Assessment of Flow Control Devices for Transonic Cavity Flows using DES and LES

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Abstract. Since the implementation of internal carriage of stores on military aircraft, transonic flows in cavities were put forward as a model problem for validation of CFD methods before design studies of weapon bays can be undertaken. Depending on the free-stream Mach number and the cavity dimensions, the flow inside the cavity can become very unsteady. Below a critical length-to-depth ratio (L/D), the flow has enough energy to span across the cavity opening and a shear layer develops. When the shear layer impacts the downstream cavity corner, acoustical disturbances are generated and propagated upstream, which in turn causes further instabilities at the cavity front and a feedback loop is maintained. The acoustic environment in the cavity is so harsh in these circumstances that the noise level at the cavity rear has been found to approach 170 dB and frequencies near 1 kHz are created. The effect of this unsteady environment on the structural integrity of the contents of the cavity (e.g. stores, avionics, etc) can be serious. Above the critical L/D ratio, the shear layer no longer has enough energy to span across the cavity and dips into it. Although this does not produce as high noise levels and frequencies as shorter cavities, the differential pressure along the cavity produces large pitching moments making store release difficult. Computational fluid dynamics analysis of cavity flows, based on the Reynolds-Averaged Navier-Stokes equations was only able to capture some of the flow physics present. On the other hand, results obtained with Large-Eddy Simulation or Detached-Eddy Simulation methods fared much better and for the cases computed, quantitative and qualitative agreement with experimental data has been obtained.

Key words: transonic cavity flow, LES, DES, flow control.

1. Introduction

Numerous experimental investigations have been performed on cavity flows in an attempt to better understand the problem. Most cavity experiments were originally based on unsteady pressure measurements in wind tunnels. Ross *et al.* from QinetiQ [1, 2] and Tracy *et al.* from NASA Langley [3] are two examples of researchers who have conducted a significant number of wind tunnel experiments on cavities of several configurations over a broad range of Mach and Reynolds numbers. Ross and Peto [4] also provided experimental data on cavity acoustical suppression methods including leading-edge spoilers and vortex-shedding rods amongst others. Recent experimental endeavours have exploited non-intrusive, optical techniques such as Schlieren Photography [5] and Optical Reflectometry [6] to study cavity flows. More advanced non-intrusive methods such as Particle Image Velocimetry (PIV) [7] and

Laser Doppler Velocimetry (LDV) [8] are also beginning to appear in cavity flow studies as a means of obtaining high-fidelity, high-resolution data for the instantaneous flow-field and the velocity variations inside the cavity. Such methods are, however, expensive and are either restricted to low Reynolds number flows.
Recent studies of cavity flows have therefore attempted to use Computational Fluid Dynamics (CFD) as an analysis tool, with most emphasis on the use of Reynolds-Averaged Navier-Stokes (RANS) equations in conjunction with various turbulence closures. Most applications of Unsteady RANS (URANS) to cavity flows have employed algebraic turbulence models, especially different versions of the Baldwin-Lomax models, due to their simplicity[9, 10, 11]. However, such simple eddy viscosity models were realised to be generally incapable of accurately predicting the turbulent cavity flow-field[12], and investigations with more advanced turbulence models such as the two-equation $k-\varepsilon$ and $k-\omega$ models were made. Most references to cavity flow modelling with two-equation models were related to supersonic flow conditions [13, 14] while applications of two-equation models to transonic cavity flows are rare. A detailed survey of published works on cavity flow can be found in [15].
One of the major drawbacks of URANS is the difficulty in predicting the full spectrum of turbulent scales. In high Reynolds flows, for instance, a broad range of turbulent length and time scales persist. For the cavity, this intense turbulent environment is further coupled with strong acoustic radiation, the source of which is located at the downstream corner of the cavity. The acoustical signature in the cavity is composed of broadband noise (lower-frequency, lower-energy noise contributed by the free-stream and/or the shear layer) with the narrow-band noise (a combination of higher-frequency and lower-frequency noise of different magnitude contributed by vortex-vortex, vortex-wall, vortex-shear layer, shock-shear layer and shear layer-wall interactions) superimposed on it. The narrow-band spectrum comprises of discrete acoustic tones called Rossiter modes after J. E. Rossiter who developed a semi-empirical formula to calculate them[16]. Statistical turbulence models tend to predict well the larger scales associated with the lower-frequency discrete acoustic tones but fail to provide the same accuracy in capturing the smaller, higher-frequency and more intermittent time scales. The broadband noise is not captured by these models either. The presence of these multiple acoustic tones and of a large number of turbulent scales may mean that achieving a good level of accuracy and consistency with turbulence models is difficult for cavity flows. Previous computations with a cavity L/D ratio of 5, for example, showed that the results were sensitive to the grid used. In an attempt to reduce the grid sensitivity and obtain a grid-converged solution, grids finer than those employed in previous studies[15] were used. In addition, cavities of different dimensions were investigated to determine the range of applicability of the URANS method. This was accomplished by performing parametric studies in time and space on 2D cavities of different sizes, e.g. L/D=2, L/D=10 and L/D=16.

Ever since the problems associated with cavity flows were realised (such as high acoustics and buffetting) many experiments and computations were conducted with the aim of improving the cavity environment. Some control methods involved manipulating the cavity geometry by either modifying the angle at which the cavity walls are slanted, for instance, or by adding an external device to deliberately alter the flow inside the cavity (see Figure 1). Such control techniques are referred to here as open-loop control because no feedback loop is implemented in the control method. Consequently these open-loop control methods are most effective at one particular stage in the aircraft's flight profile. Rossiter[16] and more recently Ross[2], for example, have performed extensive wind tunnel experiments on the effectiveness of spoilers as open-loop flow control devices. The non-versatility of such open-loop control devices over a larger proportion of the flight regime diverted attention to closed-loop control methods, which continually adapt to the flight conditions making them more suitable for time-varying and off-design situations. Although open-loop control studies have dominated most control efforts in cavity flows, examples of closed-loop cavity control studies are also beginning to appear in literature. For more information on the cavity flow control, the reader is directed toward an excellent review by Cattafesta *et al.* in Ref. [17], which provides an elaborate account of different open-loop and closed-loop control strategies adopted by different researchers.

2. Outline of the Experiments by Ross et al.

Experimental pressure measurements were obtained using the Aircraft Research Association Ltd (ARA) wind tunnel at Bedford, UK (see Ref. [2]). The ARA wind tunnel is a 9 by 8 foot continuous flow, transonic wind tunnel (TWT) with ventilated roof, floor and side walls. 3D clean cavities were first studied with or without doors (see Figure 1). The doors prevented any leakage at the cavity edges in the span-wise direction forcing the flow to channel into the cavity. In this configuration, the flow behaves as if it were two-dimensional and is assumed to be well represented by modelling the cavity as 2D. Several flow control devices were subsequently added to the cavity as shown in Figure 1.

The L/D=5 cavity model (with width-to-depth ratio (W/D) of 1) measured 20 inches in length and 4 inches in width and depth. The generic cavity rig model was positioned at zero incidence and sideslip and the wind tunnel was operated at a Mach number of 0.85 and atmospheric pressure and temperature. Unsteady pressure measurements were registered inside and outside the cavity via Kulite pressure transducers: 10 pressure transducers were located inside the cavity aligned along the cavity rig center, 2 on the flat plate ahead of the cavity (see Figure 1), 1 on the flat plate aft of the cavity, 2 on the front and rear walls and 4 on the port side walls[2, 18]. The data was sampled at 6 kHz using a high-speed digital data acquisition system. The measured data was presented in terms of Sound Pressure Level (SPL) and Power Spectral Density (PSD) plots. The SPL is an indication of the intensity of noise generated inside the cavity and can be obtained from the measurements using the following equation:

$$\mathrm{SPL}\,(\mathrm{dB}) = 20\log_{10}\left(p_{rms}/2\times 10^{-5}\right) \tag{1}$$

where p_{rms} is the RMS pressure normalised by the International Standard for the minimum audible sound of 2×10^{-5} Pa with the RMS pressure denoted by:

$$p_{rms} = \sqrt{(\sum p - p_{mean})^2/N} \tag{2}$$

Spectral analysis was performed using Fast Fourier Transform (FFT) to obtain the power spectral density, which presents the RMS pressure versus frequency and provides a measure of the frequency content inside the cavity. Indicative results of the SPL along the floor of the L/D=5 cavity are shown in Figure 2 where the relative effectiveness of the flow control devices is compared.

3. Results and Discussion

Several sets of results have been obtained for this work. Starting from URANS calculations, CFD grids of approximately 4 million cells were used. Figure 3 presents an overview of such a grid. Care has been taken to maintain uniform cells near the cavity region and grid dependency has been checked [19]. The LES results required finer grids with further requirements for orthogonality and aspect ratio, so grids with more than 6 million cells were employed. For the cases where flow control devices were present, the region near the front of the cavity had to be refined so that spoilers can be embedded in the grid. The details of the employed CFD solver as well as the employed turbulence models are given in [20]. For all cases computed the Mach number at the free-stream ahead of the cavity was kept at 0.85. The Reynolds number based on the length of the cavity was 1 million, and the LES solutions were forced with noise at the free-stream which corresponded to 1% of turbulence intensity. The $k-\omega$ and Spalart-Almaras turbulence models were employed along with their Detached-Eddy Simulation (DES) versions. For LES the classic Smagorinsky sub-grid scale model was employed. Table 1 summarises the obtained URANS results and gives an overall assessment of these in comparison to the experimental data. As can be seen, the employed URANS method (based on the Spalart-Almaras and the $k-\omega$ models) did not capture the changes induced by the flow control devices in the overall flow topology and the reduction in noise. Inspection of the experimental data suggests that although the overall level of pressure fluctuations is lower for the cases where flow control devices are deployed, the distribution of acoustic energy in the various frequency-bands around each Rossiter mode is not significantly affected. For this reason further LES and DES results were obtained for cavities with the control devices deployed. Indicative results of these URANS computations are shown in Figure 4 where the obtained RMS pressure at a station close to the downstream corner of the cavity is compared with the experimental data. It is evident that URANS based on the $k-\omega$ model was not able to capture even the magnitude of the pressure fluctuations measured in the wind tunnel.

3.1. LES for cavities without flow control devices

The first set of results were obtained for clean cavities with and without doors and these are compared against experimental data and Rossiter's theory in Figures 5 and 6. Given the complexity of the flow and the demanding conditions, fair agreement has been obtained with experiments, at least for the magnitude of the mean pressure and the pressure fluctuations for the lowest Rossiter frequencies. The results shown here suggest that the current LES is perhaps a good compromise for the analysis of these complex flows since it maintains good predictions for a range of cases (doors/no-doors) and compares well (at least in magnitude) with experimental data. For the cases shown in this paper, DES results were also obtained based on the

Spalart-Almaras model but these are not shown here due to space. In contrast to the URANS results, the LES/DES results show substantial unsteadiness in the flow around the cavity and the instantaneous results have enough frequency content. This encouraging result suggests that for the flow controlled cases LES and DES could also be used. Further computations on finer and coarser grids revealed much less dependency of the obtained results on grid size which was not the case with the employed URANS models.

3.2. Cavities with flow control devices

Out of all controlled cases computed, results are shown here for the cavity with a slanted downstream wall. For this test case, Table 1 indicates that stations close to the leading edge of the cavity were well-predicted by URANS. This, however, was not the case for downstream stations. Figure 4 compares the URANS predictions with experiments and as can be seen, substantial discrepancies are encountered. The overall characteristics of the URANS solution indicate that the shear layer formed just after the leading edge of the cavity remains coherent until it reached the downstream wall. This flow topology is in contrast to experimental observations and resulted in a less noisy cavity in comparison to measurements. The striking difference between LES (or DES) results and URANS for this case was the instantaneous flow-field predicted by LES and DES was not coherent downstream the middle of the cavity, and this resulted in a much more energetic flow-field with higher levels of noise. Figure 7 shows exactly this effect by comparing the RMS pressure and the pressure spectra with experiments. Although discrepancies still exist, the level of RMS pressure is much better predicted and most of the tones measured during experiments were also present in the CFD solutions (at least for the lower Rossiter frequencies). An instantaneous flow-field from our LES computations for the clean cavity case is shown in Figure 8(a) while Figure 8(b) presents results for the case where a downstream slanted wall was employed. Similar results have been obtained for the control devices shown in Figure 1, however, these are not presented here.

4. Conclusions

In this paper, results have been presented from URANS, LES and DES computations for transonic cavity flows. For clean (without control) cavity flow cases, LES and, to some extend, DES computations were in good agreement with experiments providing a reliable (though expensive in terms of computing time) method for the analysis of such complex turbulent flows. Having established confidence on the obtained results for clean cavities, several cases have been investigated where changes in the cavity geometry were introduced in an attempt to control the flow and reduce the level of noise radiated from the cavity. As was the case for clean cavities, URANS results (obtained using the Spalart-Almaras and the $k-\omega$ models) were in poor agreement with experiments and failed to predict essential pars of the cavity flow physics. LES based on wall-functions and the Smagorinsky sub-grid scale model, as well as DES results (using the Spalart-Almaras model) captured much better the energetic and unsteady flow field of the cavity and compared better with experimental data. The current set of computations generated significant amounts of data, which after further analysis could be used to better identify possible modifications to the employed URANS and DES approaches that could lead to better computing efficiencies. Further work is currently underway to obtain results using finer grids and different sub-grid models for LES so that confidence can be established in the adopted method.

Acknowledgements

The financial support of the Engineering and Physical Sciences Research Council through grant EP/C533380/1 is gratefully acknowledged. The authors would like to extend their gratitude to John Ross and Graham Foster of QinetiQ (Bedford) and Trevor Birch of DSTL for providing the experimental data.

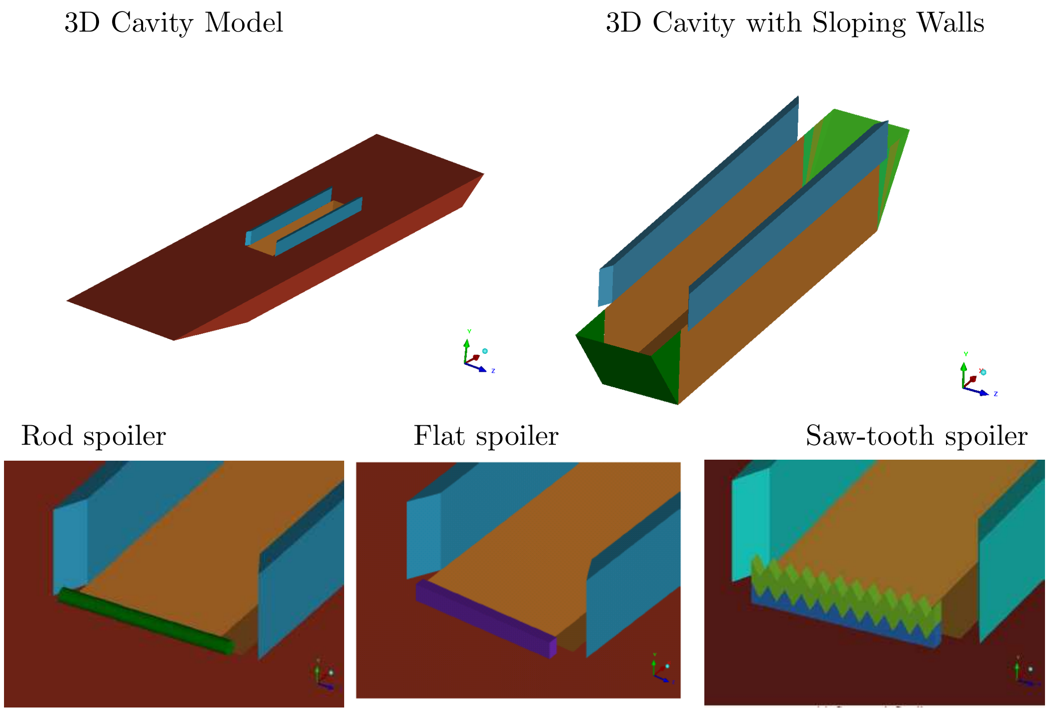


Figure 1. Flow control devices used in combination with the clean cavity.

Location	Control Device	Numerical Data	Experimental Data (Doors On)	Resonable Prediction?
X/L = 0.05	No Device	±6000	±4000	Yes
	Spoiler	±500	±2000	No
	Rear Sloping Wall	±2000	±1000	Yes
X/L = 0.55	No Device	±10000	±6000	Yes
	Spoiler	±500	±2000	No
	Rear Sloping Wall	±4000	±1500	No
X/L = 0.95	No Device	±15000	±10000	No
	Spoiler	±500	±4000	No
	Rear Sloping Wall	±5000	±2000	No

Table 1. Summary of the obtained URANS results and comparison with the experimental findings.

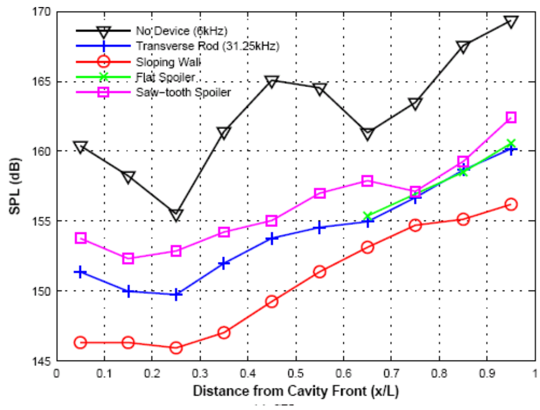


Figure 2. SPL computed using the experimental data by Ross [4] for the cavity configurations shown in Figure 1.

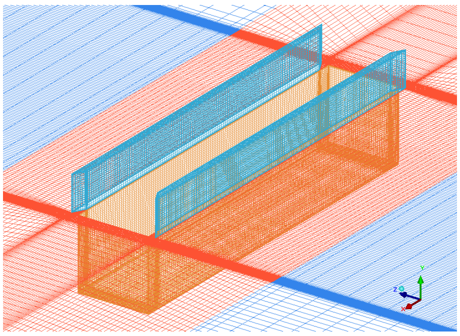


Figure 3. 3D view of the employed CFD grid for LES calculations. Almost uniform grid was applied within the cavity and around the walls, however, cell skewness had to be tolerated further away from the cavity.

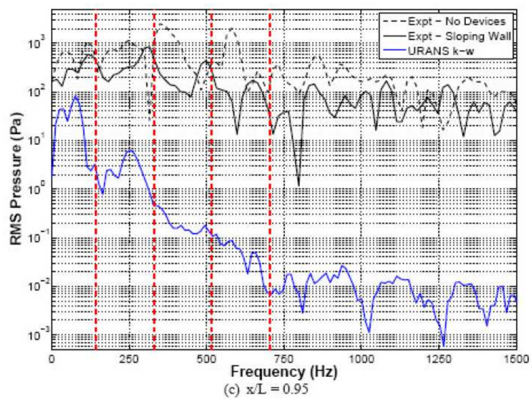


Figure 4. URANS results using the $k-\omega$ turbulence model for the case where slanted walls have been deployed at the front and back of the cavity.

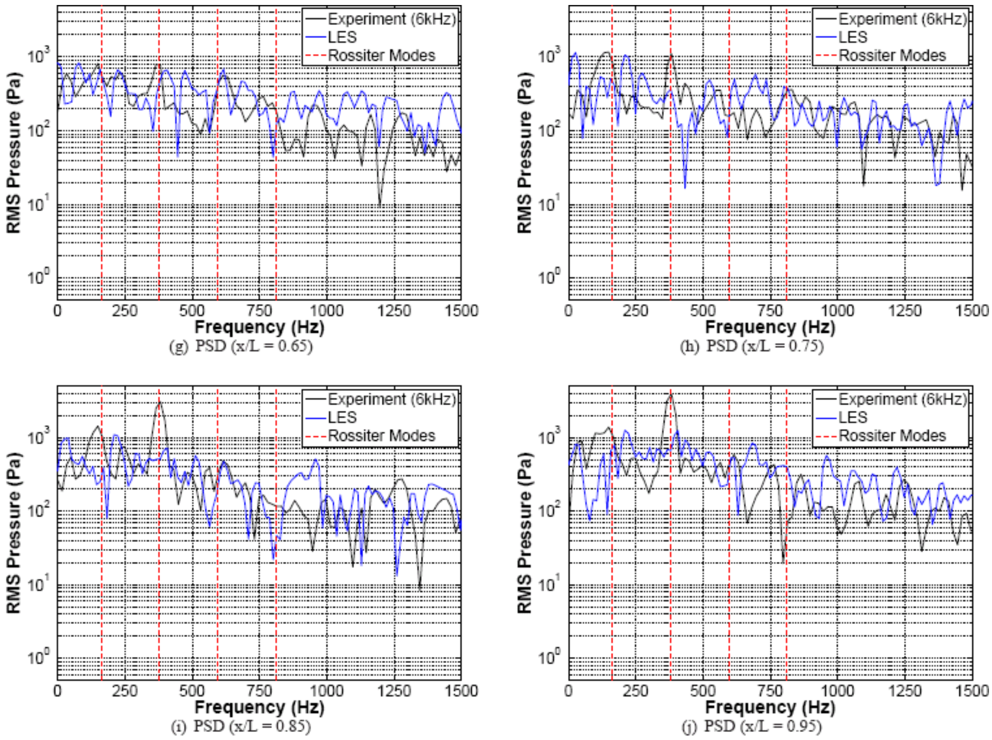


Figure 5. LES results for the clean cavity case (no doors): RMS pressure at four different stations (g,h,i and j) along the cavity floor.

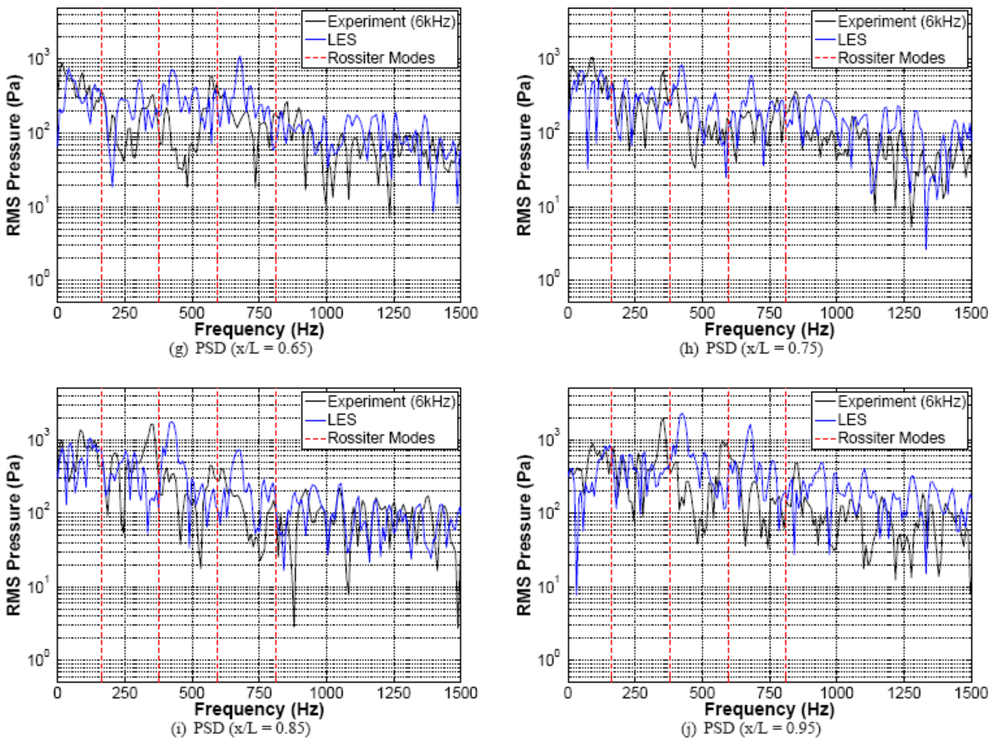


Figure 6. LES results for the clean cavity case (with doors): RMS pressure at four different stations (g,h,i and j) along the cavity floor.

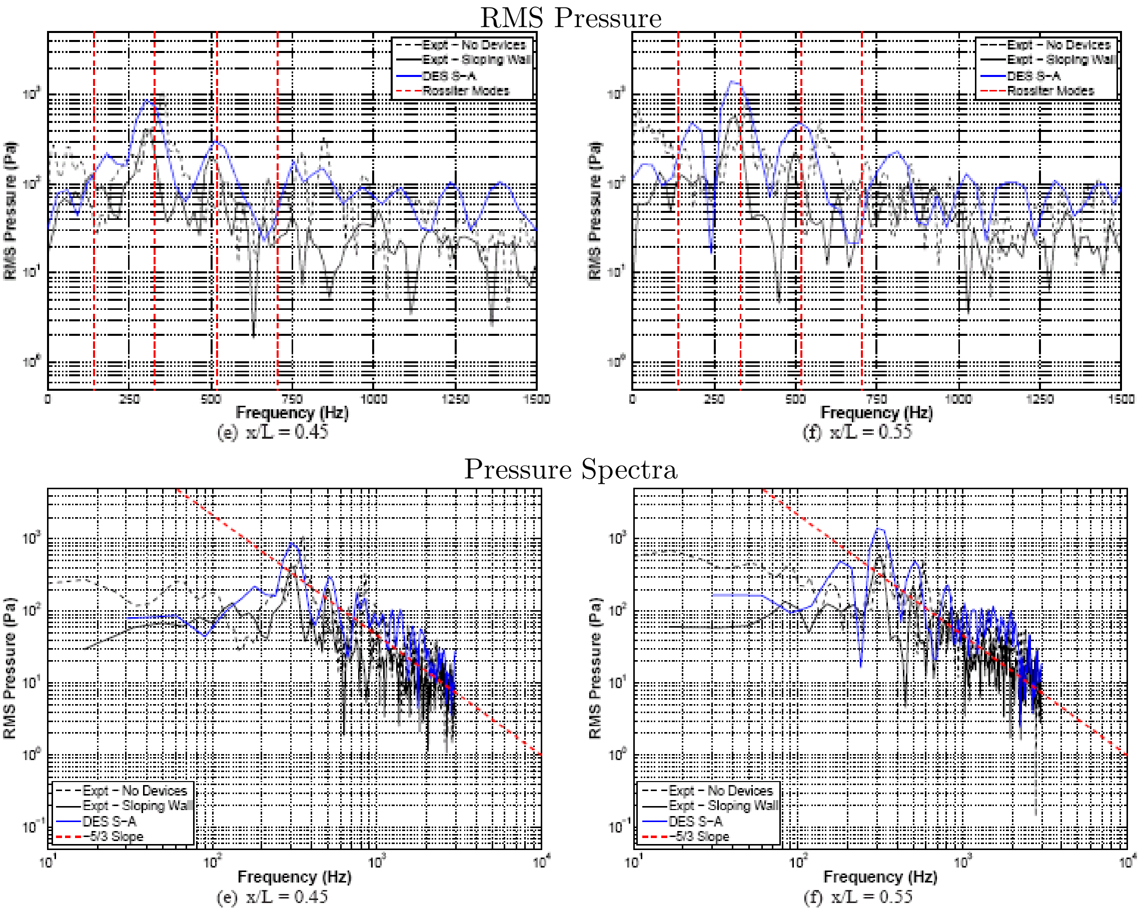
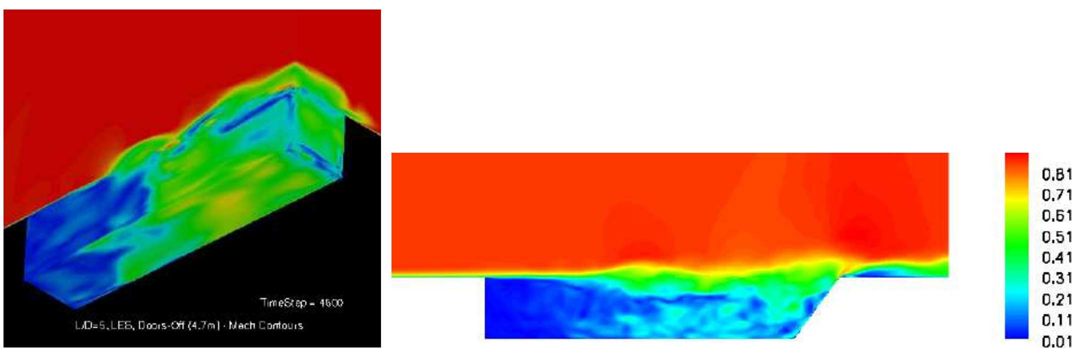


Figure 7. RMS pressure at two different stations (e and f) along the cavity floor for the case where a slanted downstream wall was used as a flow control device.



(a) Clean cavity (no doors)

(b) Slanted downstream wall (no doors)

Figure 8. Comparison between instantaneous Mach number fields for (a) the clean cavity and (b) the controlled cavity (slanted downstream wall).

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