Numerical Simulations of Fluidic Control for Transonic Cavity Flows

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Abstract
A numerical study is conducted to investigate fluidic control for transonic flow over an open cavity. Numerical results are obtained for the unsteady three-dimensional flow with different steady mass injection rates upstream of the cavity. The simulations use a hybrid two-equation turbulence model in the Detached Eddy Simulations (DES) to calculate the flow and acoustic fields. Computational results are presented for RMS pressure load, SPL and kinetic energy spectra. Vorticity, Mach number, and kinetic energy contours are shown at different injection ratios. The computed sound pressure level (SPL) spectra without injection is compared with available experimental data.

Nomenclature
L Cavity Length
D Cavity Depth
W Cavity Width
SPL Sound pressure level
TKE Turbulent Kinetic Energy
RMS Root Mean Square
dB Decibel
Re Free stream Reynolds number
X Distance along cavity floor

Introduction
Several investigations have been carried out to understand the complex flow physics associated with acoustic suppression in cavities. Passive suppression techniques like fences\(^1\) and spoilers\(^2,3\) had achieved limited success under certain operating conditions. An experimental investigation by Stanek et al.\(^4\) investigated rod/spoiler and rods modified with circular end-caps, and linked high frequency rod shedding to acoustic suppression. Active control techniques have been considered for effective noise reduction tools over a wide range of operating conditions. These techniques include oscillating flaps\(^5\), upstream mass injection\(^6\) and harmonic/pulsed blowing\(^7,8\), piezoelectric actuators\(^9,10\) and powered resonance tubes\(^11\). Shaw and Northcraft\(^8\) investigated the effect of steady mass injection upstream of the cavity, and suggested that at subsonic Mach numbers SPL decreases with an increased mass blowing rate. Stanek et al.\(^12\) conducted a thorough experimental study in subsonic and supersonic cavity flow fields using four high-frequency fluid dynamic actuators (piezo-ceramic wedge, rod in cross-flow, passive resonance tube, and powered resonance tube) and a low frequency actuator (saw-toothed spoiler). They observed that the highest level of suppression was achieved using the high-frequency powered resonance tube, and illustrated the difference between suppression mechanisms in high and low frequency forcing. In a subsequent study Stanek et al.\(^13\) compared the effect of steady and pulsed mass actuation and observed that a substantial amount of suppression can be attributed to the steady injection. They introduced the notion of superposition of steady effect and high frequency effect and proposed that high frequency forcing has stabilized the flow rather than draining energy out of the large scales as proposed by Glezer et al.\(^14\) Ukeiley et al.\(^15\) investigated a powered whistle in supersonic flow and steady mass blowing of nitrogen helium and hot air in subsonic flow. The helium injection proved to be more effective in the decimation of the Rossiter modes. For the subsonic case, steady blowing altered the resonant behavior of the cavity and resulted in a lower pressure load in the rear bulkhead. Zhuang et al.\(^16\) conducted experiments in supersonic cavity flow control using supersonic microjets at the leading

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edge, and reported a 10dB reduction in the overall SPL and 20 dB reductions at tonal frequencies.

Fewer numerical studies have been conducted for cavity flow control. Cain et al. 17,18 performed 2D URANS simulations of harmonic mass injection in subsonic cavity flows and concluded that the mean mass flow plays a more important role than the frequency of actuation for noise suppression. Rizzetta et al.19 performed large eddy simulations (LES) of high frequency mass pulsing in supersonic cavity flows and studied the resulting suppression. Arunajatesan et al.20,21 performed 2D RANS and 3D hybrid RANS/LES simulations of subsonic flow over cavity using a thin rod for suppression. They showed that the 2D simulations exhibit a wake mode behavior not observed in the experiment, and presented auto and cross-correlation functions, two-point correlation tensors and turbulent and kinetic energy budgets from the 3D simulations to explain the control mechanism. Several studies have reported computational results for cavity flow without actuation based on DNS 22, DES 23,24 and URANS 25. The DNS results indicated a noticeable increase in pressure fluctuation amplitude with Mach number while the DES simulations 23,24 indicated that the sound pressure level increases with the flow Reynolds number.

Numerical simulations can be used to gain an understanding of the mechanism involved in acoustic suppression provided that the fidelity of the numerical prediction is established for the unsteady flow behavior. CPU and computational grid requirements have restricted DNS and LES simulations to lower Reynolds numbers than those employed by practical applications and hence precluded their use as a tool to conduct parametric studies of different control devices. On the other hand, the URANS results indicate that their predictions are strongly influenced by the turbulence models. The two-equation models could not predict unsteady flow because they were highly dissipative, while the predictions with algebraic turbulence models exhibited a multimodal behavior. In the current investigation, detached eddy simulations (DES) were used to study the effect of steady mass injection on supersonic cavity flows. The hybrid method has been demonstrated to provide the required dynamic range resolution with computational resources comparable to URANS 23,24. The computational results at different mass injection ratios are compared to gain an understanding of the suppression mechanism involved.

### Methodology

Numerical solutions were obtained for the three-dimensional unsteady compressible Navier-Stokes equations using the WIND 26,27 code. A hybrid-based SST Menter’s two-equation model was used in the detached eddy simulations. A third-order upwind Roe scheme was used for spatial discretization with a TVD operator to suppress the numerical instabilities in the shear layer and near the shock waves. An explicit time marching scheme with Newton-like sub iterations was used for temporal advancement.

The solution domain 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 9D above the cavity opening. First order extrapolation was also applied at the downstream boundary, 3.5D behind the rear bulkhead. The cavity width, W, was equal to 0.5D and periodic boundary conditions were applied in the span-wise direction. The computational grid of 298 x 117 x 80 points in the stream-wise, normal and span-wise directions, respectively, is shown in Figure 2. The grid was clustered at the wall with y’ < 1.5 for the first grid. In order to maintain the incoming boundary layer thickness δ at 10% of the cavity depth D, the upstream plate length was 4.5D for a Reynolds number of 0.60 x 10^6/ft. The grid was clustered upstream of the cavity with 35 grid points in the injection region (4.2D and 4.35D). Total mass flow rate was specified through the injection slot. The solution domain was decomposed into twelve non-overlapping zones upstream, across and downstream of the cavity across the span-wise direction. Parallel computations for the twelve zones were performed with a Linux cluster using exclusive message passing with (PVM) libraries. The simulations were initiated in the unsteady mode from an established solution without injection and continued over 100,000 constant time-steps of 4.2345 x 10^-7 seconds to obtain sufficient data for statistical analysis.

### Results and Discussions

Computational results are presented for a L/D=5 and W/D=0.5 cavity at a Reynolds number of 0.60 x 10^6/ft and a free stream transonic Mach number of 1.19 with different injecting mass flows upstream. The computed SPL spectra are compared to the available experimental results of Ross et al.28. The Reynolds number in the experiment was 4.336 x 10^6/ft, but the simulations were performed at one-seventh this value to optimize the use of available computational resources while maintaining a fully turbulent
Table 1. Simulated injection mass flow rates

<table>
<thead>
<tr>
<th>Mach Number</th>
<th>Reynolds Number (per feet)</th>
<th>Injection ratio ($\frac{\dot{m}<em>{injection}}{\dot{m}</em>{boundary \ layer}}$)</th>
<th>Actual mass injection rate (lbm/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.19</td>
<td>0.60x10^6</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>1.19</td>
<td>0.60x10^6</td>
<td>0.6</td>
<td>0.017646</td>
</tr>
<tr>
<td>1.19</td>
<td>0.60x10^6</td>
<td>0.9</td>
<td>0.02647</td>
</tr>
</tbody>
</table>

boundary layer at the cavity lip. Simulated injection mass flow rates are as listed in Table 1. Results are presented for RMS pressure load in Figure 5, SPL spectra in Figure 6, TKE spectra in Figure 7 and TKE profiles in Figures 8 and 9.

The computed SPL spectra for the baseline case with no injection are presented and compared with experimental data in Figures 3 and 4 at two different locations along the cavity floor. The simulations predict dominant modes at approximately 500 and 1000 Hz, which is in agreement with experimental observations. However, a lower frequency peak at 250Hz is not captured in the numerical simulations. One can see that the dominant frequency matches the experimental data at approximately 500 Hz. The peak SPL is however under-predicted by 5dB compared to experimental. Rizzetta et al.21 predicted a dominant mode at approximately 420 Hz in an identical cavity configuration from LES at Re=0.12x10^6/ft.

Figure 5 shows the RMS pressure load across the cavity floor for different mass injections. RMS pressure is indicative of the time averaged dynamic load variation and overall sound pressure levels (OASPL) and hence provides a gross estimate of the acoustic control. An ‘s-shaped’ load distribution is predicted without injection, where the load gradually decreases in the first half of the cavity and then steadily increases in the second half. On the other hand, the controlled cavity results predict a slightly different trend with a small bump in the middle of the cavity floor, indicating a change in the vortex shedding pattern. It can be seen that RMS pressure load decreases by 7.5% for the injection ratio of 0.6 and 10% for the injection ratio of 0.9.

Figure 6 present computed SPL spectra at the cavity mid-plane near the rear bulkhead (X/L=0.95) for injection ratios 0.0, 0.6 and 0.9. It can be observed that injection shifts the dominant frequency of 500 Hz to a higher value of 1050 Hz. A reduction of 8 dB reduction in peak amplitudes is predicted for injection ratio=0.6, while a 12 dB reduction is predicted for injection ratio=0.9. Rizzetta et al.21 predicted a shift of the dominant mode from 420 Hz to approximately 650 Hz with pulsed injection and a 15 dB reduction in the amplitude from LES simulations. The experimentally measured narrow band spectra of Ukeiley et al.17 showed reduction of both broad band and tonal frequencies with steady and pulsed injections for subsonic and supersonic cavities. The results of Figure 5 support the contention that steady mass injection is responsible for a considerable amount of peak SPL reduction.

Figure 7 presents the computed turbulent kinetic energy (TKE) spectra at the middle of the cavity opening within the shear layer. An overall reduction in TKE amplitude with injection can be observed. Rizzetta et al.21 reported similar changes in the TKE spectra with pulsed injection from LES calculations. The computed results for the TKE profiles, presented in Figures 8 and 9, also confirm the reduction of turbulent kinetic energy with injection. Rizzetta et al.21 predicted a reduction in TKE downstream with mass actuation after an initial increase near the injection region.

Mach number contours are presented for the three injection mass ratios in Figure 10, which shows the formation of a shock upstream of the cavity. One can see that with increased injection the shock becomes stronger and moves further upstream. Zhuang et al.16 observed experimentally similar shock movement in the case of supersonic cavities with microjets. Rizzetta et al.21 reported similar behavior with pulsed injection from LES simulations.

Vorticity contours for the baseline and controlled cases are illustrated in Figure 11, which indicate that the hybrid turbulence model captured fine scales within the cavity and shear layer. One can see a considerable reduction in the resolved scale within the cavity using upstream mass injection. This suggests that injection is responsible for decreasing the production of the fine scales. Arunajatesan et al.21 predicted similar behavior in case of supersonic cavity with rod in cross flow.
Figure 12 presents the computed autocorrelation coefficient at different axial locations along the cavity floor for the three injection ratios. The coefficient is maximum at $t=0$ and gradually decreases with time. It can be seen that the coefficient exhibits a periodic behavior and the number of cycles increases with injection. This indicates that the scales within the flow field undergo faster variation and are consistent with the shift to a higher dominant frequency with injection as shown in Figure 6. The relative dispersion of the correlation coefficient with zero injection may be attributed to the small-scale coherent structures. The regular periodic distribution of the injection cases can be associated with the decimation of the small structures as shown in Figure 11.

**Conclusions**

Computational results are presented from the 3D detached eddy simulations for supersonic cavity flow with steady mass injection. The presented results indicate that DES could be successfully used as a computational tool to analyze flow control techniques with resources comparable to URANS. The predictions indicate a 7.5–10% reduction in RMS pressure load across the cavity floor and 8–12 dB reduction in SPL at the peak frequency using a 6–9% injection mass ratio. The computed turbulent kinetic energy spectra revealed an overall reduction in amplitude. The TKE profiles indicate that the energy level decreases downstream of injection. The vorticity contours indicate that injection is responsible for the reduction of fine scales inside the cavity.

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**References**


Figure 1. Schematic of the cavity and injection slot

Figure 2. Computational domain
Figure 3. Sound pressure level spectra at X/L = 0.1

Figure 4. Sound pressure level spectra at X/L = 0.95

Figure 5. Comparison of dynamic pressure load for baseline and controlled cases.
Figure 6. SPL Spectra

Figure 7. TKE Spectra

Figure 8. TKE Profile at X/L=0.4

Figure 9. TKE Profile at X/L=0.8
Figure 10. Mach number contours

Figure 11. Vorticity Contours

Figure 12. Auto correlation of pressure traces