. This has been installed on several commercial aircraft engines already.

There are several other noise reduction concepts currently being studied. Most concepts, such as plasma actuators [2], fluidic injection [3], tabs [4,5] and lobed mixers (figure 2) [6] aim to increase mixing and modify the jet turbulence similar to the chevron nozzle. Papamoschou has developed a series of concepts that are referred to as offset fan flow technology nozzles [7,8]. The main idea is to divert the fan flow below the engine and change the noise directivity and intensity. Implementation of the offset fan flow idea would be through devices such as vanes or wedges (figure 3).

Design and analysis of these concepts can be greatly enhanced through the use of computational fluid dynamics (CFD). CFD has been successfully used for years 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 [9]. Much work has been done in the area of advanced RANS models specifically for jets [10–12]. The results have been mixed, and generalizing these models to 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 [13]. 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.

Acoustic predictions based on RANS solutions are done using the acoustic analogy [14,15]. This acoustic modeling relies heavily on modeling the acoustic source based on the RANS solutions [16]. The results

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from this method are reasonable for cold round jets. Results are poor for heated jets and non-axisymmetric geometries.

Large-Eddy Simulation (LES) is the next logical step towards 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. Since 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 farfield to compute the noise directly. The propagation of the sound to the farfield is a linear process and can instead be predicted by several simpler methods. Shih et al. gives a good discussion and evaluation of these methods [17].

LES has the potential to vastly improve the prediction of jet flows and impact designs of noise suppressing nozzles. However, there is much work that needs to be done before LES can be used reliably in this manner. The intent of this paper is to provide a goal for developers of LES methods, give an overview of the current status of LES and identify issues that must be addressed to reach this goal.

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 [18–20]. They employ a sixth-order compact differencing in space [21] and an explicit low-dispersion Runge-Kutta (LDRK) differencing in time. They use a dynamic sub-grid model. 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 have simulated several subsonic jets [22–24]. Their method uses an thirteen 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 [25]. They also use a LDRK scheme for time advancement. Their earlier work employed explicit modeling of the sub-grid scales. However, recent work has relied on filtering without sub-grid models. They have also examined the influence of eddy viscosity on the effective Reynolds number of the flow.

Shur, Spalart and Strelets have taken a different approach [26,27]. They have adapted a RANS code which uses a finite volume approach that employs 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 sub-grid 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 utilized 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, Spalart and Strelets, 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 imposed velocity perturbations.

DeBonis has performed large-eddy simulations on a supersonic jet, Mach 1.4 and a subsonic jet, Mach 0.9, where the nozzle geometry was modeled [28,29]. 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.

Paliath and Morris [30] 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.

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 sub-grid 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 sub-grid scales are modeled using any one of a number of sub-grid 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 sub-grid 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 sub-grid 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

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 (DRP) 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 [25]. 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. Since 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 thirteen point stencil [31]. Such a wide stencil makes implementation of the scheme difficult near boundaries and block interfaces.

2. *Compact Schemes*

Compact schemes implicitly compute the derivative [21,32,33]. An example of a sixth-order compact scheme which results in a tridiagonal system is shown [34].

$$\frac{1}{15}\left(14\delta_{2x}f_j + \delta_{4x}f_j\right) = \frac{1}{5}\left[\left(\frac{df}{dx}\right)_{j+1} + 3\left(\frac{df}{dx}\right)_{j} + \left(\frac{df}{dx}\right)_{j-1}\right] \tag{1}$$

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 utilizing compact schemes for jet analyses have been developed by Lele [21], Gaitonde and Visbal [35], and Hixon [32].

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 [21], Gaitonde and Visbal [33] and Hixon [36]. Other filters by have been developed by Kennedy and Carpenter [37], Vasilyev [38] and Bogey and Bailly [31]. 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 [39, 40].

4. *Upwinded Schemes*

The vast majority of modern CFD codes are finite volume RANS solvers utilizing upwinded schemes such as the popular Roe scheme [41]. 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 [26, 27]. They are particularly suited for the Monotonically Integrated Large-Eddy Simulation (MILES) approach [42, 43].

The importance of the spatial discretization scheme in LES cannot be overstated. As illustration, figure 4 shows the difference between two numerical schemes with differing amounts of dissipation. The simulations, from Shur, Spalart and Strelets [26], 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 [44]. 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 comprised 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 [45] and optimized low-dissipation and low-dispersion schemes are used [46–48]. 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 analyses 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 [49, 50]. 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 multi-block grids with varying topologies [51–54]. LES simulations do utilize 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 high-order of accuracy must be developed. Non-point 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 [55–57]. 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 [58]. 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 on-going issues regarding boundary conditions for jet LES. The first is a non-reflecting outflow boundary condition. Waves that reflect from the outflow back into the computational domain can contaminate the solution. There are many self-contained boundary conditions written to eliminate these reflections using characteristic wave relations [59–62]. 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 [63]. 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 farfield. Glaze and Frankel found that random fluctuations based on a Gaussian distribution dissipated quickly downstream [50]. Bogey and Bailly studied both the effects of forcing different modes and the effect of shear layer thickness, with significant differences in results [49].

The initial mixing layer thickness affects the stability of the flow and also has a great effect on the jet development. Shur, Spalart and Strelets [26] 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 [28, 29] 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 can not 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, Goldberg and Chakravathy [64] 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 [65, 66].

D. Sub-grid Modeling

There are numerous approaches to sub-grid modeling, many of which have been applied to jet flows with success. Piomelli has an excellent discussion of the types of sub-grid scale models in his review paper [67]. This explicit modeling of the sub-grid scales has been the traditional approach. Recently, there have been several works where the sub-grid dissipation has been represented implicitly by dissipation inherent in the filter or numerical scheme. Bogey and Bailly forego sub-grid modeling and rely on the dissipative effect of an explicit filter to remove energy from the large scales [49]. Shur, Spalart and Strelets also use no sub-grid modeling, relying on the dissipation present in their hybrid upwinded scheme [26, 27]. The success of the MILES approach also indicates that the details of the sub-grid model are unimportant. In some circumstances sub-grid modeling may be detrimental. Bogey and Bailly have found that the added viscosity from a sub-grid model effectively decreases the Reynolds number of the flow; altering the mean axial velocity, turbulence intensity and sound spectrum [68].

Explicit sub-grid 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 sub-grid 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 sub-grid modeling approach will provide the proper dissipation at different levels of resolution. In other words, the results from a simulation using explicit sub-grid 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 sub-grid model can be seen in the solution of a high Reynolds number Mach 0.9 jet (figure 5) [29]. The method for both solutions was identical save for the coefficient in the Smagorinsky sub-grid model [69]. The first solution uses the generally accepted "standard" value of 0.012 (figure 5(a)). 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 (figure 5(b)). This solution shows only a few large-scale structures, the Reynolds number effect quantified by Bogey and Bailly. But, the centerline velocity profile is a close match with the experiment (figure 5(c)). 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 [13]. Other's 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, since 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 non uniform 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 non-uniform grids [70]. This error is relatively large compared to the error of high-order schemes. Vasilyev, Lund and Moin developed a class of filters with arbitrary accuracy to enable higher-order solutions [38]. It should be pointed out that these same filters were previously derived by Kennedy and Carpenter without the issue of commutation error in mind [37].

F. Matching Solution Components

A large-eddy simulation code is a combination of many components; numerical scheme, boundary conditions, sub-grid model, filters, etc. An accurate solution can only be had if there is a proper balance among these components. It is not possible to simply hand pick the best components from several different works and expect them to work well together. A good understanding of all the underlying issues is key. In order to strike this delicate balance, a fair amount of empiricism is usually involved. Examples of this include; adjusting the coefficient of the sub-grid 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. This is not a criticism of these actions but merely an illustration of the current situation. LES cannot become a predictive tool until this empiricism is removed.

G. 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 sub-grid 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 sub-range. In these cases, the assumptions upon which most sub-grid models are developed may not apply and the errors in the sub-grid model are increased. While 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.

H. 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 start-up 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 2 or 3 “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 (DNS). 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 to 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 pratical 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 sub-grid 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.

I. 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 (PIV) [71] and Planar Doppler Velocimetry (PDV) [72] are two examples of new techniques with great spatial resolution. Rayleigh scattering, a density-based point-wise technique, is completely non-intrusive (no probes or particle seeding). This method was used by Panda to experimentally evaluate the implications of Favre averaging [73] and to characterize the initial mixing layer of the jet [74].

In order 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 successfully used to simulate turbulent jets. Many varied approaches have been used and despite large differences in numerics and modeling they have produced good 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 an usually employs high-order numerical schemes, explicit filtering and sub-grid 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 sub-grid 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. While, others have specified the profile without forcing or 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, in order 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, sub-grid model coefficient, filter order and coefficient, numerical scheme, etc.

References

[1] Janardan, B., Hoff, G., Barter, J., Martens, S., Gliebe, P., Mengle, V., and Dalton, W., "AST Critical Propulsion and Noise Reduction Technologies for Future Commercial Subsonic Engines Separate-Flow Exhaust System Noise Reduction Concept Evaluation," NASA CR 2000-210039, 2000.

[2] Samimy, M., Adamovich, I., Webb, B., Kastner, J., Hileman, J., Keshav, S., and Palm, P., "Development and Character-

ization of Plasma Actuators for High Speed and Reynolds Number Jet Control," *Experiments in Fluids*, Vol. 37, No. 4, 2004, pp. 577–588.

[3] Behrouzi, P. and McGuirk, J., "Jet Mixing Enhancement Using Fluid Tabs," AIAA Paper 2004-2401, 2004.

[4] Tam, C. and Zaman, K., "Subsonic Jet Noise from Nonaxisymmetric and Tabbed Nozzles," *AIAA Journal*, Vol. 38, No. 4, 2000, pp. 592–599.

[5] Hileman, J. and Samimy, M., "Effects of Vortex Generating Tabs on Noise Sources in an Ideally expanded Mach 1.3 Jet," *International Journal of Aeroacoustics*, Vol. 2, No. 1, 2003, pp. 35–63.

[6] Waitz, I., Qiu, Y., Manning, T., Fung, A., Elliot, J., Kerwin, J., Krasnodebski, J., O'Sullivan, M., Tew, D., Greitzer, E., Marble, F., Tan, C., and Tillman, T., "Enhanced Mixing with Streamwise Vorticity," *Progress in the Aerospace Sciences*, Vol. 33, 1997, pp. 323–351.

[7] Papamouschou, D., "A New Method for Jet Noise Reductiion in Turbofan Engines," AIAA Paper 2003-1059, 2003.

[8] Papamouschou, D., "Parametric Study of Fan Flow Deflectors for Jet Noise Suppression," AIAA Paper 2005-2890, 2005.

[9] Georgiadis, N., Yoder, D., and Engblom, W., "Evaluation of Modified Two-Equation Turbulence Models for Jet Flow Prediction," AIAA Paper 2006-0490, 2006.

[10] Yoder, D., *Algebraic Reynolds Stress Modeling of Planar Mixing Layer Flowst*, Ph.D. thesis, University of Cincinnati, 2005.

[11] Kenzakowski, D., Papp, J., and Dash, S., "Modeling Turbulence Anisotropy for Jet Noise Prediction," AIAA Paper 2002-0076, 2002.

[12] Kenzakowski, D., Shipman, J., and Dash, S., "Turbulence Model Study of Laboratory Jets with Mixing Enhancements for Noise Reduction," AIAA Paper 2000-0219, 2000.

[13] Wilcox, D. C., *Turbulence Modeling for CFD*, DCW Industries, 2nd ed., 1998.

[14] Lighthill, M. J., "On Sound Generated Aerodynamically, I. General Theory," *Proceedings of the Royal Society of London A*, Vol. 211, 1952, pp. 564–587.

[15] Lighthill, M. J., "On Sound Generated Aerodynamically, II. Turbulence as a Source of Sound," *Proceedings of the Royal Society of London A*, Vol. 222, 1954, pp. 1–32.

[16] Khavaran, A., Bridges, J., and Georgiadis, N., "Prediction of Turbulence-Generated Noise in Unheated Jets, Part 1: JeNo Technical Manual," NASA TM 2005-213827, 2005.

[17] Shih, S., Hixon, D., Mankbadi, R., Pilon, A., and Lyrintzis, A., "Evaluation of Far-Field Jet Noise Prediction Methods," AIAA Paper 97-0282, 1997.

[18] Bodony, D. and Lele, S., "On Using Large-Eddy Simulation for the Prediction of Noise from Cold and Heated Turbulent Jets," *Physics of Fluids*, Vol. 17, No. 085103, 2005, pp. 1–20.

[19] Constantinescu, G. S. and Lele, S. K., "Large Eddy Simulation of a Near Sonic Turbulent Jet and Its Radiated Noise," AIAA Paper 2001-0376, 2001.

[20] Boersma, B. J. and Lele, S. K., "Large Eddy Simulation of a Mach 0.9 Turbulent Jet," AIAA Paper 99-1874, 1999.

[21] Lele, S. K., "Compact Finite Difference Schemes with Spectral-Like Resolution," *Journal of Computational Physics*, Vol. 103, 1992, pp. 16–42.

[22] Bogey, C. and Bailly, C., "Computation of a High Reynolds Number Jet and its Radiated Noise Using Large Eddy Simulation Based on Explicit Filtering," *Computers in Fluids*, 2006, to appear.

[23] Bailly, C. and Bogey, C., "Contributions of Computational Aeroacoustics to Jet Noise Research and Prediction," *International Journal of Computational Fluid Dynamics*, Vol. 18, No. 6, 2004, pp. 481–491.

[24] Bogey, C., Bailly, C., and Juve, D., "Noise Investigation of a High Subsonic Moderate Reynolds Number Jet Using a Compressible LES," *Theoretical and Computational Fluid Dynamics*, Vol. 16, 2003, pp. 273–297.

[25] Tam, C. K. W. and Webb, J. C., "Dispersion Relation-Preserving Finite Difference Schemes for Computational Aeroacoustics," *Journal of Computational Physics*, Vol. 107, 1993, pp. 262–281.

[26] Shur, M., Spalart, P., and Strelets, M., "Noise Prediction for Increasingly Complex Jets. Part I: Methods and Tests," *International Journal of Aeroacoustics*, Vol. 4, No. 3 & 4, 2005, pp. 213–246.

[27] Shur, M., Spalart, P., and Strelets, M., "Noise Prediction for Increasingly Complex Jets. Part II:Applications," *International Journal of Aeroacoustics*, Vol. 4, No. 3 & 4, 2005, pp. 247–266.

[28] DeBonis, J. R. and Scott, J. N., "A Large-Eddy Simulation of a Turbulent Compressible Round Jet," *AIAA Journal*, Vol. 40, No. 5, 2002, pp. 1346–1354.

[29] DeBonis, J. R., "A Large-Eddy Simulation of a High Reynolds Number Mach 0.9 Jet," AIAA Paper 2004-3025, 2004.

[30] Paliath, U. and Morris, P., "Prediction of Noise From Jets With Different Nozzle Geometries," AIAA Paper 2004-3026, 2004.

[31] Bogey, C. and Bailly, C., "A Family of Low Dispersive and Low Dissipative Explicit Schemes for Flow and Noise Computations," *Journal of Computational Physics*, Vol. 194, 2004, pp. 194–214.

[32] Hixon, R., "A New Class of Compact Schemes," AIAA Paper 98-0367, 1998.

[33] Gaitonde, D. V. and Visbal, M. R., "Further Development of a Navier-Stokes Solution Procedure Based on Higher-Order Formulas," AIAA Paper 99-0557, 1999.

[34] Durran, D., *Numerical Methods for Wave Equations in Geophysical Fluid Dynamics*, Springer-Verlag, 1999.

[35] Visbal, M. R. and Gaitonde, D. V., "High-Order Accurate Methods for Unsteady Vortical Flows on Curvilinear Meshes," AIAA Paper 98-0131, 1998.

[36] Hixon, R., "Prefactored Compact Filters for Computational Aeroacoustics," AIAA Paper 99-0358, 1999.

[37] Kennedy, C. A. and Carpenter, M. H., "Comparison of Several Numerical Methods for Simulation of Compressible Shear Layers," NASA TP 3484, 1997.

[38] Vasilyev, O. V., Lund, T. S., and Moin, P., "A General Class of Commutative Filters for LES in Complex Geometries," *Journal of Computational Physics*, Vol. 146, 1998, pp. 82–104.

[39] Al-Qadi, I. and Scott, J., “Simulations of Unsteady Behavior in Under-Expanded Supersonic Rectangular Jets,” AIAA Paper 2001-2119, 2001.

[40] Visbal, M. and Gaitonde, D., “Shock Capturing Using Compact-Differencing Based Methods,” AIAA Paper 2005-1265, 2005.

[41] Roe, P., “Characteristic-Based Schemes for the Euler Equations,” *Annual Review of Fluid Mechanics*, Vol. 18, 1986, pp. 337–365.

[42] Fureby, C. and Grinstein, F., “Monotonically Integrated Large Eddy Simulation of Free Shear Flows,” *AIAA Journal*, Vol. 37, No. 5, 1999, pp. 544–556.

[43] Grinstein, F. and Fureby, C., “Recent Progress on MILES for High Reynolds Number Flows,” *Journal of Fluids Engineering*, Vol. 124, 2002, pp. 848–861.

[44] DeBonis, J. R. and Scott, J. N., “Truncation Error Characteristics of Numerical Schemes for Computational Aeroacoustics,” AIAA Paper 2001-1098, 2001.

[45] Jameson, A., Schmidt, W., and Turkel, E., “Numerical Solutions of the Euler Equations by Finite Volume Methods Using Runge-Kutta Time-Stepping Schemes,” AIAA Paper 81-1259, 1981.

[46] Stanescu, D. and Habashi, W. G., “2N-Storage Low Dissipation and Dispersion Runge-Kutta Schemes for Computational Acoustics,” *Journal of Computational Physics*, Vol. 143, No. 12, 1998, pp. 674–681.

[47] Hu, F. Q., Hussaini, M. Y., and Manthey, J. L., “Low-Dissipation and Low-Dispersion Runge-Kutta Schemes for Computational Acoustics,” *Journal of Computational Physics*, Vol. 124, 1996, pp. 177–191.

[48] Carpenter, M. H. and Kennedy, C. A., “Fourth-Order 2N-Storage Runge-Kutta Schemes,” NASA TM 109112, 1994.

[49] Bogey, C. and Bailly, C., “LES of a high Reynolds, high subsonic jet: effects of the inflow conditions on flow and noise,” AIAA Paper 2003-3170, 2003.

[50] Glaze, D. and Frankel, S., “Stochastic Inlet Conditions for Large-Eddy Simulation of a Fully Turbulent Jet,” *AIAA Journal*, Vol. 41, No. 6, 2003, pp. 1064–1073.

[51] Yoder, D., Georgiadis, N., and Wolter, J., “Quadrant CFD Analysis of a Mixer-Ejector Nozzle for HSCT Applications,” NASA TM 2005-213602, 2005.

[52] Engblom, W., Khavaran, A., and Bridges, J., “Numerical Prediction of Chevron Nozzle Noise Reduction Using Wind-MGBK Methodology,” AIAA Paper 2004-2979, 2004.

[53] Thomas, R. and Kinzie, K., “Jet-Pylon Interaction of High Bypass Ratio Separate Flow Nozzle Configurations,” AIAA Paper 2004-2827, 2004.

[54] Massey, S., Thomas, R., Abdol-Hamid, K., and Elmiligui, A., “Computational and Experimental Flow Field Analyses of Separate Flow Chevron Nozzles and Pylon Interaction,” AIAA Paper 2003-3212, 2003.

[55] Mahesh, K., Constantinescu, G., and Moin, P., “A Numerical Method for Large-Eddy Simulation in Complex Geometries,” *Journal of Computational Physics*, Vol. 197, 2004, pp. 215–240.

[56] Liu, Y. and Vinokur, M., “Multi-Dimensional Spectral Difference Method for Unstructured Grids,” AIAA Paper 2005-0320, 2005.

[57] Hesthaven, J. and Warburton, T., “High-Order Unstructured Grid Methods for Time-Domain Electromagnetics,” AIAA Paper 2002-1092, 2002.

[58] Pope, S., “Ten questions concerning the large-eddy simulation of turbulent flows,” *New Journal of Physics*, Vol. 6, No. 35, 2004.

[59] Rowley, C. and Colonius, T., “Discretely Nonreflecting Boundary Conditions for Linear Hyperbolic Systems,” *Journal of Computational Physics*, Vol. 157, 2000, pp. 500–538.

[60] Colonius, T., Lele, S. K., and Moin, P., “Boundary Conditions for Direct Computation of Aerodynamic Sound Generation,” *AIAA Journal*, Vol. 31, No. 9, 1993, pp. 1574–1582.

[61] Poinsot, T. and Lele, S., “Boundary Conditions for Direct Simulation of Compressible Viscous Flows,” *Journal of Computational Physics*, Vol. 101, 1992, pp. 104–129.

[62] Giles, M. B., “Nonreflecting Boundary Conditions for Euler Equation Calculations,” *AIAA Journal*, Vol. 28, No. 12, 1990, pp. 2050–2058.

[63] Freund, J. B., “Proposed Inflow/Outflow Boundary Condition for Direct Computation of Aerodynamic Sound,” *AIAA Journal*, Vol. 35, No. 4, 1997, pp. 740–742.

[64] Batten, P., Goldberg, U., and Chakravarthy, S., “Interfacing Statistical Turbulence Closures with Large-Eddy Simulation,” *AIAA Journal*, Vol. 42, No. 3, 2004, pp. 485–492.

[65] Arunajatesan, S., Kannepalli, C., and Dash, S., “Progress Towards Hybrid RANS-LES Modeling for High-Speed Jet Flows,” AIAA Paper 2002-0428, 2002.

[66] Urbin, G. and Knight, D., “Compressible Large Eddy Simulation using Unstructured Grid: Supersonic Turbulent Boundary Layer and Compression Corner,” AIAA Paper 99-0427, 1999.

[67] Piomelli, U., “Large-Eddy Simulation: Achievements and Challenges,” *Progress in Aerospace Sciences*, Vol. 35, 1999, pp. 335–362.

[68] Bogey, C. and Bailly, C., “Decrease of the Effective Reynolds Number with Eddy-Viscosity Subgrid-Scale Modeling,” *AIAA Journal*, Vol. 43, No. 2, 2005, pp. 437–439.

[69] Smagorinsky, J., “General Circulation Experiments with the Primitive Equations, Part I: The Basic Experiment,” *Monthly Weather Review*, Vol. 91, 1963, pp. 99–152.

[70] Ghosal, S. and Moin, P., “The Basic Equations for the Large-Eddy Simulation of Turbulent Flows in Complex Geometry,” *Journal of Computational Physics*, Vol. 118, No. 1, 1995, pp. 24–37.

[71] Bridges, J. and Wernet, M., “Measurements of the Aeroacoustic Sound Source in Hot Jets,” AIAA Paper 2003-3130, 2003.

[72] Thurow, B., Blohm, M., Lempert, W., and Samimy, M., "High Repetition Rate Planar Velocity Measurements in a Mach 2.0 Compressible Axisymmetric Jet," AIAA Paper 2005-0515, 2005.

[73] Panda, J. and Seasholtz, R., "Experimental Investigation of the Differences Between Reynolds' Averaged and Favre Averaged Velocity in Supersonic Jets," AIAA Paper 2005-0514, 2005.

[74] Panda, J. and Zaman, K. B. M. Q., "Measurement of Initial Conditions at Nozzle Exit of High Speed Jets," AIAA Paper 2001-2143, 2001.

Figure 1. Chevron nozzle with pylon, installed in the NASA Langley Low Speed Aeroacoustic Wind Tunnel (from Thomas and Kinzie [53])

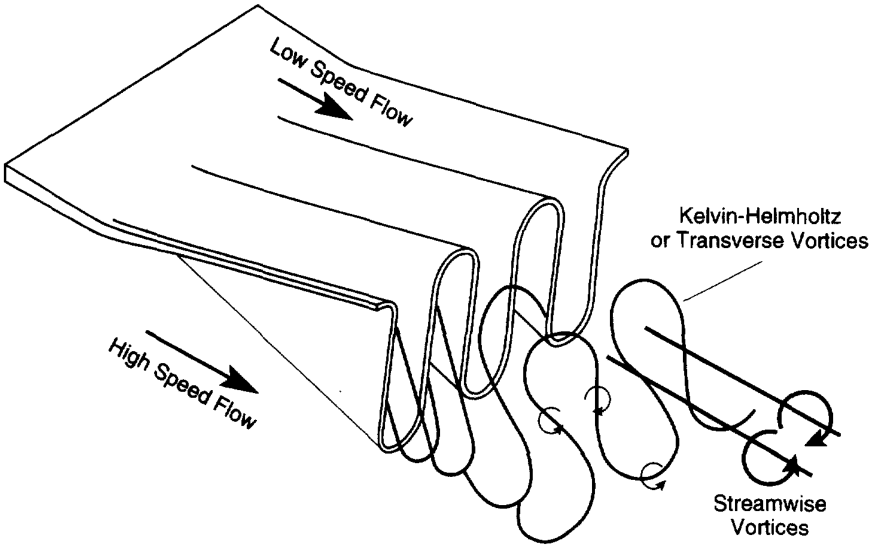
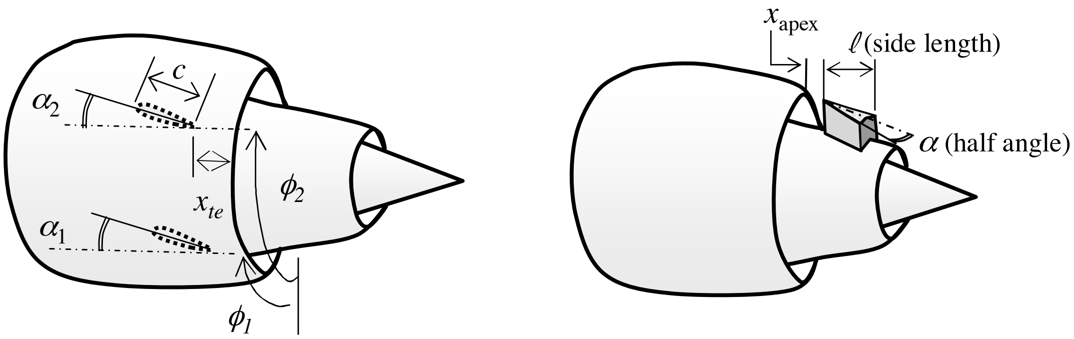


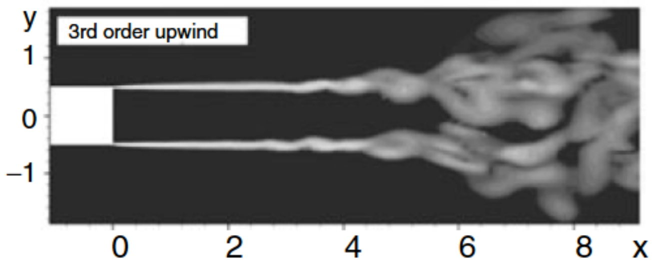
Figure 2. Schematic of a lobed mixer (from Waitz et al. [6])



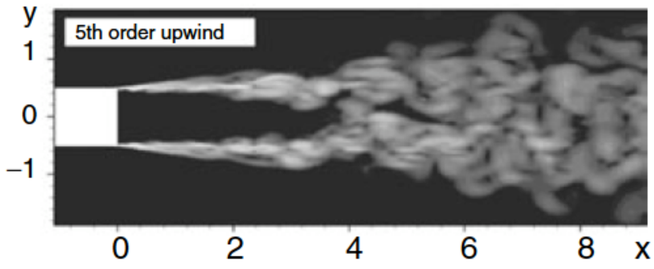
(a) Vane deflector

(b) Wedge deflector

Figure 3. Offset fan flow nozzle concepts (from Papamoschou [8])

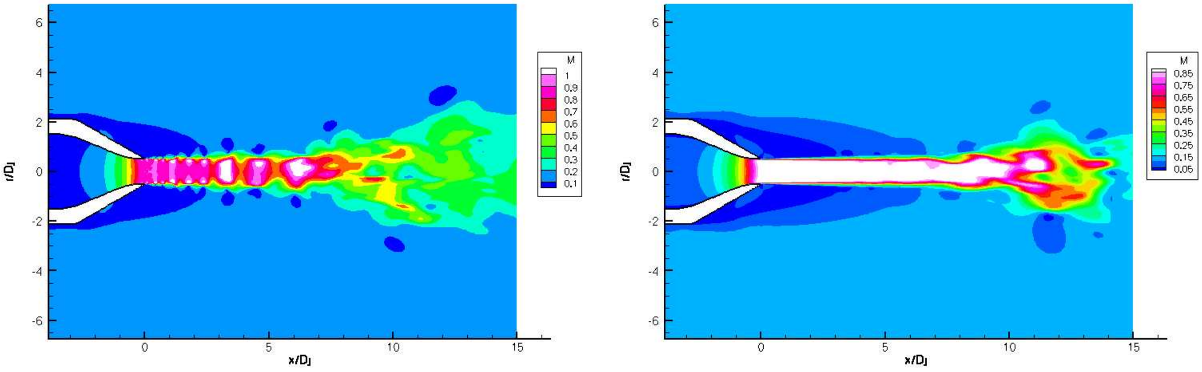


(a) 3rd order upwind



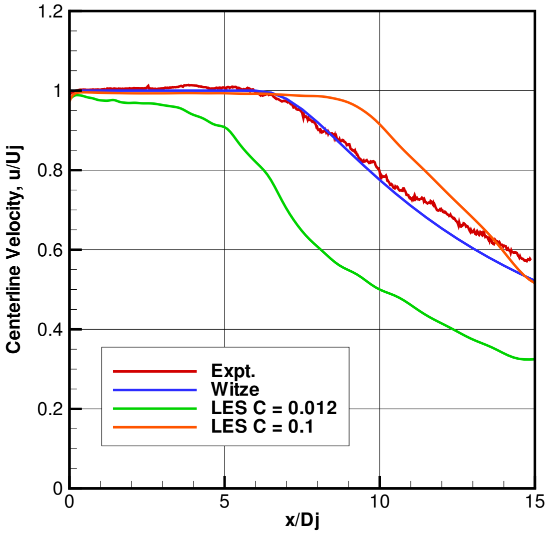
(b) 5th order upwind

Figure 4. Effect of numerical dissipation on resolution of turbulent scales (from Shur, Spalart and Strelets [26])



(a) Mach contours using Smagorinsky coefficient $C = 0.012$

(b) Mach contours using Smagorinsky coefficient $C = 0.10$



(c) Centerline mean velocity profiles

Figure 5. Effect of sub-grid model on resolution of turbulent scales (from DeBonis [29])