DES Validations of Cavity Acoustics over the Subsonic to Supersonic Range

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The present work follows on from a successful validation study into the use of 3D CFD with advanced turbulence modeling to predict narrowband and broadband flow noise in a rectangular cavity (L/D=5,W/D=1) at M=0.85. In the present study, this body of work is extended in three ways: first, from the transonic case to a range of flow speeds, from subsonic through to supersonic, M=0.6 to 1.35. Secondly, comparison is made between three DES variants; two of which are frequently referenced in the literature, namely Spalart-Allmaras and k-ω-SST, and our own variant based on the standard k-ε model as used in the previous work. Thirdly, we reduce uncertainties due to mesh and discretisation scheme dependence by comparing results from coarse and fine meshes, and blended discretisation schemes. The Mach number sweep predictions are then compared with the M219 cavity measured point spectra along the cavity ceiling, and RMS pressure along its length. The results are in good agreement with the measurements.

Nomenclature

L, D, W = Length, Depth, Width cavity dimensions (inches)
M = Mach Number (dimensionless)

I. Introduction

In the design of cavities in aircraft, consideration should be given regarding the structure and its contents being subjected to aeroacoustic excitation comprising narrowband and broadband contributions. The broadband spectra may have lower energy content than the narrowband (per unit frequency), but from a structural design viewpoint, to minimize possible fatigue damage, it is vital to avoid the possibility of a structural mode coinciding with any flow excitation. As reported in the validation challenge[1], wind tunnel testing has shown the variability of Rossiter mode frequency with aircraft operating parameters such as Mach number. Consequently it is desirable to design aircraft cavity structures to have modal frequencies outside the expected frequency range of any flow excitations.

As discussed in our previous paper[2], unsteady RANS methods are capable of partial success in the modeling the narrowband Rossiter modes, but are currently unable to predict the broadband contribution. However, more advanced turbulence modeling methodologies such as Detached Eddy Simulation (DES) have been shown to successfully predict both. Therefore significant effort is being invested in predictive studies, with a view towards amelioration of the broadband spectra through the development of affordable LES-type methodologies in design analysis.

In this paper, CFD calculations are performed on the M219 cavity at three Mach numbers over the sub- to supersonic range: 0.6, 0.85, and 1.35. These results are then compared with experimental data supplied by QinetiQ[3]. The cavity has a width/depth ratio of unity and a length/depth ratio of 5 exhibiting flow in the ‘open’ mode, so called because the separated shear layer at the cavity front edge does not attach to the cavity ceiling. The cavity configuration assessed is empty with the bay doors removed. This case represents a significant challenge for simulation as shown in our previous study[2], as the first three Rossiter modes are of similar magnitude and are broadband in nature.

The work presented here is a continuation of that undertaken previously[2]. This time we focus special attention on the effects of Mach Number, and we examine the integrity of the modeling parameters chosen previously; i.e., mesh size, spatial discretisation, variants of the DES turbulence model, and different data samples.

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It will be shown that the CFD results are in good agreement with the experiment. Also, that the cavity flow at the subsonic freestream Mach Numbers is so dominated by the broadband noise - corresponding to the LES component of DES - that the choice of model variant is of little significance. Finally, we demonstrate that broadband signal processing is highly dependent on the size of the data sample.

II. Cavity Configuration

Figure 1 illustrates the cavity rectangular plan-form of 20x4in. cut into a flat plate 31in. from the rig’s sharp leading edge and 1in. off-centre from the rig centreline. The inclined sides of the rig are not modeled, but only the flow inside cavity and below the flat plate. Ten equidistant Kulite transducers (K20 closest to the cavity fore wall, consecutively numbered to K29 closest to the aft wall) were located on the cavity ceiling along the rig centreline, equally spaced between 1 and 19 inches from the front of the cavity.

![Figure 1. Experimental rig schematic of the M219 4in. cavity model (dimensions in inches).](image)

III. Computational Model

A. Mesh Structure

Trimmed cell meshing technology was used to produce two grids containing approximately 1,100,000 and 2,800,000 predominantly perfect hexahedral cells, coarser in the freestream with successive 2x2 refinement approaching the separated shear layer and walls. This ensures that all cells are perfectly orthogonal. Figure 2 illustrates the longitudinal and transverse mesh distributions for the coarse mesh.

The computational domain extends 31 inches upstream of the cavity, corresponding to the sharp leading edge of the rig, at which freestream momentum conditions are applied. A freestream pressure boundary is defined 21 inches downstream of the cavity aft wall. Boundaries to the side are placed 4 inches from the cavity side edges, and the bottom boundary 68 inches normal to the rig surface. These settings ensure that the flow inside the cavity is not affected by boundary interference.

The near-wall mesh spacing results typically in $y^+$ values of less than 300 everywhere, except very close to the attachment at the cavity aft wall. We recall that DES requires only RANS-type resolution in the near-wall region.

The fine mesh contains refinements in the shear layer and span-wise resolution, chosen so as to retain cell aspect ratios of unity everywhere within the cavity. This is necessary to ensure that eddy structures are not artificially distorted or preserved due to stretching of the cells mainly in the span-wise direction. The finer mesh distribution is shown in Fig. 3.
B. DES Variants

All variants behave in such a way that the source terms dominate the transport equations for the turbulence variables in regions where the flow becomes detached and the turbulence is in equilibrium.

1. DES based on Spalart-Allmaras

Equating the production and dissipation terms, we recover the same form as a Smagorinsky sub-grid scale viscosity,

\[ v_t = \left( \frac{C_{b1}}{C_{\text{ol}} f_{\omega}} \right) \Delta^2 \, S^{1/2} \]  

(1)

If the length scale \( \Delta \) is reinterpreted as the DES filter length based on a mesh dimension and pre-multiplier, \( C_{\text{DES}/S-A} \Delta \), then \( C_{\text{DES}/S-A} \) takes the value 0.65 according to the usual values for the Smagorinsky constant, \( C_s \), and Spalart-Allmaras coefficients,

\[ C_{\text{DES}/S-A} = \left( \frac{C_s \, C_{\text{ol}} f_{\omega}}{C_{b1}} \right)^{1/3} \]  

(2)

This is confirmed to be the appropriate value by numerical calibration tests.
2. DES based on \( k-\omega \)-SST

Travin\(^6\) describes modifications necessary for Menter’s \( k-\omega \)-SST to behave as an LES sub-grid viscosity model. The length scale comes from,

\[
l_{k-\omega} = \frac{k^2}{\beta \omega}
\]

The DES modified length scale then becomes,

\[
l_{DES/k-\omega} = \min(l_{k-\omega}, C_{DES/k-\omega} \Delta)
\]

where \( C_{DES/k-\omega} \Delta \) is the DES filter length. \( C_{DES/k-\omega} \) takes the value 0.61, and the dissipation term in the \( \omega \)-equation is written as,

\[
D_{DES/k-\omega}^k = \frac{\rho k^3}{l_{DES/k-\omega}}
\]

3. DES based on \( k-\varepsilon \)

Our own DES-variant\(^2\) for \( k-\varepsilon \) follows identically. The length scale comes from \( k \) and \( \varepsilon \) as follows,

\[
l_{k-\varepsilon} = \frac{k^2}{\varepsilon}
\]

The DES modified length scale then becomes,

\[
l_{DES/k-\varepsilon} = \min(l_{k-\varepsilon}, C_{DES/k-\varepsilon} \Delta)
\]

where, \( C_{DES/k-\varepsilon} \Delta \) is the DES filter length and \( C_{DES/k-\varepsilon} \) takes the value 0.73. This means that the dissipation term in the \( k \)-equation is written as,

\[
D_{DES/k-\varepsilon}^k = \frac{\rho k^3}{l_{DES/k-\varepsilon}}
\]

A \( y^+ \)-independent, or ‘hybrid’, near-wall treatment\(^2\) was used in the present work; activated in conjunction with a low-Reynolds number formulation of the associated RANS model to provide appropriate viscous damping away from the near-wall cell.

C. Discretisation

All calculations were performed using STAR-CD\(^4\), which employs the PISO algorithm\(^7\) for transient calculations. A time step advance of \( 2 \times 10^{-5} \) seconds corresponds to mean convection Courant numbers of approximately 2, and local maximum Courant numbers below 10. STAR-CD can be run using second-order upwind (‘monotone advection and reconstruction scheme’, MARS) or centered spatial schemes. The latter is preferred for LES.

Following the suggestion of Travin\(^6\), the solver employs advection scheme blending based on local vorticity and strain, which aims to ensure that the centered scheme is used where the turbulence model is likely to be performing in LES mode, and MARS elsewhere.
To assess the effect of this blending scheme a comparison was made with a calculation running central differencing blended with only 5\% upwinding everywhere. This is a common practice among CFD practitioners when running LES.

**D. Simulation Procedure**

All DES transient calculations commenced from laminar steady-state simulations, run for 1000 iterations. For the datum case, \( M=0.85 \), calculations of 0.5 seconds elapsed time on the coarse mesh (1.1 million cells) take approximately 5.5 days on eight 2.8GHz Intel Pentium 4 XEON processors under Linux. The same elapsed time on the fine mesh (2.8 million cells) took approximately 12 days; with the \( M=0.6 \) case taking slightly less (10.5 days), and the \( M=1.35 \) case slightly more (13.5 days).

If we define the characteristic time to be the time for the freestream to pass between the fore and aft walls, 0.5 seconds corresponds to just over 275 passes for the \( M=0.85 \) case (approximately 200 and 450 for the \( M=0.6 \) and \( M=1.35 \) runs, respectively.)

**IV. Results**

For this configuration the first three Rossiter modes are of a similar magnitude over most of the ten Kulite measurement points. The fourth mode has lower amplitude.

Band-limited RMS pressures reveal the contribution from each Rossiter mode in more detail. Each modal band is calculated by processing the Power Spectral Density (PSD), choosing frequencies that bracket the peak. The resulting \( P_{\text{rms}} \) curves are then observed to have unique shapes identifying the mode (see Table 1);

<table>
<thead>
<tr>
<th>Mode</th>
<th>Mode Shape</th>
<th>( M=0.6 )</th>
<th>( M=0.85 )</th>
<th>( M=1.35 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>skewed ‘V’ shape</td>
<td>50-250 Hz</td>
<td>50-250 Hz</td>
<td>100-350 Hz</td>
</tr>
<tr>
<td>2nd</td>
<td>skewed ‘W’ shape</td>
<td>250-400 Hz</td>
<td>300-500 Hz</td>
<td>350-600 Hz</td>
</tr>
<tr>
<td>3rd</td>
<td>skewed ‘V-W’ shape</td>
<td>400-550 Hz</td>
<td>500-700 Hz</td>
<td>650-850 Hz</td>
</tr>
<tr>
<td>4th</td>
<td>skewed ‘W-W’ shape</td>
<td>550-700 Hz</td>
<td>750-900 Hz</td>
<td>850-1000 Hz</td>
</tr>
</tbody>
</table>

**A. Cavity Cell Aspect Ratio (Mesh) Dependency**

The comparison between the coarse and fine meshes was performed using the benchmark \( M=0.85 \) case.

It is clearly visible from Fig. 4 that refining the mesh around the cavity region yields no significant improvement in the predicted RMS pressure. The band-limited RMS pressure curves in Fig. 4 do indicate very minor improvements in the 2\(^{nd}\) mode and shape of the 4\(^{th}\) modes, but this is countered by an increased over-prediction of the 1\(^{st}\), 3\(^{rd}\) and 4\(^{th}\) mode results.

Therefore, the coarse mesh can be trusted as providing sufficient mesh resolution for these cases. Nevertheless, the \( M=0.6 \) and 1.35 cases reported in Section IV.E were performed on the fine mesh.

![Figure 4. Overall and band-limited \( P_{\text{rms}} \) (kPa) along the cavity ceiling (Mesh Dependency)](image-url)
B. Discretisation
As above, the effects of discretisation scheme were assessed on the benchmark transonic case, $M=0.85$.
Similarly to the mesh refinement result, Fig. 5 shows that there is no significant difference in the level of accuracy of the results from either discretisation method; hence both may be used with confidence. In the figure, ‘blend-on’ refers to the blended advection scheme, and ‘blend-off’ to central differencing with 5% upwinding.

![Figure 5. Overall and band-limited $P_{rms}$ (kPa) along the cavity ceiling (Blending Function)](image)

C. DES Variants
Figure 6 provides a comparison of the three DES variants for the $M=0.85$ from Ref. 8. DES performs consistently, with the four mode shapes captured accurately.
For this application, such a result is clearly desirable, demonstrating that the flow is dominated by large-eddy structures and that the modeling parameters were properly chosen and calibrations correctly performed.

![Figure 6. Overall and band-limited $P_{rms}$ (kPa) along the cavity ceiling (DES Variants)](image)

D. Data Sampling Effects
In Ref. 8 the effect of selecting different time-windows as data samples was tested extensively. It was found that even the experimental data required at least 1.0 seconds of data to get a result that was comparable to the overall 3.4 second sample\(^1\).
Our findings recommended that DES runs should provide data equivalent to an elapsed time of 0.5 seconds, allowing the first 0.1 seconds (during which initial transient start-up effects are washed out of the cavity) to be discarded and the remaining 0.4 seconds to be processed. Shorter samples should be interpreted with care.

E. Mach Sweep
As the freestream Mach Number increases from $M=0.6$ to $M=1.35$ we observe from the experimental data corresponding increases in the levels of acoustic excitation in the cavity, and these are faithfully reproduced in the predictions. The faster flow imparts more energy to the flow structures inside the cavity; hence the increase in the $P_{rms}$ levels seen in Fig. 7. Also clear from this plot is that the nature of the aeroacoustic signature changes with increasing Mach Number: the $M=0.6$ graph, like that at $M=0.85$, is representative of a combination of strong $1^{st}$, $2^{nd}$ and $3^{rd}$ modes, whereas the $M=1.35$ graph has the ‘W’-shape characteristic of second Rossiter mode dominance\(^2\). This will be discussed in greater detail below.
Figure 7. Overall $P_{\text{rms}}$ (kPa) along the cavity ceiling (Experiment)

Figure 8. Overall $P_{\text{rms}}$ (kPa) along the cavity ceiling (CFD)

Figure 9. Overall and band-limited $P_{\text{rms}}$ along the cavity ceiling (M=0.6)

Figure 10. Overall and band-limited $P_{\text{rms}}$ (kPa) along the cavity ceiling (M=0.85)

Figure 11. Overall and band-limited $P_{\text{rms}}$ (kPa) along the cavity ceiling (M=1.35)
Figures 7 and 8 provide a comparison of the overall RMS pressure along the cavity ceiling for the CFD with experiment. The calculations are in good agreement with experimental data, with both the correct increasing trend and the change in the spectral characteristics being predicted.

More quantitative comparisons including mode shapes are shown in Figs. 9-11. The over-predictions that are reported in Ref. 2 for the M=0.85 case are also evident in the M=0.6 prediction. However, the M=1.35 result is more accurately predicted, and the aforementioned 2nd mode dominance is clear; although the levels of the other modes are comparable to those seen in the M=0.85 case.

The Sound Pressure Levels (SPL, dB) for the three cases confirm these findings (see Figs. 12-14). The subsonic, M=0.6, and transonic, M=0.85, cases are comparable in nature, with the first three modes being broadband and similar in magnitude. The overall SPL is over-predicted by about 5dB, but by as much as 10dB in places, whereas the mode frequencies and magnitudes are general well predicted. The supersonic case still contains broadband excitations, but the largest energy content is at around 500Hz in the second mode; thus giving an overall acoustic spectrum faithfully and to a good level of accuracy.

Reducing the over-predictions at the lower Mach numbers will be one focus for future work.

Another point of note is the frequency shift of the main modes as the flow velocity increases. This is to be expected, since the shear layer instability will lead to vortex shedding which correlates with freestream velocity (constant Strouhal Number). At a certain speed, corresponding to shear layer vortex shedding (nominally the second Rossiter mode) at the resonant frequency of the cavity, one would expect a maximization of the magnitude of RMS pressures and noise spectra. This is yet to be demonstrated and will form the focus of future work.

V. Conclusion

We have demonstrated the validity of DES/k-ε based turbulence modeling for the M219 cavity over a range of freestream Mach numbers from sub- to supersonic by predicting the character of cavity RMS pressures and point spectra faithfully and to a good level of accuracy.

Consistently good Rossiter mode shape predictions are observed: only slightly over-predicting RMS pressure and Sound Pressure Levels for the M=0.6 and M=0.85 cases, and with very good agreement in the M=1.35 case. Reducing the over-predictions at the lower Mach numbers will be one focus for future work.

Confidence was gained that the level of mesh resolution used in previous studies was adequate; and the solver proved robust, accurate and performed consistently with different types of second-order discretisation scheme.

For this cavity configuration, we recommend that a minimum of 0.5 seconds should be simulated, allowing for startup effects to be neglected and a full 0.4 seconds of simulation data to be processed.

All DES variants, namely Spalart-Allmaras, k-ε and k-ω-SST, produce broadly similar results that match the measurements well, indicating that the flow is dominated by large eddy structures and that the chosen combination of numerical parameters are appropriate.

References

3Ross J.A., QinetiQ, Bedford, MK41 6AE, UK
7Allen, R. and Mendonça, F., “DES Predictions on the M219 Cavity at M=0.85", Colloquium EUROMECH 449, Chamonix, France, December 9-12, 2003

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Figure 12. Sound pressure level (dB) at M=0.6 (… experiment; ___ prediction)
Figure 13. Sound pressure level (dB) at M=0.85 (… experiment; ___ prediction)
Figure 14. Sound pressure level (dB) at M=1.35 (… experiment; ___ prediction)