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Numerical Analysis of the Cavity Flow subjected to Passive Controls Techniques

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Abstract. Open-source flow solvers are getting more and more popular for the analysis of challenging flow problems in aeronautical and mechanical engineering applications. They are offered under the GNU General Public License and can be run, examined, shared and modified according to user's requirements. SU^2 and OpenFOAM are the two most popular open-source solvers in Computational Fluid Dynamics (CFD) community. In the present study, some passive control methods on the high-speed cavity flows are numerically simulated using these open-source flow solvers along with one commercial flow solver called ANSYS/Fluent. The results are compared with the available experimental data. The solver SU^2 are seen to predict satisfactory the mean streamline velocity but not turbulent kinetic energy and overall averaged sound pressure level (OASPL). Whereas OpenFOAM predicts all these parameters nearly as the same levels of ANSYS/Fluent.

1. Introduction

Cavity flows are encountered frequently in aeronautical and mechanical engineering applications. Studies related to high-speed cavity flows date back to 1960s with the pioneering experimental study [1] by which the pressure oscillation modes were analysed. Later on, at subsonic and transonic regimes the cavity flows were classified as open, transitional and close in [2]. The flow is immediately separated from the leading edge of the cavity similar to the flow behaviour of backward facing step. Open cavity flow is maintained when the high shear emerged after the separation meets the trailing edge following a hypothetical straight line. Transitional flow occurs when the flow penetrates the cavity but it is not attached on the cavity floor. As for the closed cavity flow, the flow attaches the cavity floor but separates again to reach the leading edge of the cavity. The control of the cavity flow is utmost important to decrease the cavity noise. One of the most cited study on the passive control of the cavity flow is known by the M219 case [3]. Here the Mach number is kept constant at 0.85 for a cavity of L/D ratio of 5 and W/D ratio of 1. Five passive control cases are available: M219 cavity slanted wall (M219-SW), M219 transverse rod (M219-TR), M219 1δ flat-top spoiler (M219-FTS) where δ is the boundary layer height, M219 2δ saw-tooth spoiler Type 1(M219-STS1) and Type 2 (M219-STS2). A schematic illustration of the clean cavity and the adopted passive control models are given in Figure 3 and 4, respectively.

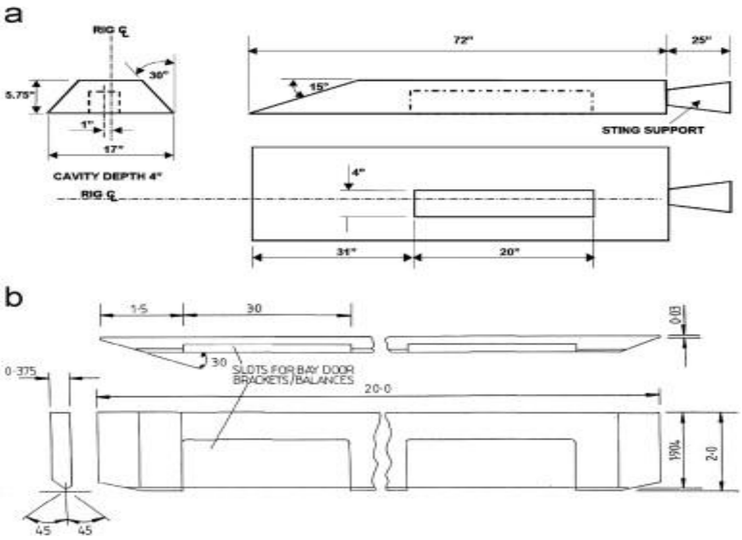


Figure 1. M219 experimental cavity geometry [3]

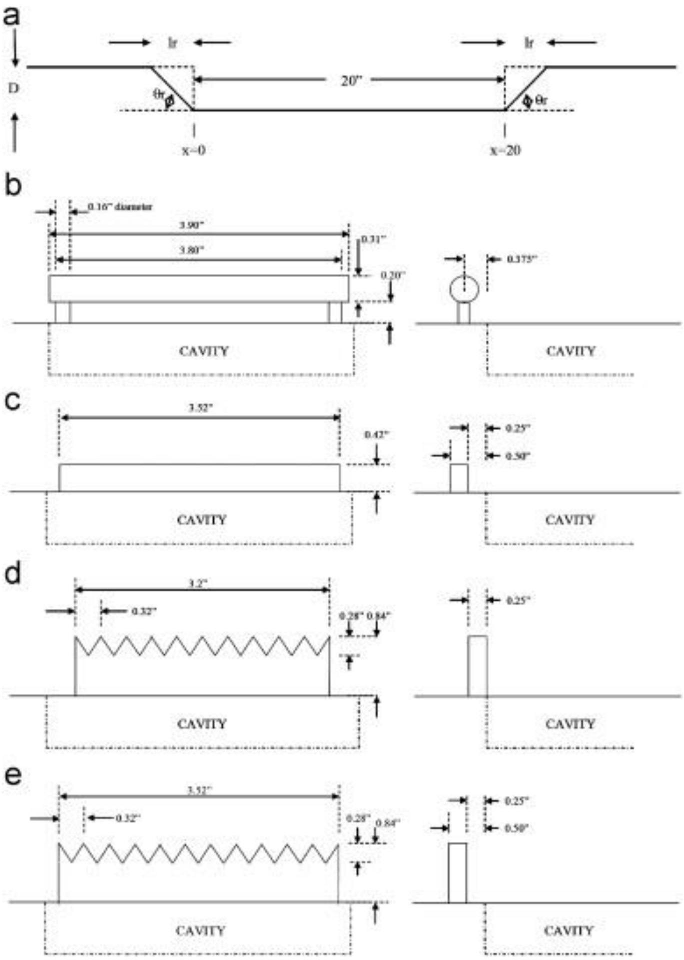


Figure 2. M219 passive control geometries.

Slanted wall (M219-SW) (a), Transverse rod (M219-TR) (b), Flat-top spoiler (M219-FTS) (c), Saw-tooth spoiler Type 1(M219-STS1) (d) and Type 2 (M219-STS2) (e) [3].

The aim in this study to conduct numerical analysis of the turbulent flow subjected to the M219 geometries seen in Figures 1 and 2 with the available commercial and open-source flow solvers and compare the results with the available experimental [3] and LES data [4]. Firstly, mean streamwise velocity and turbulent kinetic energy are compared for the clean cavity (M219-CC). Then, OASPL data are compared for M219-CC, M219-SW, M219-TR and M219-STS2.

2. Methodology

The fluid domain for each analysis is constructed using the sketches of the related experimental cavity models. Computational domain and the boundary conditions adopted for this domain is shown in Figure 3 and Table 1, respectively. Free stream Mach number and temperature is kept constant at 0.85 and 288 K, respectively. The same number of mesh (around 600 000) is used for RANS and URANS cases. For LES, around 6 million mesh number is employed. Pressure based solution is preferred for ANSYS/Fluent software for LES and RANS (k-w SST) cases. For OpenFOAM URANS solutions, the sonicFoam module is used. As for the SU2 RANS cases, the methodology explained in [5] is preferred.

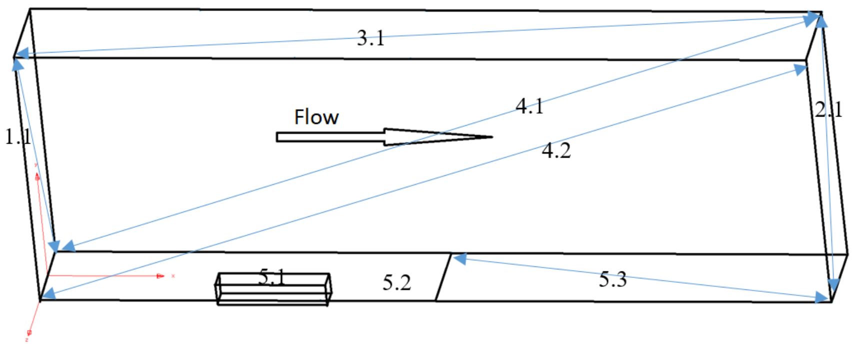


Figure 3. Computational domain for M219 flow analysis

Table 1. Formatting sections, subsections and subsubsections

#	Boundary	Dimension	Applied Boundary Condition		
			ANSYS Fluent	SU^2	OpenFOAM
1.1	Inlet	0.43×1.27	Farfield	Farfield	Wave transmissive
2.1	Outlet	0.43×1.27	Outlet	Outlet	Wave transmissive
3.1	Top	$\mathbf{0.43 \times 3.66}$			
4.1	Side left	$\mathbf{1.27 \times 3.66}$	Farfield	Farfield	Wave transmissive
4.2	Side right	$\mathbf{1.27 \times 3.66}$			
5.1	Cavity	$\mathbf{0.1 \times 0.1 \times 0.5}$			
5.2	Cavity near	$\mathbf{0.43 \times 1.83}$	Adiabatic, no-slip	Adiabatic, no-slip	Adiabatic, no-slip
5.2	Cavity downstream	$\mathbf{0.43 \times 1.83}$			

3. Results

Firstly, mean streamwise velocity and turbulent kinetic energy predictions are shown in cavity regions as reported in Figures 4 and 5. For the comparisons with the current predictions, LES data of [3] is used. To validate these LES data, LES of ANSYS/Fluent is performed for M219-CC case. As seen our LES predictions are in good agreement with LES predictions of [3]. OpenFOAM streamwise velocity results are very promising except the profile at x/L=4 where the streamwise velocity is underpredicted at -0.5 < y/D < 0.5. There is also a small zigzag region which is suspected to occur due to some numerical deficit which could be related to the data sampling of streamwise velocity. SU^2 predictions agree well with LES of [3] apart from some small underpredictions at x/L=3 and 4. Considering the predictions of OpenFOAM URANS and ANSYS/Fluent RANS, one can say that SU^2 is superior to both flow solvers in calculation of the streamwise velocity. However, this situation is not seen in Figure 4. SU^2 underpredicts the turbulent kinetic energy significantly at x/L=3 and 4 where ANSYS/Fluent RANS performs better than those two open-source flow solvers. However, noticeable underpredictions and over predictions exist at x/L=2. OpenFOAM URANS predictions agree very well with LES predictions for the first half of the cavity, but later they are overpredicted close to the trailing edge of the cavity. Considering both the trend and accuracy of the turbulent kinetic energy results, once can conclude the OpenFOAM is superior over ANSYS/Fluent and SU^2.

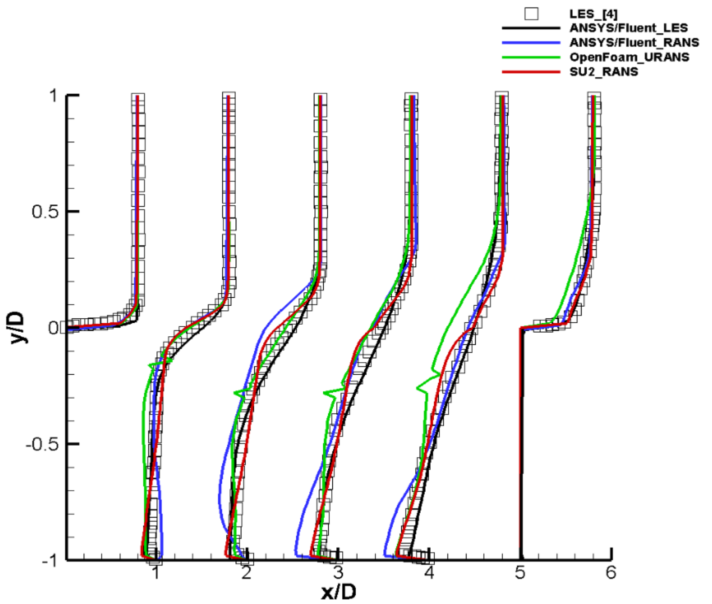


Figure 4. Streamwise mean velocity predictions (U_x/U_∞)

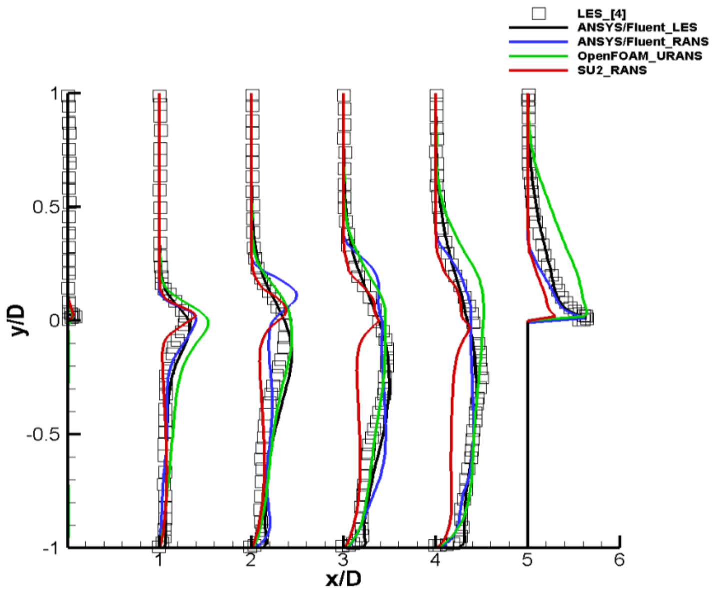
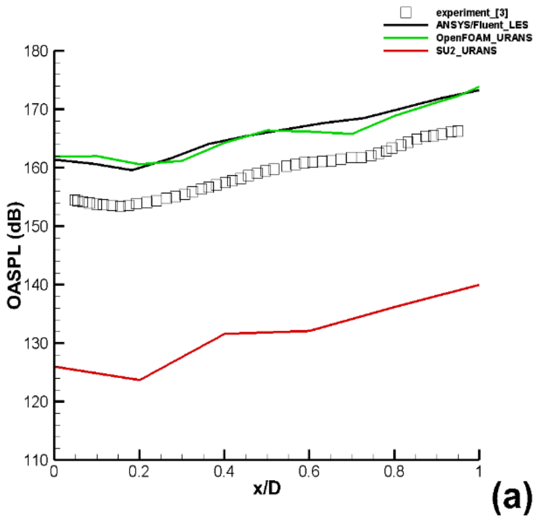


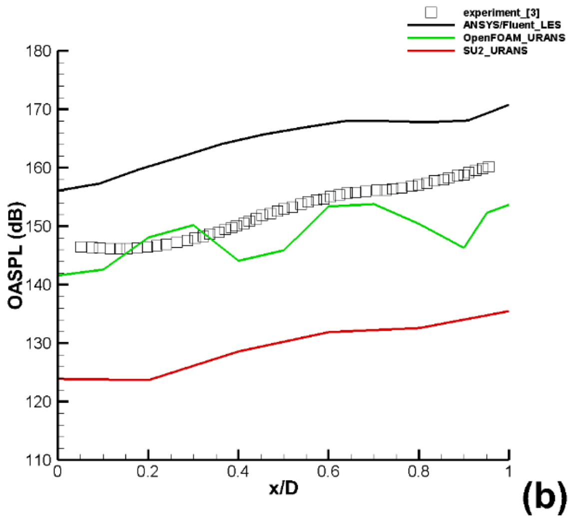
Figure 5. Turbulent kinetic energy predictions (k/ U_∞^2)

The success of a passive control method lies on the fact that the sound pressure level associated with the cavity surface decreases in comparison to that of the clean cavity where no passive control exists. Figure 6 shows the overall-average sound pressure level (OASPL) on the mid-line of the cavity floor for the clean cavity (Figure 6a) and for the passive control methods (Figure 6b,6c and 6d). OpenFOAM and SU^2 URANS as well as ANSYS/Fluent LES OASPL data are compared with previous experimental OASPL data [3]. Current LES overpredicts OASPL data for all cavity simulations. Nevertheless, the monotonic increase from the cavity leading edge to the cavity trailing edge reported by the experiment is satisfactory captured by our LES. OpenFOAM predictions show a very close trend with LES prediction for clean cavity case but indicate underpredictions and overpredictions for the passive control cases. Therefore, one can say that OpenFOAM predicts accurately but not precisely. It is believed high precision can be obtained by increasing the number of mesh and it will be in the plans of future work. Unlike the good performance of SU^2 for velocity and turbulence kinetic energy, its performance in OASPL predictions is truly disappointing. In fact, SU^2 underpredictions in OASPL reach sometimes 30 dB. These underpredictions are attributed to the available wall-functions in the code. It is not shown here but it was seen that decreasing the y^+ around 10 improves OASPL results significantly.

4. Conclusion and Future Work

In the present work, the most common open-source flow solvers OpenFOAM ve SU^2 are tested for the flow predictions of high speed cavity flows by comparing the available experimental and LES data. A relatively coarse grid (around 600 000) with high y^+ values (~100-300) are deliberately chosen for both flow solvers. Considering the predictions of velocity, turbulent kinetic energy and sound pressure levels, OpenFOAM is seen to perform satisfactorily and can be used as a design tool of passive and active control methods to alleviate the sound caused by the high-speed cavity flows.





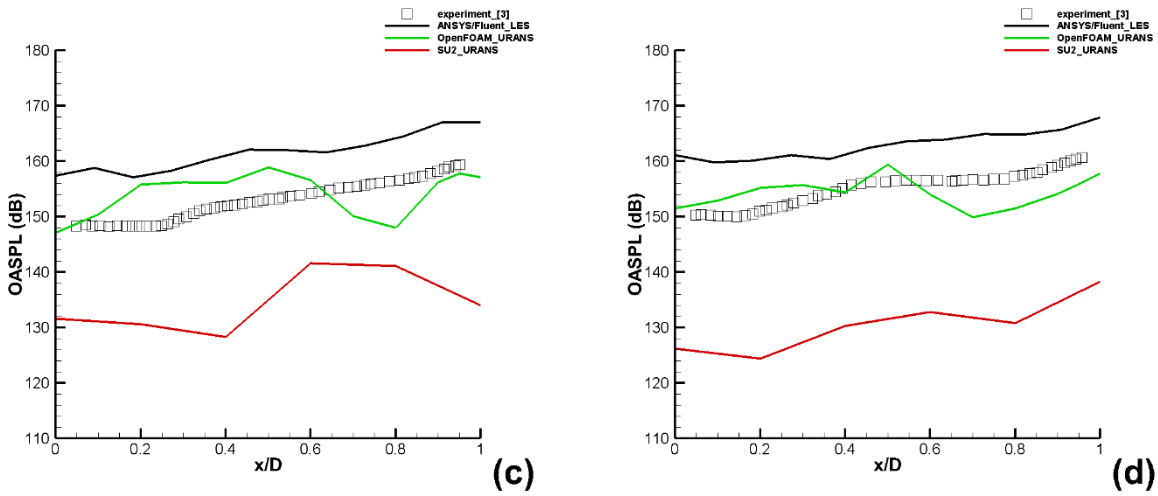


Figure 6. OASPL predictions for M219-CC (a), M219-SW (b), M219-TR (c), M219-STS (d)

Acknowledgement

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