Numerical and Experimental Analysis of Transonic Cavity Flows

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Abstract
Comparisons between numerical and experimental results for a clean, open rectangular cavity with a length-to-depth ratio of 5 and a width-to-depth ratio of 1 in doors-on and doors-off configurations are presented. The flow conditions correspond to a Mach number of 0.85 and a Reynolds number of 6.783 million based on the cavity length. CFD results using Unsteady Reynolds-Averaged Navier-Stokes, Large-Eddy Simulation and Detached-Eddy Simulation methods are compared with experimental unsteady pressure and Particle Image Velocimetry measurements. Experiments were used to determine which turbulence simulation option would be best applicable for cavity flows. Results demonstrated that both Detached-Eddy and Large-Eddy Simulations fare much better than URANS in resolving the higher frequencies and velocity distributions inside the cavity.

Keywords: Cavity Flows, LES, DES, CFD, turbulence modelling

1 Introduction

Modern high performance aircraft carry stores placed inside cavities embedded in the aircraft’s fuselage. This implies that for store release the aircraft will have to fly with the cavities exposed to the free-stream of air. During this phase, an unsteady, highly energetic flow field develops inside the cavity causing structural, acoustic and aerodynamic problems. Recent designs, however, are to operate at extreme conditions and have additional requirements for quieter operation and more lightweight structures. For this reason, aerospace engineers are now revisiting the cavity flow problem attempting to develop better understanding of this complex flow and improve their design methodologies.

Investigations into the flow physics of cavities were conducted initially by Rossiter[1], among others, in the 1960s at the Royal Aircraft Establishment. He performed numerous wind tunnel experiments and developed a semi-empirical formula to predict the frequencies produced in the cavity. Further advances in the experimental front in the recent years, has seen the application of less intrusive and more accurate high-resolution methods such as Particle Image Velocimetry (PIV)[2] to cavity flows. Such modern experimental methods are however either expensive or not readily available. Combined with rising wind tunnel costs, efforts in the last decade have therefore been made toward using Computational Fluid Dynamics (CFD) as an analysis tool for cavity flows. The bulk of the numerical analysis on cavity flows in the late 1980s and 1990s concentrated on the numerical analysis of cavity flows using the Reynolds-Averaged Navier-Stokes (RANS) equations. This requires the use of turbulence models to resolve the mean flow and turbulence properties. A significant proportion of these analyses have employed simple algebraic turbulence models[3], typically for supersonic flows.
Based on the difficulties associated with the turbulence modelling of cavity flows, some current research has looked at the simulation of cavity flows via methods such as Large-Eddy Simulation (LES)[4]. LES works by filtering the flow structures in terms of scale size, with the larger scales explicitly resolved and the much smaller ones modelled using a sub-grid scale (SGS) model. With a significantly lower proportion of the flow modelled compared to Unsteady Reynolds-Averaged Navier-Stokes (URANS) methods, LES solutions are potentially more useful. For high Reynolds number flows, however, LES is expensive. Recent endeavours have therefore looked at developing hybrids of URANS and LES to obtain the best of both methods. One example of such developments includes Detached-Eddy Simulation (DES) introduced by Spalart[5].

This paper compares numerical and experimental results for a clean, open rectangular cavity with a length-to-depth ratio (L/D) of 5 and a width-to-depth ratio (W/D) of 1. The flow conditions correspond to a Mach number of 0.85 and a Reynolds number of 6.783 million based on the cavity length. Experimental data in the form of pressure measurements along the cavity floor (depicted in Figure 1) and PIV measurements performed by Ross et al. of DERA[6] were available. Numerical data was obtained using the Parallel Multi-Block (PMB) code developed at the University of Glasgow. Comparisons between the experimental and numerical measurements are made for both doors-on and doors-off cases. The set-up for the numerical simulations was based on experiments. For instance, the size of the computational domain and the corresponding time-step used for numerical simulations was based on the frequencies to be resolved, information about which was provided from experiments. In addition, the experiments also played a key role in determining which turbulence simulation option would be best applicable for cavity flows.

Experimental Set-Up

Unsteady Pressure Measurements

Wind tunnel experiments conducted by Ross[6] at Aircraft Research Association Ltd (ARA), Bedford, UK, were used for validation. The ARA wind tunnel is a 9 by 8 foot continuous flow, transonic wind tunnel (TWT) with ventilated roof, floor and side walls. Where 2D cavity results are mentioned, the comparison is made against the 3D clean cavity experimental case, where the bay doors were open vertically at 90°. The doors prevented any leakage at the cavity edges in the spanwise direction forcing the flow to channel into the cavity. In this configuration, the flow is expected to behave as if it was 2D and is well represented by numerical modelling/simulation of a 2D cavity.

The L/D=5 cavity model (with W/D=1) measured 20 inches in length, and 4 inches in width and depth. In the doors-on configuration, the doors were positioned at the front and rear walls in the z-direction and spanned the entire length of the cavity (see Figure 3(a)) and measured 0.375 inches width and 2 inches in height. The generic cavity rig model (designated as Model M219) 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 at the cavity floor via 10 Kulite pressure transducers (as shown in Figure 1).

PIV Measurements

Measurements of the cavity flow-field were provided by PIV experiments conducted by Ross. A stereoscopic two-camera system was employed for velocity measurements accompanied with a two-head Nd-YaG laser. Each laser pulse was fired within time intervals of 1µs. Four data acquisitions were taken with each acquisition comprising of two photographic images taken at 1µs intervals. The width of the laser sheet was limited to approximately 5.5 inches so the total cavity length of 20 inches was captured in four sections using a motorised camera/laser traverse (Figure 3(b)). Seeding was provided by various combinations of water droplets sprayed in the settling chamber and vegetable oil mist diffusion from small holes in the cavity floor. Analysis of the data signals was performed by phase-locking onto each peak of signal and introducing a series of delays to synchronise image acquisitions at a particular part of the cycle. A number of acquisitions were then taken and averaged to define the flow-field at that part of the cycle. For highly unsteady flows with multiple cyclic components, it was recognised that phase-
locking on any one component does not ‘freeze’ the flow-field. As highlighted by Ross*, combined with the highly turbulent background, all aspects of a cavity flow are not likely to be accounted for. For a complete definition of the flow-field with time-dependency, very high-speed image acquisition equipment would be required.

**Numerical Set-Up**

The CFD grids used in this work are described in Table 1. All dimensions in these grids were scaled with respect to the cavity length. The set-up for the numerical simulations was designed to approximate the configuration tested in the wind tunnel. The computational domain, for instance, was designed to be similar to the experimental wind tunnel set-up. Flat plates were specified on either side of the cavity and their corresponding lengths were set to the same values as in experiment (Figure 3). A flat plate 1.5 times the cavity length was therefore used ahead of the cavity to allow the oncoming boundary layer to develop naturally. The resulting boundary layer thickness at the cavity lip from numerical calculations was found to be similar to the experimental value of 0.42 inches (0.021L) so no special treatment was applied in the modelling of near-wall properties for LES computations. For the DES and LES grids, the far-field length was set to 3.5 times the cavity length so as to minimise any spurious results from acoustic wave reflections.

The time-step used for numerical simulations was estimated using the frequencies expected to be resolved, information about which was provided from experiments. The highest frequencies approached 1 kHz so based on Nyquist’s sampling criterion, a sampling frequency of 2 kHz was used. The non-dimensionalised time-step was then calculated by

$$t^* = \frac{t U_\infty}{L}$$

(1)

where $t$ is the real time and is equivalent to the reciprocal of the sampling frequency, $f$, $U_\infty$ is the free-stream velocity and $L$ the reference cavity length. The minimum time-step required to capture frequencies of 1 kHz was thus found to be about 0.27. From past experience, this was however found to be too coarse and time-steps of at least an order of magnitude lower were required. Although the experiments used a minimum sampling rate of 6 kHz, it was found that numerical simulations required a sampling rate approximately an order of magnitude higher to achieve the same accuracy.

**Data Analysis**

The experimental pressure measurements were then post-processed and presented in terms of Sound Pressure Levels (SPLs) and Power Spectral Density (PSD). The SPLs are an indication of the intensity of noise generated inside the cavity and can be obtained from the measurements using the equation

$$\text{SPL (dB)} = 20 \log_{10} \left( \frac{p_{\text{rms}}}{2 \times 10^{-5}} \right)$$

(2)

where the $p_{\text{rms}}$ is the RMS pressure and is defined by

$$p_{\text{rms}} = \sqrt{\frac{\sum_{i=1}^{N} (p_i - p_{\text{mean}})^2}{N}}$$

(3)

with $N$ denoting the number of samples, $p_i$ denoting the instantaneous pressure at every measurement and $p_{\text{mean}}$ representing the mean pressure, which is given by

$$p_{\text{mean}} = \frac{\sum_{i=1}^{N} p_i}{N}.$$ 

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*Private Communication
In Equation 2, the RMS pressure is normalised by the International Standard for the minimum audible sound of $2 \times 10^{-5}$ Pa. Spectral analysis was performed using Fast Fourier Transform (FFT) to obtain the Power Spectral Density (PSD), which presents the RMS pressure versus frequency and provides a measure of the frequency content inside the cavity. To compute the FFT of the data signal, the Welch’s method was employed where the Hanning function is used as the apodization function, which is already integrated in the MATLAB software package.

**Post-Processing**

When comparing the numerical results with experiments, it was ensured that the numerical data was post-processed in the same manner as the experimental data. This required two steps to be undertaken. First, the numerical data was sampled at the same rate as experiments. For the doors-on configuration, the numerical data was sampled at 31.25 kHz and compared with the 6 kHz and 31.25 kHz sampled experimental data that were available. Comparisons of the two experimental signals also illustrated the differences between the two datasets and highlighted the importance of high resolution experimental data. For the doors-off case, numerical data was sampled at 6 kHz and compared with the corresponding experimental results.

The second step involved using the same signal duration for both numerical and experimental datasets. All CFD computations were run to an approximate real-time of 0.1 or 0.2 seconds while experiments were run for 3s. If the entire signal was compared with the numerical data, differences between the results would be significant. This is because longer experiment signal lengths increase the number of samples, denoted by $N$ in Equation 3, proportionally and therefore reduce the RMS pressure values. The frequency magnitudes are therefore much lower and because of the larger number of samples, the resolution, for the longer duration signal, is much sharper with thin sidelobes at the main acoustic tone locations. SPLs are calculated using logarithms so effects of experiment signal duration are less evident.

In addition to this, the first 0.02s of the numerical signal was truncated in order to discard the initial transient. Based on the reasoning provided above, the first 0.02s was also discarded for proper comparisons.

**2 Mathematical Model**

**2.1 CFD Solver**

All computations were performed using the Parallel Multi-Block (PMB) flow solver[7] of the University of Glasgow, which has been continually revised and updated over a number of years. The solver has been successfully applied to a variety of problems including cavity flows, hypersonic film cooling, spiked bodies, flutter and delta wing flows amongst others.

The code solves the unsteady Reynolds Averaged Navier-Stokes equations on multi-block structured grids, in serial or parallel mode. Governing equations are discretised using a cell-centred finite volume method. The convective terms are discretised using either Osher’s or Roe’s scheme. MUSCL interpolation is used to provide nominally third order accuracy and the Van Albada limiter is used to avoid spurious oscillations across shocks. The time-marching of the solution is based on an implicit, dual time-stepping method. The final algebraic system of equations is solved using a Conjugate Gradient method, in conjunction with Block Incomplete Lower-Upper factorisation. A number of turbulence models including one and two-equation statistical models as well as Large-Eddy Simulation (LES) and Detached Simulation (DES) formulations have been implemented into the code[8]. At the moment, the standard Smagorinsky Sub-Grid Scale (SGS) model is used for LES whereas DES with both the one-equation Spalart-Allmaras and the two-equation $k-\omega$ and SST turbulence models have been integrated.
2.2 DES Formulation

Spalart[5] modified the one-equation Spalart-Allmaras model to achieve a DES equivalent. The only modification is in the dissipation term of the transport equation of \( \tilde{\nu} \), given as

\[
-C_{w1} f_w \left( \frac{\tilde{\nu}}{\tilde{d}} \right)^2 .
\]

(5)

Originally,

\[
\tilde{d} = d = \text{distance of the nearest wall}
\]

(6)

whereas for DES, it is

\[
\tilde{d} = C_{DES} \Delta
\]

(7)

where \( C_{DES} \) is the DES coefficient and \( \Delta \) is the metric of the grid size.

In practice, the following is employed

\[
\tilde{d} = \min (d, C_{DES} \Delta), \quad \Delta = \max (\Delta_x, \Delta_y, \Delta_z) \quad \forall \text{ cell},
\]

(8)

although other metric relations are also possible.

3 Results & Discussion

3.1 Doors-off Results

Results from the clean, doors-off cavity for the URANS, DES and LES methods are depicted in Figures 4 to 5, with unsteady pressure comparisons with experiment revealing best agreement with DES and LES (Figure 4(a)). URANS results were based on the coarse grid with Menter’s Baseline \( k - \omega \) model[9]. A time-step of 0.01 \((\equiv 1.814 \times 10^{-5} \text{s})\) was used for this computation—details of the grid are provided in Table 1. The fine grid was used for the DES computation with a time-step of 0.001 \((\equiv 1.814 \times 10^{-6} \text{s})\) and the very fine grid for the LES computation with the same time-step. This corresponded to a numerical sampling rate of about 550 kHz. As mentioned previously, the experimental signal was sampled at 6 kHz so the numerical results were sampled at the same rate for proper comparison.

The shape of the SPL curve for Menter’s Baseline \( k - \omega \) model was found to resemble a ‘W’ shape, which is characteristic of the doors-on case and will be discussed in greater detail in the following section (Figure 6(a)). Without doors, the flow inside and outside of the cavity is less constrained to move in the spanwise direction. The fact that Menter’s Baseline \( k - \omega \) model predicts a completely incorrect SPL shape (unlike LES and DES) suggested that it had difficulty in accommodating effects of the greater transport and redistribution of energy and momentum in the spanwise direction. The difference in frequencies without the doors is clearly represented by the spectral analysis in Figure 4(b). The 3rd Rossiter mode \((\approx 600 \text{ Hz})\) is more dominant for the doors-off cavity case compared to the 2nd mode \((\approx 380 \text{ Hz})\) for the doors-on case. Although Menter’s Baseline \( k - \omega \) model predicts the 3rd mode relatively well, it fails to account for either the lower or higher frequencies. This is however not surprising since URANS can only account for the most energetic coherent structures in a flow. The 3rd Rossiter mode is the dominant frequency in the doors-off cavity configuration and thus URANS captures this well. It however fails to account for any of the lower or higher frequencies.

Instantaneous Mach contours for both Menter’s Baseline \( k - \omega \) model and DES (with the one-equation Spalart-Allmaras model) along the cavity centreline are illustrated in Figure 5. The Mach number plots distinctly demarcate the lower-velocity regions (blue) inside the cavity from the transonic regions (yellow) outside the cavity. Where these two regions coalesce is where the shear layer is located. Menter’s Baseline \( k - \omega \) model always predicts a larger single primary vortex structure at the cavity rear with some combination of two or more counter-rotating vortices at the cavity front. The shear layer is also consistently found to span the cavity with distinct deflection at the cavity rear (Figure 5). It is this dual-vortex cycle inside the cavity that results in the ‘W’-shaped
SPL curve in Figure 4(a). The difference between the DES and URANS flow-field results lies in the behaviour of the shear layer and this is evident in Figure 5. At no point for the DES computations does the shear layer extend across the entire length of the cavity. At the most, the shear layer can be observed to be coherent up to the middle of the cavity at which point, if not earlier, it breaks down. What follows is intensive mixing and spreading of the energy from the shear layer and the free-stream with the lower-velocity flow region inside the cavity. The pressure at the cavity rear rises due to this mixing process and is manifested in the form of a rising SPL curve (Figure 4(a)).

3.2 Doors-on Results

Figure 6 shows the difference between the DES, LES and URANS methods in the prediction of noise levels and frequencies for the clean, doors-on cavity configuration. The coarse grid was used with Menter’s Baseline $k - \omega$ model for URANS computations with a time-step of 0.01 ($\equiv 1.814 \times 10^{-5}$s), the fine grid for the DES computation with a time-step of 0.001 ($\equiv 1.814 \times 10^{-6}$s) and the medium grid for the LES computation with a time-step of 0.005 ($\equiv 9.07 \times 10^{-6}$s). Results for the 2D cavity (with the SST model) were also included, as the 2D cavity was found to be a reasonable representation of the full 3D cavity with doors-on. Due to the success of the DES with the one-equation Spalart-Allmaras turbulence model for the doors-off case, it was decided to run a fine grid computation using DES rather than using very fine grids with LES. Both the 6 kHz and 31.25 kHz experimental signals are included in Figure 6 to emphasise the importance of high resolution experimental data. All numerical results were sampled at 31.25 kHz.

Menter’s Baseline $k - \omega$ turbulence model was used for URANS while the one-equation Spalart-Allmaras model was used with DES to realise the turbulent near-wall properties. Variations in SPLs across the cavity length along its floor is illustrated in Figure 6(a). All three methods agreed reasonably well with experiment, with URANS agreeing even better with experiment in some cases. Near the front of the cavity, for instance, the shape of the SPL curve for Menter’s Baseline $k - \omega$ model follows the experiment better than the DES and LES counterparts.

A closer inspection of the frequency content at the cavity rear ($x/L=0.95$) illustrated a less satisfactory agreement between Menter’s Baseline $k - \omega$ model and experiment (Figure 6(b)). Neither the 1st ($\approx 160$ Hz) nor the 3rd ($\approx 600$ Hz) Rossiter modes were captured. The 2nd Rossiter mode ($\approx 400$ Hz) was well captured but is over-predicted by about 1 kPa. This over-prediction was found to be a common occurrence for most URANS comparisons with experiment.

3.3 PIV Comparisons

The PIV experiment by Ross et al. [6] was conducted for the 3D cavity in the doors-on configuration only. Streamwise and transverse velocity profiles for three different stations inside the cavity ($x/L=0.05$, $x/L=0.55$ and $x/L=0.95$ - see Figure 1 for the positions of these pressure taps) for both DES and LES computations are illustrated in Figure 7. The black line denotes the PIV results. The three other plots included in the velocity profile plot correspond to the time-averaged 2D cavity results for the SST model (solid green line), DES results with the one-equation Spalart-Allmaras model (dashed red line) and LES results with the standard Smagorinsky sub-grid scale model (dashed-dot blue line) for the coarse grid (refer to Table 1 for information on the grids used) at a time-step of 0.01 ($\equiv 1.814 \times 10^{-5}$s). The results were encouragingly consistent for both DES variants and LES.

Agreement with PIV was, however, sensitive to the station analysed. At the first two stations, at $x/L=0.05$ (cavity front) and at $x/L=0.55$ (cavity middle), the agreement between DES, LES and PIV was good. At the cavity rear ($x/L=0.95$), agreement with PIV deteriorated. The explanation for this may lie in the manner in which the PIV experiment was conducted. As mentioned previously, the laser used for the PIV experiment had a width of approximately 5.5 inches, which was roughly equivalent to a quarter of the cavity length. The laser was fired at four different sections in order to cover the entire length of the cavity (Figure 3(b)). The resolution of the PIV experiment was found to be good at the first two stations that the computational results were analysed at, i.e. at $x/L=0.05$ and $x/L=0.55$, but was not at the third station, i.e. at $x/L=0.95$. This is illustrated in Figure 8, which indicates the variations in the streamwise and transverse velocity components along the length of the cavity for the PIV experiment at a distance equal to the depth of the cavity above the cavity lip. In sections 1 and 3 of the PIV
experiment, which are where the first two stations x/L=0.05 and x/L=0.55 respectively lie, the laser resolution is good and the streamwise velocity is close to its anticipated value of 296 m/s (Figure 8(a)). In section 4, however, which is where the third station x/L=0.95 lies, the resolution deteriorates and the streamwise fluctuations are significantly larger. A consistent story is told by the transverse streamwise plots in Figure 8(b). This possibly explains the discrepancies between the LES, DES and PIV data at the cavity rear. The fact that the resolution of the PIV experiment was equally poor near the walls further emphasises the problems with using PIV for highly unsteady flows at high Mach and Reynolds numbers. As mentioned by Ross, higher imaging and data acquisition equipment is likely to be required for consistently good resolution throughout the cavity cross-section.

4 Conclusions

CFD results for weapon bays modelled by a 3D cavity with L/D=5 and W/D=1 have been presented. All computations were conducted at a free-stream Mach of 0.85 and at Reynolds number of 6.783 million using the PMB code developed by University of Glasgow. Analysis of clean weapon bays was first presented and CFD results from URANS, LES and DES were compared.

Comparison of unsteady pressure predictions with measurements revealed that both DES and LES consistently gave better agreement than URANS in terms of frequency content, phase and noise levels for doors-on and doors-off configurations. URANS, however, had difficulties in capturing most of the higher (and in some cases, some of the lower) frequencies in both configurations. Flow-field visualisation for the doors-off cavity with Menter’s Baseline $k-\omega$ model and DES revealed that only DES predicted a breakdown of the shear layer. It was concluded that URANS had difficulties in accounting for the larger transport and diffusion of energy and momentum present in the doors-off case. For the doors-on case, URANS appeared to give good predictions of the noise levels but closer inspection revealed that only the dominant Rossiter mode (∼ 380 Hz) was well predicted and frequencies lower and higher than this mode were not. Streamwise and transverse velocity plots compared for the doors-on case with PIV measurements showed consistently good agreement at the cavity front and middle for different DES variants and LES. At the cavity rear, the agreement with PIV deteriorated and these discrepancies may be attributed to poor resolution in the PIV experiment at this position.

Analysis between the experiments and numerical results in this manner identified that LES and DES were more suited to predicting the flow-field in the L/D=5 cavity than URANS.

5 Acknowledgements

The work detailed in this paper was supported by both BAE SYSTEMS and the Engineering and Physical Sciences Research Council (EPSRC). The authors would like to extend their gratitude to Dr’s. John Ross and Graham Foster of QinetiQ (Bedford) for providing the experimental data.

References


<table>
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<th>Grid Type</th>
<th>Pts. in Cavity (Overall)</th>
<th>Wall-Spacing (Overall)</th>
<th>Blocks in cavity (Overall)</th>
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Table 1: Details of CFD grids used for both the clean cavity in the doors-off and the doors-on at 90° configurations.

![Figure 1](image.png)

Figure 1: Schematic describing cavity geometry and notation used. The ten pressure taps denoted by black dots correspond to the experimental pressure locations and represent where the SPL and PSD data was calculated and compared, i.e. at z/W=0.25 and along the cavity floor (y/D=1).
Figure 2: Schematic of the wind tunnel cavity geometry (including the doors-on configuration) on the left and an illustration of the 4 different sections along cavity for which laser data acquisitions were taken with the PIV experiment on the right.

Figure 3: Views of the grids used for numerical simulations.
Figure 4: SPL and PSD plots (at \(x/L = 0.95\)) for the 3D, \(L/D=5\), \(W/D=1\), clean cavity with doors-off using the coarse grid for: URANS (with Menter’s Baseline \(k-\omega\) model), fine DES grid (with Spalart-Allmaras model) and very fine LES grid (with standard Smagorinsky SGS). Plots taken at \(z/W=0.25\) and along the cavity floor (\(y/D=1\)).
Figure 5: Instantaneous Mach contours with streamlines for the 3D L/D=5, W/D=1 clean cavity with doors-off at 4 time-steps of flow cycle for: coarse URANS (Menter’s Baseline $k - \omega$ turbulence model) and fine DES (one-equation Spalart-Allmaras turbulence model) computations. Plots taken along the cavity centreline ($z/W = 0.5$).
Figure 6: SPL and PSD plots (at $x/L = 0.95$) for the L/D=5, W/D=1, clean cavity with doors-on at 90° vertically for: 2D coarse URANS (with Menter’s SST turbulence model); 3D URANS (with Menter’s Baseline $k-\omega$ model); fine DES (Spalart-Allmaras model); medium LES (Smagorinsky SGS). Plots taken at $z/W=0.25$ (for 3D results) and along the cavity floor ($y/D=1$).
Figure 7: Time-averaged streamwise ($u_\infty$) and transverse ($v_\infty$) velocity profiles for the clean cavity with doors-on at 3 locations along cavity floor at $x/L=0.05$, $x/L=0.55$ and $x/L=0.95$. Results from coarse grid with time-step of 0.01 ($\equiv 1.814 \times 10^{-5}$s) used for 2D URANS, fine grid with time-step of 0.01 ($\equiv 1.814 \times 10^{-6}$s) used for DES-SA and medium grid with time-step of 0.005 ($\equiv 9.07 \times 10^{-6}$s) for LES. PIV data denoted by black line.
Figure 8: Streamwise and transverse velocity traces at a distance equal to the depth of the cavity above the cavity lip.