EFFECT OF REYNOLDS NUMBER ON THE UNSTEADY FLOW AND ACOUSTIC FIELDS OF SUPERSONIC CAVITY

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ABSTRACT

Numerical simulations are conducted to study the flow and acoustic fields for unsteady supersonic turbulent flow over an open cavity using Detached Eddy Simulations for two different Reynolds numbers. Results are presented for pressure fluctuations history, vorticity iso-surfaces and turbulent kinetic energy and sound pressure levels spectra. The results reveal higher sound pressure levels (SPL), and finer scale structures within the cavity at the higher Reynolds number.

INTRODUCTION

High speed flows over open cavities produce complex unsteady interactions, which are characterized by a severe acoustic environment. Such flow fields are comprised of both broadband small-scale fluctuations typical of turbulent shear layers, and discrete resonance whose frequency and amplitude depend upon the cavity geometry and external flow conditions. Recent research on cavity flow control [1,2,3,4,5] underlines the need for understanding the unsteady flow mechanisms involved in acoustic emissions and their control.

Simulation of cavity flow field is challenging because of the massive separation regions and the complex coupling between turbulence and acoustics through a feedback process that leads to large amplitude; self sustained flow oscillations [1]. Early correlations of cavity acoustic resonance frequency were developed by Rossiter [6] based on the linear acoustic theory. However, the amplitude of pressure oscillations and the SPL is more challenging to predict.

Numerical investigations of flow over open cavities based on time dependent Reynolds Averaged Navier- Stokes (URANS) simulations have been carried out for both two-dimensional [7-10] and three-dimensional [11,12] configurations. In general, these RANS simulations did not capture the cavity acoustic field. This was attributed to excessive turbulent dissipation in the used turbulence models. In addition, some studies reported that some two-equation turbulence models damped the cavity flow-field unsteadiness [13,14].

Direct Numerical Simulations (DNS), which do not recourse to conventional turbulence models have been limited by computational resources requirements to laminar flow over 2-D cavity. Large Eddy Simulations (LES) reduce the grid resolution requirements by resolving the larger, energy containing scales and modeling the smaller, more homogeneous scales. Sinha et al. [13,17] developed a hybrid LES/RANS code and to perform 2-D cavity flow simulations and compared the VLES results with the URANS results. Rizzetta et al.[18] performed LES to study L/D = 5 cavity flow control on a parallel computing platform of IBM SP3 with 254 processors. The simulations which were conducted at Re = 0.12x10^5/ft required perturbation of the incoming flow variables to produce transition, and sufficiently long runs to generate statistically meaningful data for the LES simulations at the upstream boundary.

Detached Eddy Simulations (DES) were initiated by Spalart et al. [19], who proposed that a single turbulence model can be used to function as a sub-grid scale model in the LES regions and as turbulence model in the RANS regions [20]. Hence, DES combined the fine-tuned RANS technology in the attached boundary layers and the power of LES in the separated region to enable three-dimensional unsteady Navier-Stokes simulations at high Reynolds number with realistic computational resources. Strelets [21] and Bush et al. [22] developed a Mentor’s SST [23] based DES model through the introduction of an equivalent length scale, and implemented it into the WIND code [24]. Hamed et al. [14] used the SST based DES to investigate 3-D unsteady flow and acoustic fields in supersonic cavity.

Our previous DNS investigations [16] demonstrated a dramatic increase in the pressure oscillations amplitude and the associated sound pressure level with free stream Mach number. However these DNS simulations were limited to laminar 2-D cavity. Subsequent DES investigations [14] revealed both broadband as well as tonal frequencies in the computed SPL spectra. In the present paper, the unsteady supersonic 3D cavity flow is investigated using SST [23] based DES model to
determine the effects of Reynolds number on the flow and acoustic fields.

**RESULTS AND DISCUSSIONS**

The DES simulations were performed for the L/D = 5 and W/D = 0.5 cavity at free stream Mach number of 1.19 and Reynolds numbers of 0.12×10^6/ft and 0.60×10^6/ft.

Computational results are presented for the pressure fluctuations, sound pressure levels and turbulent kinetic energy spectra, Mach number contours and vorticity iso-surfaces. Figure 1 presents sample pressure fluctuations histories near the front and rear bulkheads at the cavity mid-span. One can see that, in general, the pressure fluctuations are chaotic and the amplitude is higher at the rear bulkhead. The SPL spectra were computed from the pressure fluctuations based on 2048 sample data points. Figure 2 compares the computed sound pressure level (SPL) spectra variation along the cavity opening mid-span for the two Reynolds numbers. One can see that the SPL spectra have a broadband content with a wide range of frequency scales and that the SPL level increases towards the rear bulkhead. According to figure 2, the maximum SPL increased from 145 dB to 160 dB with the increase in Reynolds number from 0.12×10^6/ft to 0.60×10^6/ft.

Figure 3 shows sample turbulent kinetic energy (TKE) spectra in the shear layer near the cavity’s rear bulkhead. One can see that the spectra have a broadband content over a wide range of frequency. The classical −5/3 Kolmogorov slope is shown in the figure for reference.

Sample results for the axial vorticity iso-surfaces at Re=0.60×10^6/ft are presented in figure 4. This figure demonstrates eddies’ formation within the cavity since the axial vorticity is zero in the incoming flow upstream of the cavity. The span-wise vorticity iso-surfaces are compared for the two Reynolds numbers in figure 5. They show the roll up of the shed vortex and the impingement of the shear layer on the rear bulkhead. Figure 5 shows a tangible deeper range of fine scale structures within the cavity at the high Reynolds number and a reduction in the size of the shed vortex.

Figure 6 presents Mach number carpet plots at mid-span for the two Reynolds numbers. The figures show that an oblique shock is formed upstream of the cavity with a subsequent increase in the incoming boundary layer thickness due to shock interactions. One can see that the thickening of the boundary layer and the subsequent deflection of the shear layer is greater at the low Reynolds number. In addition to the different eddy structures inside the cavity, figure 5 shows that the Reynolds number also affects the shock and expansion waves pattern and strength outside the cavity.

**CONCLUSIONS**

Detached Eddy Simulations (DES) were performed to study the unsteady three-dimensional flow and acoustic fields of an open L/D = 5 cavity at free-stream Mach number of 1.19 for two different Reynolds numbers. The presented results reveal the basic flow features, including the vortex shedding, shock waves, the small scale eddy formation within the cavity and the three-dimensional flow characteristics. The results showed an increase in the range of predicted fine scale structures and an increase in the predicted SPL with the increase in Reynolds number.

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REFERENCES


24) http://www.grc.nasa.gov/www/wind
Table 1: Summary of computational parameters for numerical simulations

<table>
<thead>
<tr>
<th>Reynolds Number</th>
<th>Grid</th>
<th>Δy minimum</th>
<th>Grid Points</th>
<th>Grids within BL (δ)</th>
<th>Grid points within cavity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.12×10⁶/ft</td>
<td>205×94×40</td>
<td>1×10⁻³D</td>
<td>770,800</td>
<td>15</td>
<td>184,040</td>
</tr>
<tr>
<td>0.60×10⁶/ft</td>
<td>253×112×80</td>
<td>6×10⁻³D</td>
<td>2,266,800</td>
<td>20</td>
<td>396,800</td>
</tr>
</tbody>
</table>

Figure 1 Pressure fluctuation history (Re = 0.60 × 10⁶/ft)

Figure 2 Sound Pressure Level spectra
Figure 3 Turbulent kinetic energy spectra in the cavity shear layer (Re=0.60 × 10^6 /ft)

Figure 4 Iso-surfaces of axial vorticity component (Re=0.60 × 10^6 /ft)
Figure 5 Iso-surfaces of span-wise vorticity

Figure 6 Mach number contours at cavity mid-span