Recent Developments on the Turbulence Modeling Resource Website (Invited)

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The NASA Langley Turbulence Model Resource (TMR) website has been active for over five years. Its main goal of providing a one-stop, easily accessible internet site for up-to-date information on Reynolds-averaged Navier-Stokes turbulence models remains unchanged. In particular, the site strives to provide an easy way for users to verify their own implementations of widely-used turbulence models, and to compare the results from different models for a variety of simple unit problems covering a range of flow physics. Some new features have been recently added to the website. This paper documents the site's features, including recent developments, future plans, and open questions.

I. Introduction

Creating universally accurate and reliable turbulence models for the Reynolds-averaged Navier-Stokes (RANS) equations is inherently difficult (many would say impossible!), but for now we are stuck with them; RANS models will be necessary for many decades to come.[1] The NASA Langley Turbulence Model Resource (TMR) website (http://turbmodels.larc.nasa.gov) provides a one-stop on-line location where RANS turbulence models are documented and explored. It is guided by the Turbulence Modeling Benchmark Working Group (TMBWG), which is under the auspices of the AIAA Fluid Dynamics Technical Committee. The idea for the site was conceived after its originators noted that at many computational fluid dynamics (CFD) validation workshops, different codes with ostensibly the same turbulence model would produce inconsistent results. Part of the reason for the inconsistencies could be due to numerical discretization error (grids not fine enough), part due to use of different boundary conditions, and part due to errors or differences in turbulence model coding. With all three possible sources of inconsistency in play, it was difficult, if not impossible, to draw firm conclusions regarding the efficacy of the turbulence models tested. The first two possible causes (discretization error and use of inconsistent boundary conditions) seemed to be relatively easy to fix in the long term, but how could the third possible cause ever be tackled? The decision was made to try to use the power of the internet to help the developers and users of CFD codes in the aerospace community identify and eliminate errors/differences in turbulence model coding.

To acquire confidence in computed solutions, verification and validation (V&V) is extremely important in computational modeling and simulation.[2] Verification is the process that insures that a computer code solves a set of given equations as intended. There are several ways to help verify a computer code implementation. One is by comparison to known analytical solutions, but this method is not possible in general for turbulence models. Another is the method of manufactured solution (MMS).[3] Unfortunately, MMS involves additional computer coding, and many software developers do not undertake the effort. A third method of verification we call "verification by comparison." Roache[4] calls this method "inter-code comparisons." Its concept is very simple. By demonstrating that two or more independently-coded CFD codes (with a given turbulence model) go to the same answer for basic problems as the grids are refined, we gain confidence that the coding for that model is very likely "valid." The more independent codes that agree and the more cases that they agree on, the more confidence is built up. Furthermore, additional confidence is accrued if one or more of the CFD codes has tested its particular implementation via MMS.

This is the essential concept behind verification on the TMR website. We currently provide a set of four verification test cases (2-D flat plate, 2-D planar shear, 2-D bump, and 3-D bump), including all grids, for which two (or more) CFD codes have been demonstrated to yield the same results with a given turbulence model as the grids are refined. Originally, the two codes used were NASA Langley's block-structured CFL3D solver[5] and unstructured FUN3D solver.[6] Both of these codes underwent MMS for their implementations of the Spalart-Allmaras (SA) turbulence model,[7] as described in Rumsey and Thomas.[8]

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Although not 100% fool-proof, this concept of verification by comparison has so far stood the test of time, with many additional CFD codes agreeing with TMR's results, adding to the confidence in its solutions. We are aware of several instances where users have reported bugs uncovered in their software as a result of disagreeing with the TMR's posted results and tracking down the cause. The website has provided benefits for its curator as well: in one case, a user uncovered an implementation issue in one of the TMR's results. In other words, by openly providing equations, grids, boundary conditions, and solutions for many simple CFD cases, the TMR website has created an easy forum for cross-checking CFD codes. This type of cross-checking benefits everyone.

The website includes a "confidence measure," called the Model Readiness Rating (MRR) system. Ranging from 0 to 3, the MRR rating can give users a feel for the likely reliability in the displayed results. The level 0 indicates that no results exist on the website, and only the model itself is described and is referenceable. The level 1 indicates that the model has only been implemented and used in one code (for the website), so its results given on the website are not necessarily reliable. The level 2 indicates that two or more codes have been shown to agree, while the level 3 indicates that two or more codes from different organizations have been shown to agree via independent analysis.

Some of the TMR website cases were used as verification exercises at two recent validation workshops: DPW-5[9] and HiLiftPW-2.[10] In the DPW-5 workshop, the 2-D flat plate and 2-D bump were used as verification tests. The use of grid convergence studies was shown to be crucial, as expected. The study helped to isolate differences in a few codes due to a particular cause: the use of an approximate minimum distance function in the SA turbulence model will change the model's results very noticeably from results that use an exact minimum distance function. Small differences in the formulation of the Menter shear-stress transport (SST) model[11] (exact vs. approximate vorticity-based production terms) were shown to yield quantifiable differences in results. A NACA 0012 validation case was also used in the DPW-5 workshop, but it was less enlightening because finer grids were needed than the ones provided at the time. (This is the subject of a new area of the website—Numerical Analysis—to be discussed in a later section.) In the HiLiftPW-2 workshop, only the 2-D bump verification case was included for verification. For this case, there was nearly perfect consistency among most of the participants who used the SA model. However, two of the participants' SA results did not match the others, and the results of these two participants for the high-lift aircraft configuration were also considerably different from the collective. Thus, inability to pass the verification by comparison test for a very simple case can serve as an indicator of inconsistent turbulence model implementation, and likely inconsistencies for more complex cases as well.

In addition to verification, another purpose of the TMR website is to provide information about the turbulence models themselves. In particular, by listing published variants of models, this site provides all equations and establishes naming conventions to help avoid confusion when comparing results from different codes. For example, there are currently 14 variants of the SA model and 7 variants of the SST model described in detail on the TMR. The turbulence model equations are often provided on the TMR with the cooperation of (or at the behest of) the model's developer. We hope that providing the equations in this way will help to overcome the lack of consistency sometimes observed between model versions published in different journals or at different times, as noted by Viti et al.[12]

The TMR site should also help CFD users to understand and compare the predictions of a variety of models on a series of fundamental flow problems in the validation database. Note that it is not the intention of this effort to provide validation of turbulence models for a wide range of complex flows for diverse applications. While this would undoubtedly be valuable, it is beyond the scope of what can be supported by current resources. Instead, the goal is to provide a set of test cases that illustrate the performance of models for flows that capture fundamental phenomena, to establish a consistent basis of comparison as a starting point from which a more thorough validation effort for flows of specific interest to users and developers can be conducted.

Finally, one of the original purposes of the site was to serve as a forum for model developers to help disseminate new models to the CFD community. However, to date there have been only a few efforts to introduce new models through this venue. Mostly, the site has been used to verify users' implementations of the "most widely-used" models in the aerospace community (such as SA and SST).

The purpose of this paper is to review the various aspects of the TMR website. This paper follows two earlier summary papers written near the time that the site was initiated.[13,14] In the next section, the website's main features are described. These main features include new aspects that may be unfamiliar to some readers. Then, in the summary, future plans for the website and open questions are discussed.

II. TMR Main Features

The TMR website is made up of a variety of sections, each with a different focus. Below, the key sections are summarized.

A. Description of Turbulence Models

The TMR currently has pages describing 12 different turbulence models (including variants), ranging from one equation through seven equations. These are:[a] Spalart-Allmaras, Nut-92, Menter k-ω SST, Menter k-ω BSL, Wilcox k-ω, Chien k-ε, k-kL, explicit algebraic stress k-ω, k-ε-Rt, Wilcox stress-omega, SSG/LRR stress-omega, and GLVY stress-epsilon. This list clearly represents only a small fraction of the many turbulence models that are available in the literature. Initially, to keep the workload manageable, only descriptions of very widely-used models (primarily for aerospace applications) were included in the TMR. Then about half of the model pages were added to the site at the request of their respective developers or someone else with a particular interest other than the site curator.

Currently, we request that anyone interested in seeing a model description added to the TMR help with creating its webpage. An easy-to-follow guide is provided, describing the process. Getting a model description page on the TMR is the first step. After this, the model is ideally run with multiple codes on the verification and validation cases. As described below, the verification cases establish confidence that the model has been coded correctly, while the validation cases show how the model performs for a variety of different flow physics.

At this time, the most thoroughly tested and documented models on the site are SA, SST, SST-V, Wilcox2006, and SSG/LRR-RSM-w2012. Others, like BSL, SA-RC, SA-QCR2000, k-kL-MEAH2013, EASMko2003-S, k-ε-Rt, and GLVY-RSM-2012, have been implemented and tested on some of the cases. And a few models (like Nut-92 and Chien k-ε) and many of the various model variants have not been tested for the TMR at all. Due to workload constraints, testing all models on all cases is not possible. The TMBWG has decided that it is more important in the near term to continue to add important new cases, and test only a limited set of models.

B. Verification Cases

The current verification test cases on the TMR are still the same original four: 2-D flat plate, 2-D planar shear, 2-D bump, and 3-D bump. These cases were conceived in an attempt to have very simple configurations for which full iterative convergence would be possible, and for which grid convergence studies would yield meaningful results. Thus, the body shapes are either flat or are analytically defined, and separation does not occur in any of the cases.

An example case is shown in Fig. 1 for the 3-D bump using the Wilcox2006 model.[15] Here, the lift coefficient from the two codes CFL3D and FUN3D appears to be converging to the same value as the grid is refined. Note in Fig. 1(b) that the C_L has been plotted as a function of an average measure of grid size $h = (1/N)^{1/3}$. If the quantity is converging at a nominal accuracy of first order, then the plot would show straight lines here. In this case, the plot shows better than first order convergence (analysis[16] shows it to be about 1.44 for CFL3D and 1.14 for FUN3D), but in our experience the convergence rate is rarely consistent over a variety of quantities for a given case, even for nominally second-order codes like CFL3D and FUN3D. The verification pages of the TMR website lists the computed apparent convergence order for many quantities of interest, along with other error measures from Ref. 16.

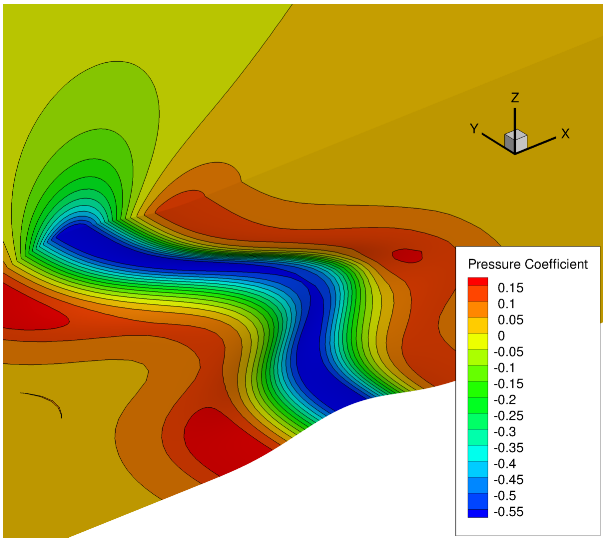
Recent additions to the verification section include results for the seven-equation SSG/LRR-RSM-w2012 model.[17] An example is shown for the 2-D planar shear case in Fig. 2. Here, three different CFD codes approach similar grid-converged results as $h \to 0$. Also, the TMR website provides solution files from CFL3D and TAU[18] in this case, with all turbulence variables included. For example, Fig. 2(c) and (d) show the R_{13} turbulent stress component; it is nearly identical for both codes. With the solution files available on the website, anyone in the CFD community can easily compare their own results when trying to implement this turbulence model.

C. Validation Cases

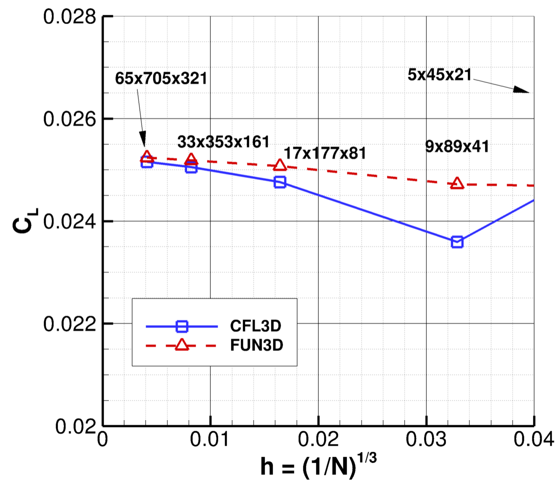
A significant number of new test cases have been added to the validation section over the last several years. Originally, only five cases were planned.[14] Now there are 15 cases: 9 considered "basic", and 6 considered "extended." The "basic" cases were chosen to cover a wide range of fundamental flow physics. The "extended" cases tend to be more difficult, such as high Mach numbers and flows with more separation and curvature. The cases are listed in Table 1, and a graphic indicating the relevant physics included in each of the validation cases is provided in Fig. 3. A green box indicates that the particular flow physics are included, and "strong" / "weak" denotes particularly strong / weak effects. A wide range of flow physics is covered. However, notice that there is no TMR case that deals with vortex flows; a simple case representing this type of flow is currently being sought.

Two of the newer cases to be added to the TMR website involve separated flow, as shown in Fig. 4. These are two of the configurations considered in NASA's "40% challenge," to be described in a later section. The first case is

[a]In the interest of space, the references for each of these models are not provided in this paper; they can be found on the TMR website on each of the respective pages.



(a) Pressure coefficients

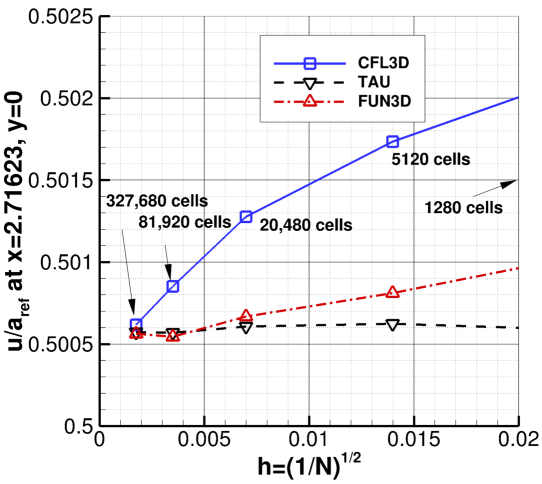


(b) Grid convergence of C_L

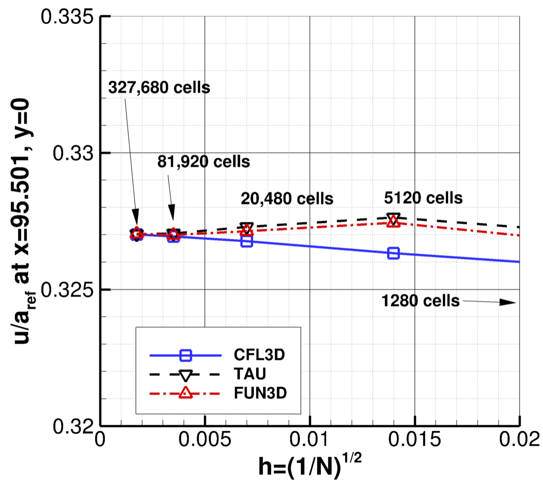
Figure 1. 3-D bump verification case, using Wilcox2006 model.

Table 1. TMR Validation Cases

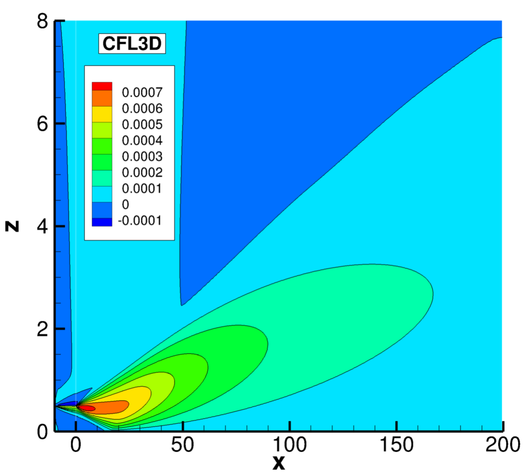
Basic Cases:		
	2DZP:	2-D Zero pressure gradient flat plate
	2DML:	2-D Mixing layer
	2DANW:	2-D Airfoil near-wake
	2DN00:	2-D NACA 0012 airfoil
	ASJ:	Axisymmetric Subsonic jet
	AHSJ:	Axisymmetric Hot subsonic jet
	ANSJ:	Axisymmetric Near-sonic jet
	ASBL:	Axisymmetric Separated boundary layer
	ATB:	Axisymmetric Transonic bump
Extended Cases:		
	2DZPH:	2-D Zero pressure gradient high Mach number flat plate
	2DBFS:	2-D Backward facing step
	2DN44:	2-D NACA 4412 airfoil trailing edge separation
	2DCC:	2-D Convex curvature boundary layer
	2DWMH:	2-D NASA wall-mounted hump separated flow
	3DSSD:	3-D Supersonic square duct



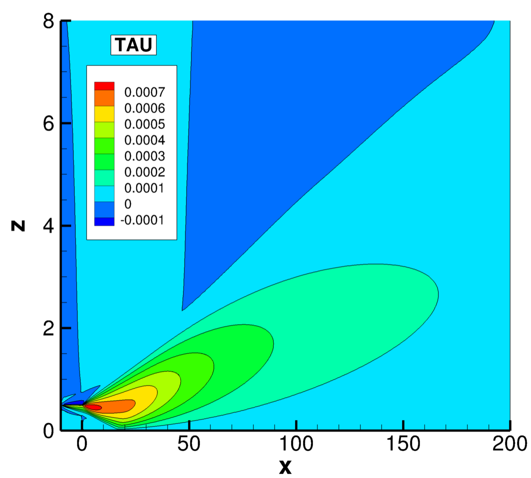
(a) Horizontal velocity at $x = 2.71623$, $y = 0$



(b) Horizontal velocity at $x = 95.501$, $y = 0$



(c) R_{13}/a_{ref}^2 from CFL3D



(d) R_{13}/a_{ref}^2 from TAU

Figure 2. 2-D planar shear case, using SSG/LRR-RSM-w2012 model.

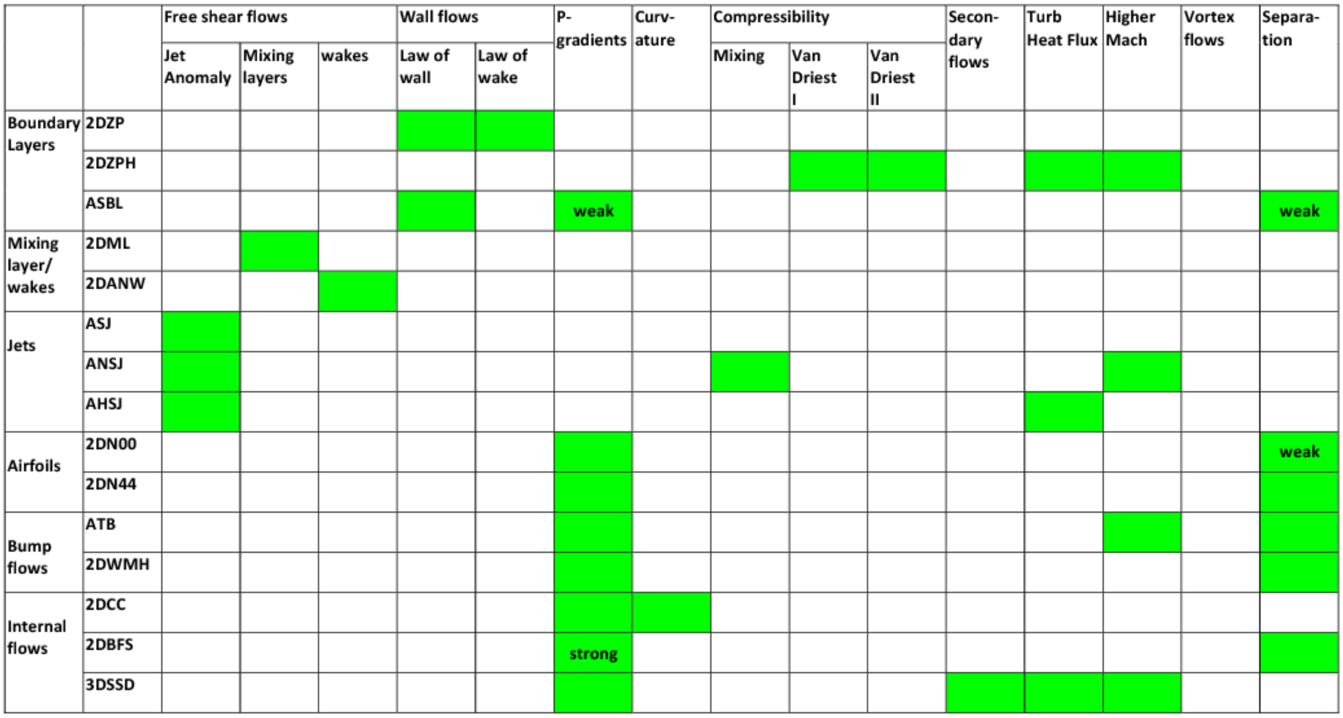


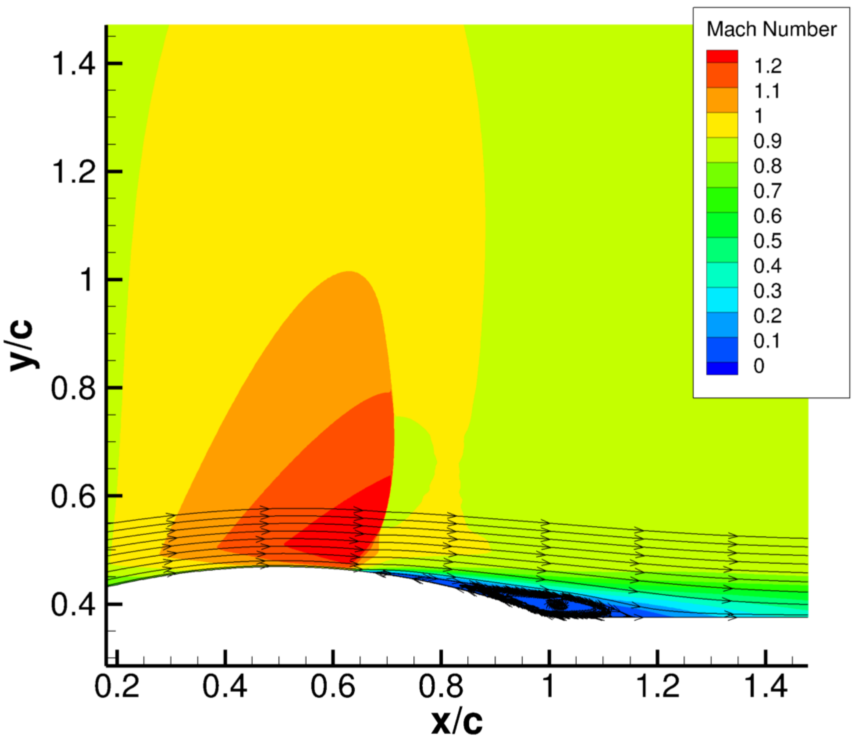
Figure 3. Physics of TMR Validation Cases (see Table 1 for meaning of acronyms in second column).

an axisymmetric transonic bump and the second is a 2-D wall-mounted hump (there is no distinction made between the nomenclatures “bump” and “hump;” these are merely the names by which these cases are commonly referred in the literature). Sample results for the axisymmetric transonic bump are given in Fig. 5. The experiment was reported by Bachalo and Johnson.[19] This configuration at Mach number 0.875 produces a shock with subsequent separation bubble. Results from three different turbulence models are shown in the figures. For this case, we have available SA and SST results from CFL3D and FUN3D, and SSG/LRR-RSM-w2012 results from CFL3D and TAU. The various codes agree very well with each other. Here, the second-finest grid with over 230,000 grid cells was used.

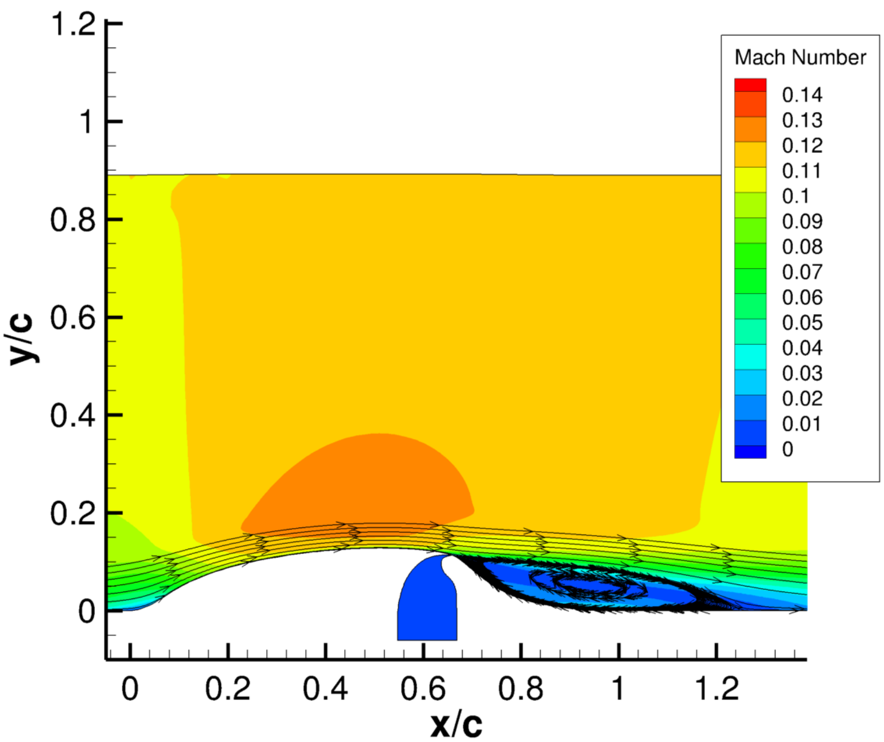
As seen in the left-hand plots of surface pressure coefficient, the SA model predicts the shock for this case slightly too far aft, whereas the SST and SSG/LRR-RSM-w2012 models produce similar results in terms of pressure coefficient, with the shock location in reasonably good agreement with experiment. (Although not shown, the Menter BSL model produces results slightly worse than SA; and the Wilcox2006 model produces results very similar to SST.) However, as shown in the right-hand plots, all models under-predict the magnitude of the turbulent shear stress downstream of separation, with the SSG/LRR-RSM-w2012 giving the closest agreement.

Example results for the 2-D wall-mounted hump are shown in Fig. 6. Experimental data are from Greenblatt et al.[20] The left-hand plots show computed surface skin friction coefficient from three different turbulence models compared with experimental data of Naughton et al.[21] Of particular importance is the fact that all CFD results yield reattachment of the bubble too far aft compared with experiment (which occurs at approximately $x/c = 1.1$). The reattachment location predicted by SSG/LRR-RSM-w2012 is closer to experiment than the others, although its C_f levels in the separated region are further off than SA or SST. Previously,[22] the poor prediction of reattachment location had been attributed to the fact that the models produce too little turbulent mixing in the separated region. The right-hand plots show profiles of the turbulent shear stress at several different locations. All turbulence models under-predict the magnitude of the negative peak level in the separated region.

For the 2-D wall-mounted hump case, we currently only have results from CFL3D and FUN3D. Also, at this time we only have available the grids from the original 2004 workshop,[23] with approximately 210,000 grid cells in the finest grid. Agreement between the codes is generally very good, with the largest differences (of about 6%) seen in the SSG/LRR-RSM-w2012 results for turbulent shear stress. These differences are believed to be primarily due to

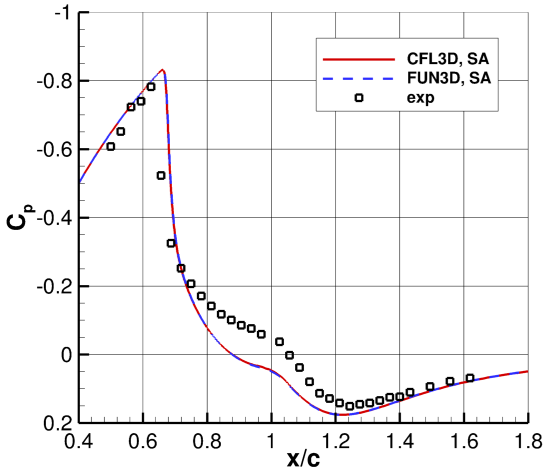


(a) Axisymmetric transonic bump

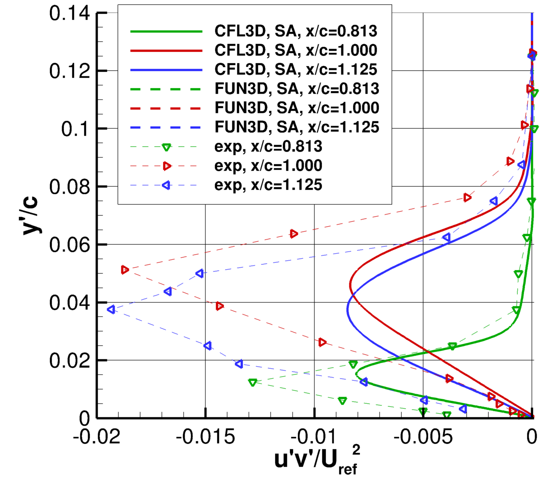


(b) 2-D wall-mounted hump

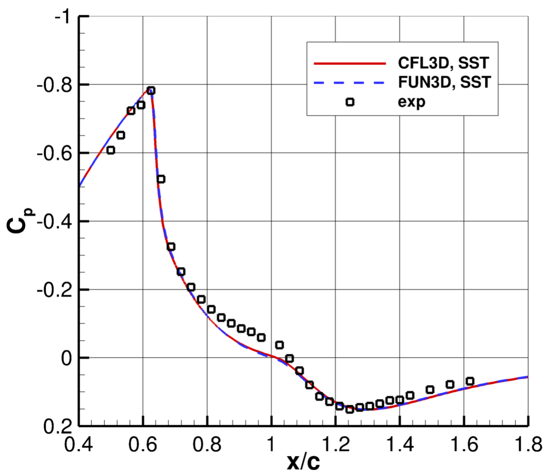
Figure 4. Typical Mach contours and streamlines for two TMR website cases.



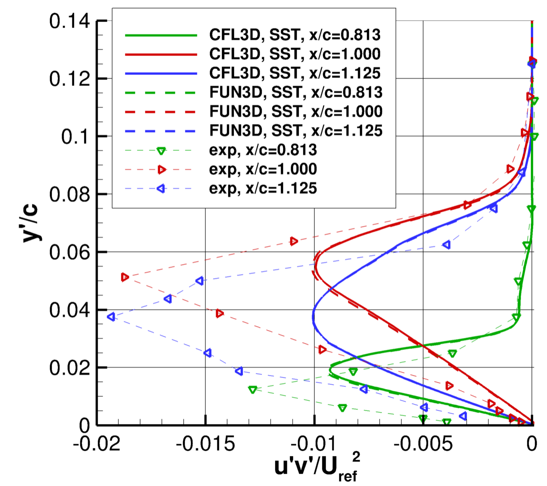
(a) SA, Surface pressure coefficients



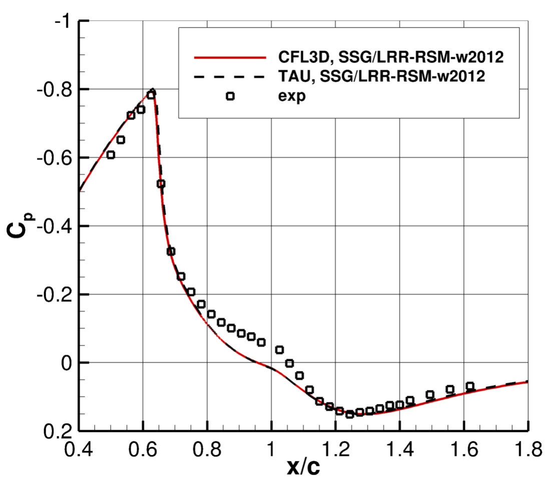
(b) SA, Turbulent shear stress profiles



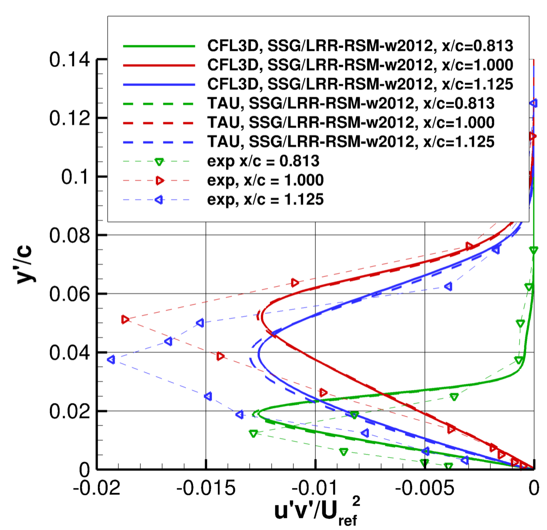
(c) SST, Surface pressure coefficients



(d) SST, Turbulent shear stress profiles

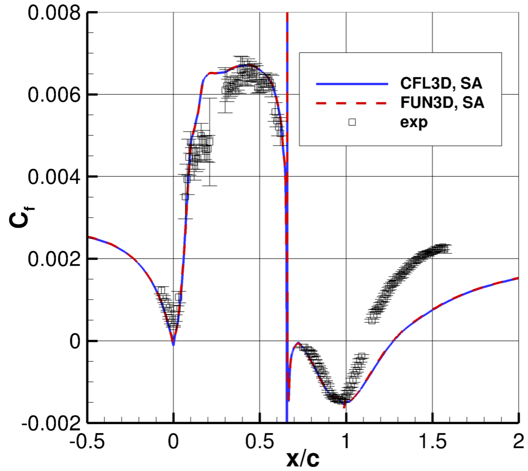


(e) SSG/LRR-RSM-w2012, Surface pressure coefficients

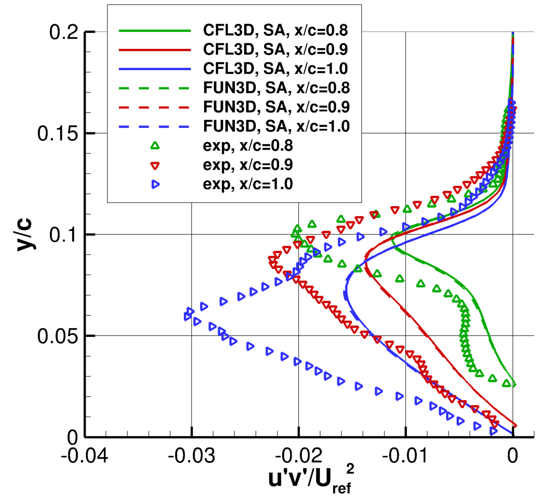


(f) SSG/LRR-RSM-w2012, Turbulent shear stress profiles

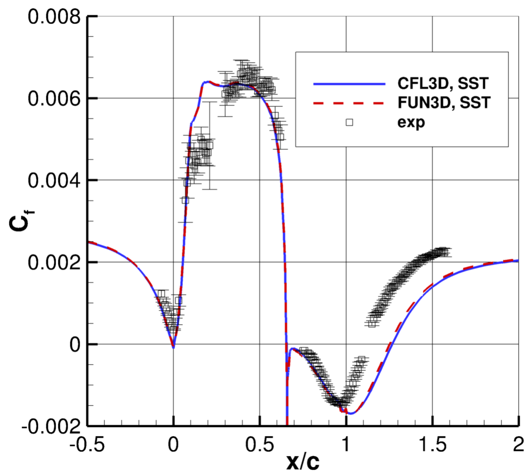
Figure 5. Axisymmetric transonic bump computed results compared with experiment.



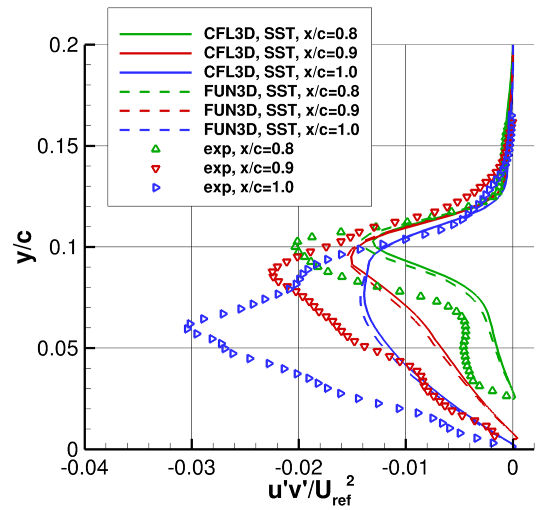
(a) SA, Surface skin friction coefficients



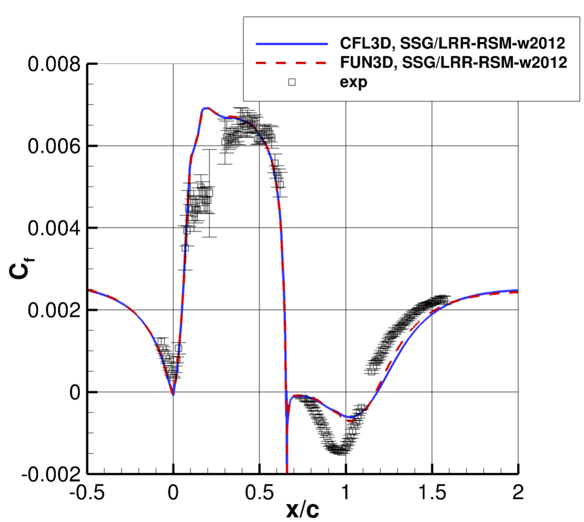
(b) SA, Turbulent shear stress profiles



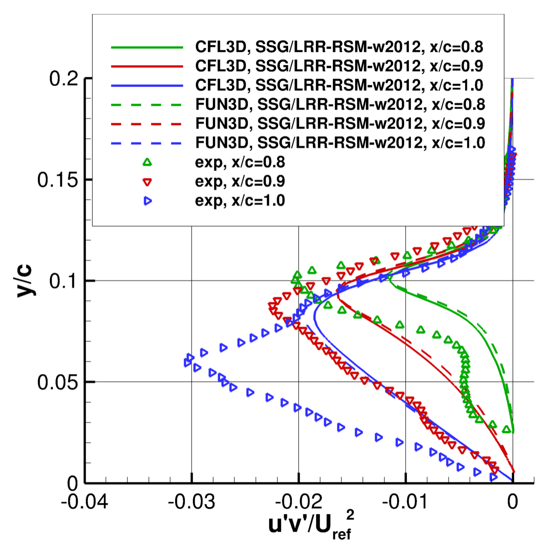
(c) SST, Surface skin friction coefficients



(d) SST, Turbulent shear stress profiles



(e) SSG/LRR-RSM-w2012, Surface skin friction coefficients



(f) SSG/LRR-RSM-w2012, Turbulent shear stress profiles

Figure 6. 2-D wall-mounted hump computed results compared with experiment.

discretization errors (i.e., finer grid is needed). Nonetheless, the differences between the codes on the current grid are far less than the differences between CFD and experiment, and the results from the three turbulence models are clearly differentiable from each other.

D. Databases

The "Turbulent Flow Validation Databases" section of the TMR website is where potentially useful turbulent flow databases from experiment, direct numerical simulation (DNS), or large eddy simulation (LES) are given. One grouping represents publicly-available data collected previously by Bradshaw et al.[24] For example, many databases from the so-called "Stanford Olympics" of 1980-81 are provided.[25]

Among experimental data collected, the TMR website currently lists eight sets. There are also six DNS and four LES databases highlighted. Some of these are hosted on separate sites and the TMR simply provides a link to them, while others provide the data directly (with permission from the originators). It is important to note that several of the cases have been selected because RANS is known to predict the flows poorly. (The 2-D converging-diverging channel of Marquillie et al.[26] is one example.) We hope that by providing experimental, DNS, and/or LES details, a turbulence model developer may readily find enough information to help develop a new model that performs better.

E. Manufactured Solutions

The TMR website also provides some information from a series of turbulence-related V&V workshops held in Lisbon, Portugal, at the Instituto Superior Tecnico (IST), where MMS was employed (see, e.g., Eça et al.[27]). The information on this TMR webpage includes manufactured solutions for wall-bounded incompressible turbulent flow, courtesy of the workshop organizer L. Eça of IST. Fortran files are included and are available for download. See Eça et al.[28,29] for details on the construction of the manufactured solutions for several one- and two-equation eddy-viscosity turbulence models.

F. Numerical Analysis

A new section on "Cases and Grids for Turbulence Model Numerical Analysis" has recently been initiated to provide more in-depth analysis of particular cases. Two cases are currently complete: the 2-D finite flat plate and the 2-D NACA 0012 airfoil. The results for both of these are reported in Diskin et al.,[30] and they were also the subject of special sessions at the AIAA SciTech meeting in January 2015 in Kissimmee, Florida. To date we only have results for the SA model. One outcome sought from the deeper analysis is a "reference solution" (what the codes should be going to on an infinitely-refined grid when a certain turbulence model is employed). In other words, we seek to take some validation case to the next level, and make them into verification cases. Such reference solutions can be extremely useful for determining numerical errors and for evaluating high-order schemes and/or grid-adaptive schemes.

The finite flat plate case is similar to the original flat plate case on the TMR website, except it includes a wake region behind the back of the plate. Typical results from three different CFD codes are shown in Fig. 7, where all codes are shown to be approaching the same result for plate drag coefficient and maximum eddy viscosity. For this case, the grid near the leading and trailing edges has been clustered so that the grid aspect ratio in their immediate vicinity is approximately one. Although not described here, Diskin et al.[30] also explored the influence of different clustering.

The NACA 0012 case at angle-of-attack $\alpha = 10^\circ$ is the same case from the validation section of the TMR website, except the grids have been modified. Here, much finer grids are employed, up to well over 14 million grid points ($7,169 \times 2,049$ C-grid), in an attempt to achieve a valid "reference solution." As part of this study, different trailing-edge clusterings are explored; and the influence of order of accuracy of the turbulence model advection scheme is assessed. (On the website, the influence of a farfield point-vortex correction[31] is also explored, but this is not discussed here.)

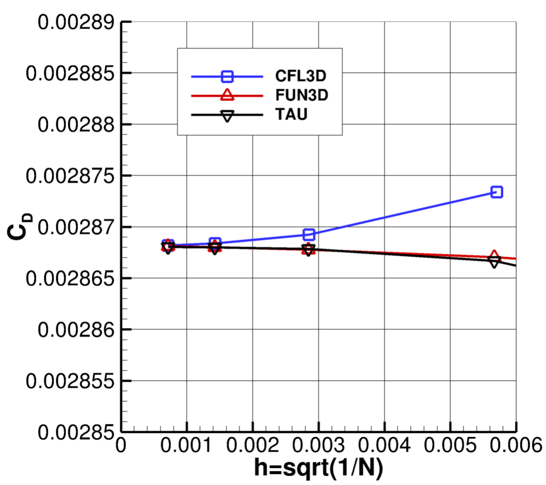
The grids with the finest trailing-edge streamwise clustering ($0.0000125c$ on the finest grid) yield the most consistent results, in the sense that they show approximately where the results on an infinite grid are headed. Surprisingly, on grids with less trailing edge clustering (3 and 10 times coarser than $0.0000125c$ on the finest grid), use of Richardson extrapolation on the finest grids do not yield very accurate results for some integrated quantities like C_L and C_M. In other words, when insufficient trailing-edge streamwise grid clustering is used, even uniformly refined grids finer than 14 million gridpoints are required in 2-D to be able to determine where the solution is heading! It is therefore not surprising that airfoil studies using multiple codes and grid sizes well less than a million gridpoints (as was done in the DPW-5 workshop[9]) were inconclusive.

A conclusion from Diskin et al.[30] is that the grid resolution in the vicinity of geometric singularities, such as a sharp trailing edge, is the major factor affecting accuracy and convergence of discrete solutions; the effects of this local grid resolution are more prominent than differences in discretization schemes and/or grid elements. The results demonstrate that CFL3D, FUN3D, and TAU solutions are very accurate on the finest grids used in the study, but even those grids are not sufficient to conclusively establish an asymptotic convergence order. From the best grids, the NACA 0012 results appear to be approaching infinitely-refined results near:

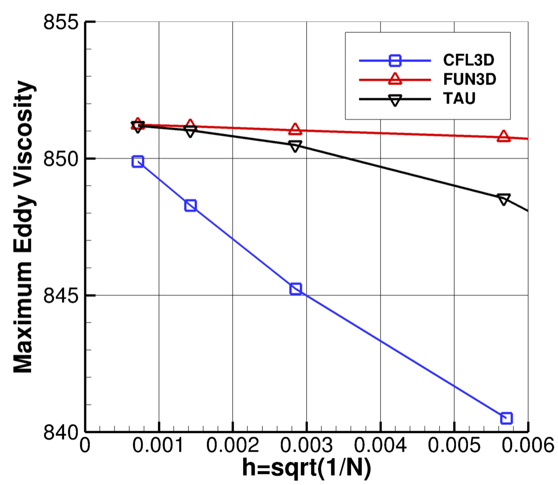
$$
\begin{aligned}
1.0909 &< C_L < 1.0911 \\
0.01226 &< C_D < 0.01227 \\
0.00606 &< C_{D,p} < 0.00607 \\
0.0062045 &< C_{D,v} < 0.0062055 \\
0.00676 &< C_M < 0.00678
\end{aligned}
$$

However, because the results do not demonstrate clear asymptotic rate of convergence, these ranges (although very narrow) are only estimates.

The influence of grid size and turbulence model advection order of accuracy are shown for the NACA 0012 airfoil in Fig. 8. Both FUN3D (which uses second-order turbulence advection) and CFL3D approach the same results as grid is refined. In CFL3D, the influence of turbulence model advection order is shown to be significant, particularly in the far wake along $x/c = 10$, where even the finest grid result for first-order turbulence model advection is poor. In the boundary layer near the trailing edge, the largest effect is near the edge of the boundary layer (near $z/c = 0.05$); however, on the finest grid the CFL3D results for both first and second order turbulence model advection are very similar over the bulk of the boundary layer.



(a) Drag coefficient

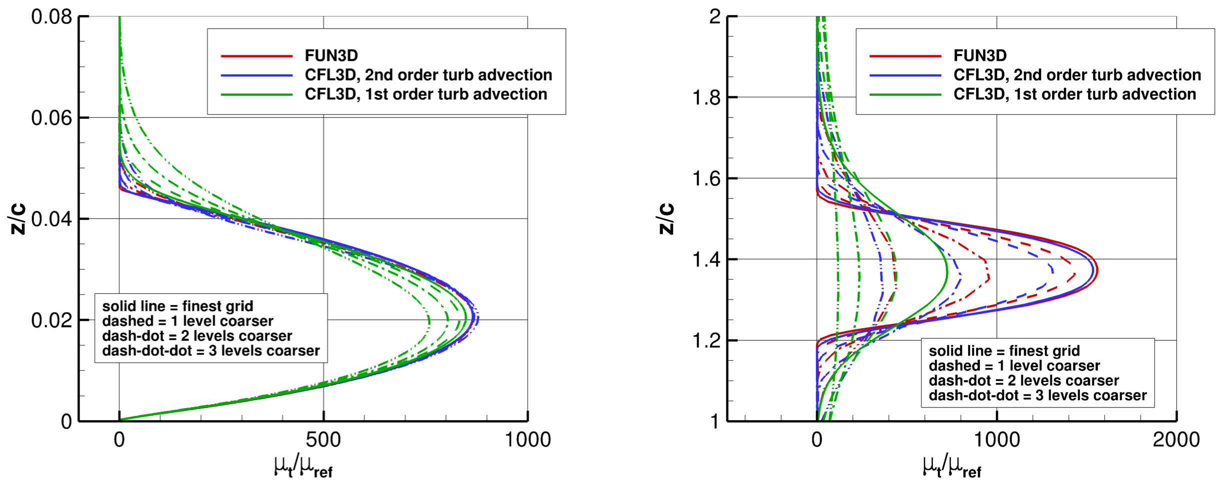


(b) Maximum eddy viscosity

Figure 7. 2-D finite flat plate using SA turbulence model.

G. NASA's 40% Challenge

Recently, NASA defined a technical challenge under its Transformational Tools and Technologies Project: to identify and down-select critical turbulence, transition, and numerical method technologies for 40% reduction in predictive error against standard test cases for turbulent separated flows, evolution of free shear flows and shock-boundary layer interactions on state-of-the-art high performance computing hardware. This challenge to the CFD community highlights several of the TMR website's cases as challenge problems for benchmarking future improvements in turbulence models. Two of these cases involving separated flow were shown earlier: the axisymmetric transonic bump and the 2-D wall-mounted hump. Results for some key metrics for these cases are given in Table 2, including separation point, reattachment point, and peak turbulent shear stress at specific x-locations. It is notable that the SSG/LRR-RSM-w2012



(a) Along x/c=0.999 (upper surface)

(b) Along x/c=10

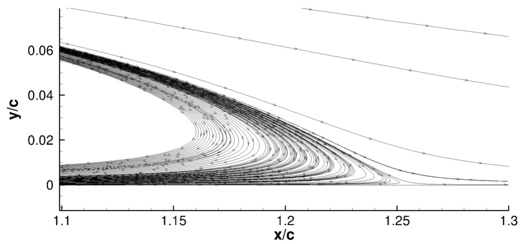
Figure 8. 2-D NACA 0012 airfoil ($\alpha = 10°$) eddy viscosity profiles using SA turbulence model.

model yields significantly lower error in the bubble length metric than SA or SST for both cases. However, this better bubble length prediction is due in part to a non-physical "back-bending" of the bubble near its reattachment point, as exemplified in Fig. 9. Here, SST and SSG/LRR-RSM-w2012 streamlines are shown near the aft end of the bubble. Although not shown, SA streamlines are similar in shape to those of SST. The SSG/LRR-RSM-w2012 model shows the bubble closing off at the wall upstream of the bubble's furthest extent. This odd behavior is a known issue[32] with some models, and does not occur in experiments. This example demonstrates the difficulty in relying on simple metrics for evaluating models. Instead, many aspects of the turbulent flow solutions need to be scrutinized. For example, as seen in Table 2, the errors in peak turbulent shear stress for all models are quite large.

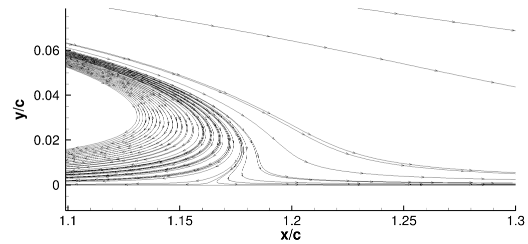
Table 2. Results for Two of NASA's 40% Challenge Cases

Quantity	exp	SA	SST	SSG/LRR-RSM-w2012
ATB Case:				
$(x/c)_{sep}$	0.70	0.69	0.65	0.66
$(x/c)_{reatt}$	1.10	1.16	1.16	1.05
$-[(u'v')/U_{ref}^2]_{min,x/c=1.0}$	0.019	0.008	0.010	0.013
Error in bubble length		18%	28%	-3%
Error in peak $u'v'$		-58%	-47%	-32%
2DWMH Case:				
$(x/c)_{sep}$	0.665	0.66	0.65	0.65
$(x/c)_{reatt}$	1.10	1.28	1.26	1.18
$-[(u'v')/U_{ref}^2]_{min,x/c=0.8}$	0.020	0.011	0.013	0.012
Error in bubble length		43%	40%	22%
Error in peak $u'v'$		-45%	-35%	-40%

Other challenge cases on the TMR website include several axisymmetric (round) jets, with experimental data from Bridges and Wernet.[33] A compressible mixing layer and shock wave boundary layer interaction (currently not included on the TMR website) are also highlighted in the NASA technical challenge.



(a) SST model



(b) SSG/LRR-RSM-w2012 model

Figure 9. Examples of 2-D wall-mounted hump streamlines near reattachment.

III. Summary, Future Plans, and Open Questions

The TMR website seeks to bring consistency to the testing, verification, and validation of the CFD community's RANS turbulence models. By providing the equations, boundary conditions, and grids required for full grid-convergence studies, the TMR gives all users the opportunity to independently verify the published results given by any particular turbulence model. For example, a modeler's claim of a new and better turbulence model could be quickly checked via this process. When using the same boundary conditions on adequately refined grids, different codes should always approach the same result.

Future plans for the site include:

- Continue to add relevant validation test cases, particularly those that feature physics not already covered (for example: vortex flows).
- Add descriptions of other existing, widely-used or promising new turbulence models.
- Continue to add experimental, DNS, and LES databases as they are made available.
- Verify and validate additional models on the existing test cases.

Among these, the last item is the most difficult and time-consuming. With 4 verification cases and 15 validation cases currently in place, plus the desire to achieve the same results with at least two independent CFD codes, the matrix of runs quickly becomes overwhelming. Although many different codes have now been demonstrated to agree for certain turbulence models (such as SA and SST) on TMR cases, it is a significant effort to introduce a new turbulence model or variant. Most of the efforts to date have involved the author working in collaboration with other researchers. To make the process more feasible in the long run, additional groups independent of the author's collaboration will probably be required, and a better procedure for collating results from different codes needs to be found.

One of the original hopes for the TMR website, to serve as a forum for turbulence model developers to help disseminate new models to the CFD community, has proved to be difficult to achieve in practice. To date, there have been only a few efforts to introduce new models through this venue. This may in part be because there are very few new RANS ideas; it may also be due to lack of connection between those with new ideas and the members of the TMBWG. Although merely documenting a new turbulence model on the TMR website is relatively easy, it can be time-consuming to apply it to a large number of cases, including full grid convergence studies and multiple CFD codes. Therefore, two open question are as follows. How can we create a stronger connection between the TMR website and the researchers with new RANS models and ideas? And how can the process of applying models to the TMR cases (including grid studies and multiple codes) be made easier?

Over the last several years, the question has come up whether there are plans to document transition models and hybrid scale-resolving LES-type models on the TMR website. To date, the answer has been no. The site's current focus is solely on "fully turbulent" RANS turbulence models. But as interest in the other methods grows, the push to include them will also increase. For hybrid RANS-LES methods, we will then need to answer the question of what processes to use to adequately verify them. This is not an easy question, as hybrid RANS-LES methods are necessarily three-dimensional and unsteady, and achieve a time-averaged statistical steady state only after long averaging time.

As the TMR website continues with its mission to provide a one-stop, easily-accessible internet site for up-to-date information on RANS turbulence models, its users are always encouraged to provide feedback. Interested researchers are also welcome to join the TMBWG, which is comprised of people with interests in turbulence model development, implementation, application, and validation/verification. Ultimately, the TMR website will continue to be useful only so long as it remains relevant and adaptable. We hope that by providing this common focus, we are helping to reduce uncertainty in turbulence modeling, in addition to inspiring new and rapid advances.

Acknowledgments

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