ASSESSMENT OF HYBRID TURBULENCE MODELS FOR UNSTEADY HIGH SPEED SEPARATED FLOW PREDICTIONS

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ABSTRACT
This paper presents the results of a study conducted to assess hybrid RANS/LES methods in the prediction of separated high-speed flows. The study focuses on the unsteady flow and acoustic fields associated with supersonic flow over an open cavity. Numerical results are obtained from explicit time marching simulations using the 3rd order Roe scheme and both SST (Shear-Stress-Transport) two equation and the S-A (Spalart-Allmaras) one equation based hybrid turbulence models. The predictions of the two models are compared in terms of sound pressure level (SPL) spectra predictions and interaction of the shock with boundary layer. The effect of turbulent kinetic energy (TKE) dissipation rate and grid resolution on the resolved flow field, the SPL spectra and the TKE is investigated for the SST based hybrid model. The computed results are compared with available experimental data for sound pressure level (SPL) spectra.

INTRODUCTION
One of the major limitations of the use of Reynolds Averaged Navier-Stokes (RANS) methodology is the uncertainty of unsteady separated flows predictions\textsuperscript{1}. Unsteady Reynolds Averaged Navier-Stokes simulations (URANS) with classical two-equation turbulence models have not been successful in predicting unsteady flows because of excessive dissipation\textsuperscript{2-3}. URANS simulations with algebraic turbulence models\textsuperscript{2} could only predict tonal modes in the power spectral density, but not the broadband content, which is characteristics of the fine scale eddies. In the last decade, DNS (Direct Numerical Simulations) and LES (Large Eddy Simulations) have been developed to compute turbulent flows by directly simulating all, and all but the small turbulence length scales respectively. However, estimates of grid and CPU requirement for DNS and LES at realistic Reynolds numbers preclude their applications to practical problems of engineering interest at realistic Reynolds numbers\textsuperscript{1}.

Hybrid RANS/LES models were developed to combine the fine tuned RANS methodology in the attached boundary layers with the power of LES in the shear layers and separated flow regions at realistic Reynolds numbers\textsuperscript{2-5}. Some investigators\textsuperscript{4,5,6} have based their hybrid models on explicitly dividing the solution domain into distinct RANS and LES regions and employing different turbulence models (RANS and SGS) in the two regions. However, initialization of the LES at interface presents a challenge because it requires the fluctuating quantities at the inflow plane while the RANS region deliver Reynolds averaged flow statistics\textsuperscript{6}. An alternative approach\textsuperscript{7} is the adoption of a single turbulence model that functions as a sub-grid scale LES model in the separated flow regions where the grid is nearly isotropic and as a RANS model in attached boundary layers regions.

Spalart et al.\textsuperscript{7} first proposed Detached Eddy Simulations (DES) based on the modification of wall distance in the original formulation of the RANS based Spalart-Allmaras (S-A) one-equation model\textsuperscript{8}. Subsequently, Strelets\textsuperscript{9}, Bush et al.\textsuperscript{10}, Batten et al.\textsuperscript{11}, Nichols et al.\textsuperscript{12} proposed parallel concepts for hybrid two-equation based turbulence models\textsuperscript{9,11,12} through modifications to the turbulent kinetic energy (TKE) dissipation rate\textsuperscript{8,10}, TKE production rate\textsuperscript{11}, and filtering of eddy viscosity\textsuperscript{12} respectively. In general, these hybrid RANS-LES methods\textsuperscript{7,8,10,11,12} use a transfer function to affect transition from the standard RANS turbulence model to the LES sub-grid type model. The transfer function for the S-A one equation based hybrid model solely depends on the local grid spacing\textsuperscript{11}. Thus, the mesh defined by the user can greatly influence the computed results. However, in the two-equation based hybrid models\textsuperscript{9,12}, the transfer

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from RANS to LES regions depends on both the local grid spacing and the local turbulent flow properties predicted by the model. This leads to smoother transition to the LES regions and more robust and physically viable numerical solutions.

A number of numerical simulations based on the hybrid RANS/LES turbulence models have been reported in the literature and the computational results presented were mainly for mean flow properties. Bush et al. conducted SST based hybrid simulations for flow over airfoil that demonstrated remarkable improvements in the predictions of the pre and post stall average lift and drag coefficients compared to the URANS simulations. Mani et al. used both S-A based and SST based hybrid turbulence models in the simulation of jet flow and investigated the use of unsteady forcing function to hasten the formation of fine scales. They compared the centerline mean velocity with experimental results and concluded that for the coarse grid solution, unsteady pulse resulted in better agreement with experimental results. However, it did not impact the solution with fine grid resolutions. Breuer et al. carried out extensive DES simulations of separated flow past an inclined flat plate using S-A based hybrid model. They also carried out RANS and LES simulations over the same configuration and determined that the grid filter width definition in the S-A based hybrid model significantly affects the accuracy of the solutions.

Recently, a number of investigations evaluated the unsteady 3-D flow predictions of hybrid RANS/LES methods. Hamed et al. presented computational results for unsteady cavity flow simulations and determined that the DES simulations with a SST based hybrid turbulence model predicted the unsteady flow, while the URANS solutions became steady. Batten et al. used the hybrid LNS (Limited Numerical Scales) model with scaled production term and computed the SPL level for a square cylinder wake. The SPL predictions were 20dB higher for the hybrid RANS-LES simulations than for URANS. Nichols et al. carried out weapons bay simulations with multi-scale SST two equation based hybrid model and compared the SPL spectra with experimental results. They predicted more energy at the higher frequencies of the turbulent spectrum, which are associated with the smaller scales of the turbulence. Morton et al. used both standard and hybrid S-A and SST models for simulations of delta wing vortical flows. The RANS predictions did not capture the physics of vortex breakdown at high Reynolds numbers. On the other hand, the computed power spectral density with the hybrid models captured a spectrum of frequencies in agreement with experimental data.

The present investigation focuses on the assessment of various parameters that control the mode switching in the DES formulation of the SST based hybrid turbulence model for high-speed flow over an open cavity. High speed flow over cavity is a good benchmark problem because it encompasses both broadband small-scale fluctuations typical of turbulent shear layers, as well as discrete resonance whose frequency and amplitude that depend upon the cavity geometry and external flow conditions like the free stream Mach number and the Reynolds number. Our previous DNS investigations of cavity flow-fields demonstrated a dramatic increase in the tonal sound pressure level with free stream Mach number. Hybrid RANS-LES results of supersonic cavity flow field demonstrated a decrease in the predicted TKE (Turbulent Kinetic Energy) spectra level with increased Reynolds number. In the present investigation, the effect of TKE dissipation rate and grid resolution on the SPL spectra, TKE spectra and flow field are studied for the SST based hybrid model. Computational results for the vorticity iso-surfaces are presented to show the unsteady 3-D flow characteristics including fine scale structures. The computed SPL spectra from the SST based and S-A based hybrid model simulations are presented and compared to existing experimental data.

**METHODOLOGY**

Hybrid methods attempt to allow the transition from the RANS to LES type solution by reducing the eddy viscosity ($\mu_t$) in proportion to the local resolution in regions where LES behavior is sought. This is accomplished through the modification of the wall destruction term in the one-equation turbulence model or the TKE dissipation rate ($\epsilon$ or $\omega$) in the two-equation turbulence models. The modification is achieved through a combination of a limiter/transfer function that is either a function of local mesh scale or a function of both local mesh scale and the turbulent length scale, and a non-universal floating coefficient/adjustable constant.

The S-A one equation hybrid model is based on the modification of the wall distance ($d$) in the destruction term. It is replaced in the hybrid model by $\bar{d}$, which is the smaller of the distance from the wall ($d$) and product of the floating coefficient and $\Delta$, the maximum length scale associated with the local grid element. This modification in the S-A model, along with simultaneous grid refinement essentially increases the destruction term in the $d \gg \Delta$ regions.
to reduce $\mu_t$ to levels consistent with the LES sub-grid model. In the original formulation\textsuperscript{7}, Spalart et al. experimented with different values for the floating coefficient. They suggested that the desired value should give a spectrum that avoids the build-up of the high-frequency oscillations and the suppression of resolvable eddies. Shur et al.\textsuperscript{25} recommended a value of 0.65 for the coefficient and applied that in the case of single airfoil at high incidence. However, subsequent investigators\textsuperscript{10,15} determined it’s value depends on the type of application and recommended a value between 0.1 and 0.5 for high shear jet flows\textsuperscript{26}.

The SST two-equation based hybrid model\textsuperscript{10} is based on the modification of the turbulent kinetic energy specific dissipation rate, $(\omega=\varepsilon/k)$ through a limiter that depends on the local grid size and also on the convection of the local velocity and turbulent kinetic energy. In the hybrid model, $\omega$ is replaced by $\omega_{b}=\max(\omega, k^{1/2}/C_{b^*} \Delta)$, where $\Delta=\max (dx, dy, dz, u^*dt, \sqrt{k^*dt})$ and $C_b$ is an adjustable constant. Essentially, the limiter increases the dissipation rate of turbulent kinetic energy (TKE)\textsuperscript{15} to reduce the value of eddy viscosity ($\mu_t$) from the level associated with RANS to a level implied by the underlying LES sub-grid model in the regions where LES behavior is desired. The TKE specific dissipation rate in the SST model is controlled by the value of $C_b$ and also by the grid. In addition, the SST based hybrid model transitions to the LES mode only when it can resolve the turbulent scales present on the existing grid\textsuperscript{12}.

Bush et al.\textsuperscript{10} and Mani et al.\textsuperscript{15} applied the SST based hybrid model to shear layers and jets and recommended that the value of $C_b$ should be between 0.1 and 0.5. Our present investigation explores the effect of $C_b$ and of grid refinement on the resolved flow-field, the SPL and TKE spectra for the SST based hybrid model over the wide dynamic range involved in the highly unsteady supersonic cavity flow field.

**COMPUTATIONAL DETAILS**

The unsteady compressible Navier-Stokes equations in conservation law form were solved using the WIND code’s cell-vertex, finite-volume discretization on structured grids\textsuperscript{27}. The third order upwind-biased Roe scheme was used for spatial discretization with TVD operator to suppress the numerical instabilities in the shear layer and near the shock waves. Explicit time marching scheme with Newton like sub-iterations was used for temporal advancement. Turbulence was simulated using both the SST and S-A based hybrid models. The benchmark problem selected in the present investigation involves transonic flow over cavity.

The computed results are compared to the experimental data of DERA\textsuperscript{24} which were obtained at a Reynolds number=4.336×$10^6$/ft. To optimize the use of available computational resources while maintaining a fully turbulent boundary layer at the front bulkhead cavity lip, the present simulations were performed at a Reynolds number of 0.60×$10^6$/ft, which is 1/7$^\text{th}$ the value of the experimental Re. The solution domain for the L/D = 5; W/D = 0.5 cavity is shown schematically in figure 1. Free stream conditions were set for the supersonic inflow and first order extrapolation was applied at the upper boundary, which was at 3D above the cavity opening. First order extrapolation was also applied at the downstream boundary, 3.5D behind the rear bulkhead. Periodic boundary conditions were applied in the span-wise direction for a cavity width, W, equal to 0.5D. The upstream plate length was 4.5D in order to maintain the incoming boundary layer thickness $\delta$ at 10% of the cavity depth D, at the simulated Reynolds number. The hybrid RANS/LES simulations were initiated in the unsteady mode and continued over 120,000 constant time-steps of 4.2345×$10^{-7}$ seconds. It took 40,000 time steps to purge out the transient flow and establish resonance and the remaining 80,000 time steps to capture 20 cycles in order to have sufficient data for statistical analysis. The sound pressure level (SPL) and the turbulent kinetic energy (TKE) spectra were computed for all cases based on 65536 sample points.

Three grid sizes were considered in the current investigation. The base line medium grid consisted of 253×122×80 points in the stream-wise, normal and span-wise directions. The grid was packed near the walls, with a minimum grid spacing of $6\times10^4$D, to maintain $y^+ < 3$ for the first grid point and 20 grid points within the boundary layer upstream of the cavity. Because hybrid RANS/LES models require a near isotropic grid distribution in the LES regions, the aspect ratio in the grid varied between 1 and 5 in all three directions. A coarser grid with 205×77×60 points and a finer grid with 323×133×100 points with the same minimum grid spacing were used in the grid sensitivity analysis. Details of the computational grids are summarized in table 1. The total numbers of grid points are 3.86×$10^6$ for the fine grid, 2.24×$10^6$ for the medium grid and 0.96×$10^6$ for the coarse grid. The number of grid points are one order of magnitude less for the medium grid compared to the 21×$10^6$ grid points required in Rizzetta et al.’s\textsuperscript{28} LES simulations at a Reynolds number 1/5$^\text{th}$ the value in the current investigation. These LES simulations\textsuperscript{28} required pulsating flow to accomplish transition upstream of the cavity front bulkhead.
The solution domain was decomposed into twelve non-overlapping zones upstream, across and downstream of the cavity for the medium and the coarse grid. For the fine grid, the solution domain was decomposed into twenty-four non-overlapping zones. Parallel computations for the non-overlapping zones were performed using clustered Linux machines and exclusive message passing with PVM libraries. The zones were constructed in such a way that the load sharing among the processors were nearly equal.

**RESULTS AND DISCUSSIONS**

Computational results are presented for the pressure fluctuations, sound pressure levels and turbulent kinetic energy spectra and turbulent kinetic energy profiles. In addition, some Mach number contours as well as vorticity iso-surfaces are presented for the resolved flowfield. Comparison of the existing experimental data with the computed SPL is used in the assessment. First, results obtained from the SST and the S-A based hybrid models are presented. Subsequently, the results obtained from the SST based hybrid model with different values of the floating coefficient \( C_b \) are presented. Finally, results are presented for the grid resolution study for the SST based hybrid model.

A qualitative comparison of the results obtained from the S-A and SST based hybrid models is presented for the baseline grid of \( 253 \times 122 \times 80 \). For the SST based hybrid model, \( C_b \) was chosen as 0.1. In the case of S-A based hybrid method it was only possible to have stable solutions in the transonic cavity with a floating coefficient \( \geq 0.3 \). Hence, solutions for the S-A based hybrid model were obtained using the floating coefficient \( = 0.3 \). The results are compared for the sound pressure level (SPL) spectra and Mach number contours in figures 2 through 3.

Figure 2 presents the computed Mach number contours at the cavity mid-span for the two models. The figure on the left for the SST model shows that a lambda shock is formed upstream of the cavity with a subsequent increase in the incoming boundary layer thickness due to shock interactions. The figure on the right for the S-A hybrid model shows the formation of a shock much closer to the cavity. This might be attributed to the fact that the SST model formulation is based on the transport of the shear stress and hence it is able to predict the shock-boundary layer interaction with separation regions much more distinctly. Similar inadequacies in predicting shock induced separation were reported by Hamed et al. in RANS simulations of over expanded CD nozzles with the S-A model.

Figure 3 presents the computed sound pressure level (SPL) spectra near the cavity front and rear bulkhead, for the two models with the experimental data. Both the SST and the S-A based hybrid model predict the dominant frequency at 500 Hz, in good agreement with the experimental results. The results with the SST model however are closer to the experimental SPL peak value. The computed peak SPL value is under-predicted by 5dB and 8dB compared to the experimental results by the S-A based and SST based hybrid model respectively. Based on this assessment, the SST based hybrid model is used for all subsequent simulations and assessments.

Results obtained from SST based hybrid model for the baseline grid of \( 253 \times 122 \times 80 \) are first compared for different values of the floating coefficient \( C_b \) in figures 4 through 8. The floating coefficient \( C_b \), which acts as a limiter, has direct relation to the turbulent kinetic energy (TKE) dissipation rate. The eddies’ formation within the cavity can be seen in figure 4 which shows the iso-surfaces of the axial vorticity for all three values of \( C_b \). The figure shows that the range of fine scale structures within the cavity 3-D flow field deepens with the reduction of \( C_b \). In the meantime, the peak vorticity increased from 25000 for \( C_b = 1.0 \) to 45000 for \( C_b = 0.5 \) and 70000 for \( C_b = 0.1 \).

Figure 5 presents the computed time averaged non-dimensional turbulent kinetic energy profiles at the cavity mid-span near the front and rear bulkheads for the three values of \( C_b \). The computed TKE profile from the URANS solution with the original SST model is also presented in the figure for comparison. It can be seen that the level of turbulent kinetic energy is the lowest for \( C_b = 0.1 \) and increases with increased \( C_b \). The kinetic energy values from the URANS simulations are generally much higher than the hybrid DES predictions. The difference in TKE profiles is greater near the rear bulkhead with a predicted peak value of 0.70 for the URANS compared to 0.02, 0.07 and 0.15 for \( C_b = 0.1, 0.5 \) and 1.0 respectively.

Figure 6 shows the effect of \( C_b \) on the instantaneous eddy viscosity \( (\mu_t) \) contours at the cavity mid-span. The instantaneous eddy viscosity \( (\mu_t) \) contours from the URANS simulations are also shown for comparison. It is evident that lowering the value of \( C_b \) decreases the eddy viscosity in the shear layer and within the cavity and that URANS predict much higher values of \( \mu_t \) within the cavity. The lower
values of eddy viscosity is an indication that significant amount of eddies are being resolved directly and don’t contribute to the turbulent stress. Similar trends were reported in the separated and wake flow region behind a sphere by Constantinescu et al.

Figure 7 presents a comparison of the computed sound pressure level (SPL) spectra with the experimental data at the cavity floor near the cavity front and rear bulkheads. The SPL spectra were obtained by transforming the pressure-time signal into the frequency domain using fast Fourier transform (FFT). The peak SPL predicted by simulations and that for the available experimental data are shown in the table below.

<table>
<thead>
<tr>
<th>Cases</th>
<th>Peak SPL at front bulkhead (dB)</th>
<th>Peak SPL at rear bulkhead (dB)</th>
<th>Difference with experimental value (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C_b=0.1</td>
<td>158</td>
<td>164</td>
<td>5</td>
</tr>
<tr>
<td>C_b=0.5</td>
<td>150</td>
<td>158</td>
<td>11-13</td>
</tr>
<tr>
<td>C_b=1.0</td>
<td>148</td>
<td>157</td>
<td>12-15</td>
</tr>
<tr>
<td>Experiment</td>
<td>163</td>
<td>169</td>
<td></td>
</tr>
</tbody>
</table>

One can see that the dominant mode, which occurs at approximately 500 Hz, is well captured by the present simulations and that the computed results for C_b=0.1 match best with the experimental data. The simulations under-predict the experimental SPL peak by 5dB, 12dB and 14dB on average, for C_b=0.1,0.5 and 1.0 respectively. However, the current simulations under-predicted the first mode and over predicted the SPL at the higher spectral frequencies. The LES simulations of Rizzetta et al. predicted the dominant mode at 440 Hz and the first mode at 220 Hz in close agreement with the experimental data. One should note that the LES simulations were carried out with fourth order compact scheme and sixth order non-dispersive filters. This offers superior resolution compared to the present investigation based on an upwind biased 3rd order Roe scheme with Jameson type scalar dissipation.

Figure 8 compares the turbulent kinetic energy (TKE) spectra in the shear layer at the cavity front and rear bulkheads for all three values of C_b. The classical – 5/3 Kolmogorov slope is shown in the figure for reference. The lower values of the calculated turbulent kinetic energy spectrum for C_b=0.1 indicate proper simulation of energy cascading phenomenon. The reductions in the energy spectra by more than two orders of magnitudes at higher frequencies indicate that adequate grid resolution was employed to capture the energy cascading.

Based on the above conclusions, C_b=0.1 was chosen in the grid sensitivity study. Figures 9 through 11 compare the computed results for the vorticity iso-surfaces, SPL spectra and turbulent kinetic energy (TKE) profiles for the three grids. Figure 9 presents the computed iso-surfaces of the axial vorticity component for the three grids. It is evident that resolved scales increase with grid solution. In addition, some fine scale structures are visible at the upstream of the cavity in the fine grid solution. In addition, peak vorticity level in the fine grid was 10% higher than the medium grid and the peak vorticity level in the medium grid was 20% higher than the coarse grid. Similar qualitative trend of increase in the peak value of vorticity with grid adaptation was reported by Viswanathan et al. for subsonic flow over an axisymmetric cavity.

Figure 10 presents the SPL spectra at the cavity floor mid-span in the front and rear bulkhead regions for the coarse, medium and the fine grids. The experimental data for the SPL are shown in figure 10 for comparison. One can see that the fine grid solution matches best with the experimental results for the peak SPL and the overall trend. The solution from the coarse grid fails to predict the dominant frequency in the experimental data. On the other hand, the solutions from the fine and the medium grid predict dominant frequency of 500 Hz in close agreement with the experimental values. However, both the medium and the fine grid solution over predict the SPL spectra at higher frequencies.

Figure 11 presents the computed time averaged turbulent kinetic energy profiles at the cavity mid-span near the front and rear bulkheads for the three grids. It can be seen that the level of turbulent kinetic energy is the lowest for the fine grid and it increases for the medium and the coarse grids.

**CONCLUSIONS**

Numerical simulations were conducted to assess the hybrid RANS/LES based turbulence models in predicting the three-dimensional unsteady flow and acoustic fields of turbulent supersonic flow over cavity. Computational results are presented and compared for the one equation S-A based hybrid and the two-equation SST based hybrid model. Results are presented for the turbulent kinetic energy (TKE) and the sound pressure level (SPL) spectra, which are compared with the experimental data. The results indicate that the hybrid turbulence models enable the
detached eddy simulations to resolve this complex flow and associated sound pressure level spectra at high Reynolds numbers. In general, the two-equation SST based hybrid model is more robust than the one-equation S-A based hybrid model. The computed SPL in general, and the peak SPL at the dominant frequency in particular are very sensitive to grid resolution. Both the grid resolution and the floating coefficient involved in the modification of the TKE specific dissipation rate, affect the computed TKE. However, the floating coefficient was found to have a more pronounced effect than the grid resolution on the TKE cascading.

ACKNOWLEDGEMENTS

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REFERENCES


Table 1: Summary of computational parameters for SST based hybrid model simulations

<table>
<thead>
<tr>
<th>Re (per ft.)</th>
<th>Grid</th>
<th>$C_b$</th>
<th>$\Delta y_{min}$</th>
<th>Grid points</th>
<th>Grid points in $\delta$</th>
<th>Grids within cavity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.6 \times 10^6$</td>
<td>$205 \times 77 \times 60$</td>
<td>0.1</td>
<td>$6 \times 10^{-4}D$</td>
<td>947,100</td>
<td>20</td>
<td>195,000</td>
</tr>
<tr>
<td>$0.6 \times 10^6$</td>
<td>$253 \times 122 \times 80$</td>
<td>0.1, 0.5, 1.0</td>
<td>$6 \times 10^{-4}D$</td>
<td>2,232,800</td>
<td>20</td>
<td>384,880</td>
</tr>
<tr>
<td>$0.6 \times 10^6$</td>
<td>$323 \times 133 \times 100$</td>
<td>0.1</td>
<td>$6 \times 10^{-4}D$</td>
<td>3,852,383</td>
<td>20</td>
<td>1,001,750</td>
</tr>
</tbody>
</table>

Figure 1 Schematic representation of the cavity configuration
**Figure 2** Mach number contour at the cavity mid-span

**Figure 3** SPL spectra at the cavity floor

**Figure 4** Iso-surfaces of axial vorticity component for different $C_b$ : SST model
Near Front bulkhead

Figure 5 Turbulent kinetic energy profiles in the cavity shear layer for different $C_b$ : SST model

$C_b=0.1$

$C_b=0.5$

$C_b=1.0$

URANS

Near rear bulkhead

Figure 6 Eddy viscosity contours for different $C_b$ and URANS : SST model

$C_b=0.1$

$C_b=0.5$

$C_b=1.0$

URANS

Near Front Bulkhead

Figure 7 SPL spectra at the cavity floor for different $C_b$ : SST model

Near Rear Bulkhead

Figure 7 SPL spectra at the cavity floor for different $C_b$ : SST model
Figure 8 TKE spectra within the cavity shear layer for different $C_b$: SST model

Figure 9 Effect of grid resolution on iso-surfaces of axial vorticity: SST model
Figure 10 Grid sensitivity effect on the SPL spectra at the cavity floor: SST model.

Near Front bulkhead

Near rear bulkhead

Figure 11 Grid sensitivity effect on the TKE profiles in the cavity shear layer: SST model.

Near Front bulkhead

Near rear bulkhead