Numerical Simulation on Flow Behaviors over a Cavity with Spoiler Pertaining to Velocity Distribution and Overall Sound Pressure Level

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Abstract

The present study covers the development of a proper numerical model concerning the supersonic flow past a three-dimensional open cavity with length-to-depth ratio of 2. The Mach number of the supersonic free-stream is 2 in addition the Reynolds number of the flow is 10^5. The numerical simulations have been accomplished through the Large Eddy Simulation (LES) practice. The simulation results have been obtained in the form of pressure field as well as overall sound pressure level at the centreline of the aft wall of the open cavity. Quite large recirculation is also witnessed within the open cavity without spoiler. But, the reduction of the recirculation within the open cavity is accomplished by attaching a spoiler in the form of one-fourth of a cylinder at the leading edge of the open cavity. With the attachment of the spoiler, the overall sound pressure level at the centreline of the aft wall of the open cavity is also decreased to some amount. Alongside, the sound pressure level is suppressed by almost 14 dB and 18 dB at both front and aft walls of the open cavity. In general, the comparisons between the simulation predictions of the cavity flows with and without the use of the spoiler is also done.

Keywords: Numerical Simulation, Open Cavity, Spoiler, LES, Velocity Vector, OASPL.

1. Introduction

The challenging flow physics pertaining to the flow over a cavity has spellbound the researchers around the world for more and more investigations and remains as a front-line area of investigation. Heller et al. [1] illustrated on flow-induced pressure oscillations in shallow cavities. Tam and Block [2] studied on the tones and pressure oscillations induced by flow over rectangular cavities. Kaufman et al. [3] reported on Mach 0.6 to 3.0 flows over rectangular cavities. Sweby [4] applied high resolution schemes using flux limiters on hyperbolic conservation laws. Rizzetta [5] performed numerical simulation on supersonic flow over a three-dimensional cavity. Anderson and Wendt [6] described about the fundamentals of computational fluid dynamics. Piomelli [7] demonstrated on achievements and challenges of large-eddy simulation. Hamed et al. [8] conducted numerical simulations of fluidic control for transonic cavity flows. Li et al. [9] carried out LES study of feedback-loop mechanism of supersonic open cavity flows. Vijayakrishnan [10] executed a validation study on unsteady RANS computations of supersonic flow over two dimensional cavity. It is apprehended that a general study on cavity flow has been done both experimentally and numerically for enhancing the aerodynamic effect.

Notwithstanding the fact, the flow over a cavity has been studied experimentally/numerically by many investigators, nevertheless, complete modelling of both large and small scales of motions at a time, not yet done which is one of the leading inadequacies. Even though, ample experiments have been conducted to quash the recirculation within the cavity, but, several are not just effective for all flow circumstances. The operation of the control devices are very portentously influenced by the Mach number. Control devices require to be appropriately designed so that they perform over a wide range of Mach numbers. The incoming boundary layer is also one more vital factor which controls the operation of the control devices.

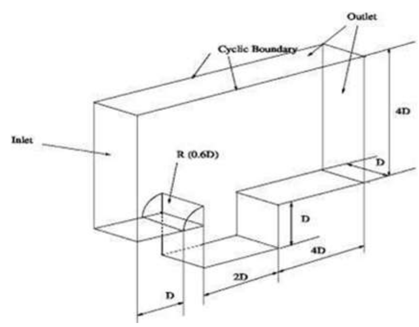
Emphasising this perspective in mind, the motivation of this investigation is to examine the flow sensation in a 3D open cavity supersonic flow. Furthermore, the reduction of recirculation within the open cavity by passive technique has been investigated by attaching spoiler at the leading edge of the cavity. The comparison between the open cavity flows with and without the attachment of spoiler has also been made. In general, the current researches involve the establishment of a three-dimensional numerical model for absolute numerical predictions of the open cavity flows in terms of velocity vector and overall sound pressure level (OASPL) at the centreline of the aft wall of the open cavity with and without the attachment of the spoilers.

2. Description of Physical Problem

Supersonic flow past a three-dimensional cavity is studied numerically. The streamwise length, depth and spanwise length of the cavity are 20 mm, 10 mm, and 10 mm, respectively. The length-to-depth ratio (L/D) for the cavity is 2. The width-to-depth ratio (W/D) is 1. The cavity is three-dimensional with streamwise length-to-spanwise length ratio (L/W) > 1. In addition, the Mach number of the free-stream along with the Reynolds number based on the cavity depth are taken as 2 and 10^5, respectively, for setting the inflow conditions.

A. Geometric model

The computational domain of the cavity used in the present simulation is shown in figure 1. The size of the computational domain, as mentioned earlier, is 2D×D×D (length × breadth × width). The inlet boundary is located at a distance of D upstream from the leading edge of the cavity. The outlet boundary is located at a distance of 4D downstream from the trailing edge of the cavity. The upper boundary is also located at a distance of 4D above the cavity.



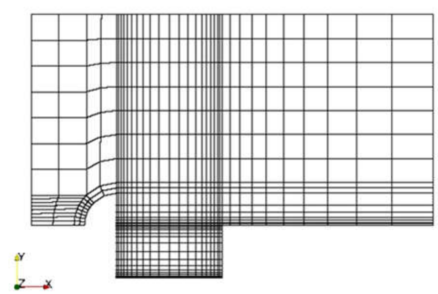


Fig 1. Computational domain with spoiler. **Fig 2.** Computational grid with spoiler.

B. Initial and boundary conditions

The inflow boundary conditions are initialized with free-stream conditions of $M_\infty = 2$, $P_\infty = 101.325$ kPa, and $T_\infty = 300$ K. The Reynolds number of the flow used in the simulation is 10^5, which is based on the cavity depth. No-slip adiabatic wall boundary conditions is applied at the wall boundaries. Zero-gradient condition is applied at all the outflow boundaries. Periodical boundary condition is applied in the spanwise direction of the cavity.

3. Mathematical Formulation and Numerical Procedures

A. Generalized governing transport equations

The most generalized governing transport equations of mass, momentum and energy for turbulent and compressible flow are as mentioned below.

Continuity: $$\frac{\partial \rho}{\partial t} + \nabla.(\rho \boldsymbol{U}) = 0 \quad (1)$$

Momentum: $$\frac{\partial (\rho \boldsymbol{U})}{\partial t} + \nabla.(\rho \boldsymbol{U}.\boldsymbol{U}) - \nabla.\nabla(\mu \boldsymbol{U}) = -\nabla p \quad (2)$$

Energy: $$\frac{\partial (\rho e)}{\partial t} + \nabla.(\rho e \boldsymbol{U}) - \nabla.\nabla(\mu e) = -p(\nabla.\boldsymbol{U}) + \mu\left[\frac{1}{2}(\nabla \boldsymbol{U} + \nabla \boldsymbol{U}^{\mathrm{T}})\right]^2 \quad (3)$$

Where, $\boldsymbol{U}$ = velocity vector = $u\hat{\imath} + v\hat{\jmath} + w\hat{k}$

$\frac{1}{2}(\nabla \boldsymbol{U} + \nabla \boldsymbol{U}^{\mathrm{T}})$ = strain rate tensor.

It is assumed that the gas is a perfect gas denoted by the equation, $p = \rho RT$ (4)

Where, R = specific gas constant = C_p - C_v (5)

For a calorically perfect gas (constant specific heats), the caloric equation of state is,

e = internal energy per unit mass = $C_v T$ (6)

B. LES turbulence modelling

The LES turbulence model is introduced by splitting the time and space varying flow variables into two constituents, the resolved one $\bar{f}$ and f', the unresolved part:

$(x,t) = \bar{f}(x,t) + f'(x,t)$ (7)

The filtering operation when applied to the Navier-Stokes equation gives:

$$\frac{\partial \bar{\rho}}{\partial t} + \nabla.(\overline{\rho \boldsymbol{U}}) = 0 \quad (8)$$

$$\frac{\partial(\overline{\rho \boldsymbol{U}})}{\partial t} + \nabla.(\overline{\rho \boldsymbol{U}.\boldsymbol{U}}) - \nabla.\nabla(\overline{\mu \boldsymbol{U}}) = -\nabla \bar{p} \quad (9)$$

$$\frac{\partial(\overline{\rho e})}{\partial t} + \nabla.(\overline{\rho \boldsymbol{U} e}) - \nabla.\nabla(\overline{\mu e}) = -\overline{p(\nabla.\boldsymbol{U})} + \mu\left[\frac{1}{2}(\nabla\overline{\boldsymbol{U}} + \nabla\overline{\boldsymbol{U}}^{\mathrm{T}})\right]^2 \quad (10)$$

The eddy viscosity models relating the subgrid-scale stresses (τ_{ij}) and the resolved-scale rate of strain-tensor ($\bar{S}_{ij}$) is denoted as, $\tau_{ij} - (\delta_{ij}/3) = -2\nu_T \bar{S}_{ij}$ (11)

Where, $\bar{S}_{ij}$ is the resolved-scale rate of strain tensor = $(\partial \bar{u}_i/\partial x_j + \partial \bar{u}_j/\partial x_i)/2$.

The algebraic model for the eddy viscosity: $\mu_{sgs} = \rho C \Delta^2 |\bar{S}| \bar{S}_{ij}$, $|\bar{S}| = (2\bar{S}_{ij}\bar{S}_{ij})^{1/2}$ (12)

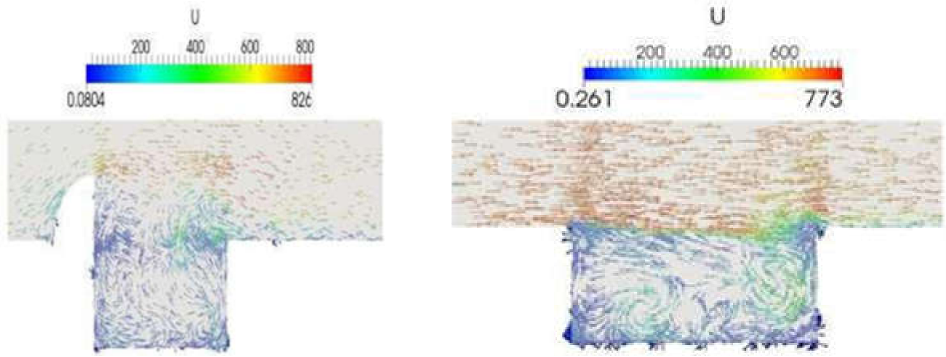
C. Numerical techniques

The transformed governing transport equations are solved by expending pressure based coupled framework relating to finite volume method (FVM) using the SIMPLER algorithm. Figure 3 shows the grid of the computational domain. As an outcome of this test, the optimum number of grid points used for the final simulation, in the upper cavity region as 360 × 150 × 1 and those of in the inside cavity region as 360 × 150 × 1. Thus, the total number of grid points is 81000. The values of ΔX^+, ΔY^+ and ΔZ^+ at the leading edge of the cavity are 5, 12.5 and 1.0, respectively. Corresponding time step taken in the simulation is 0.000001 seconds.

4. Results and Discussions

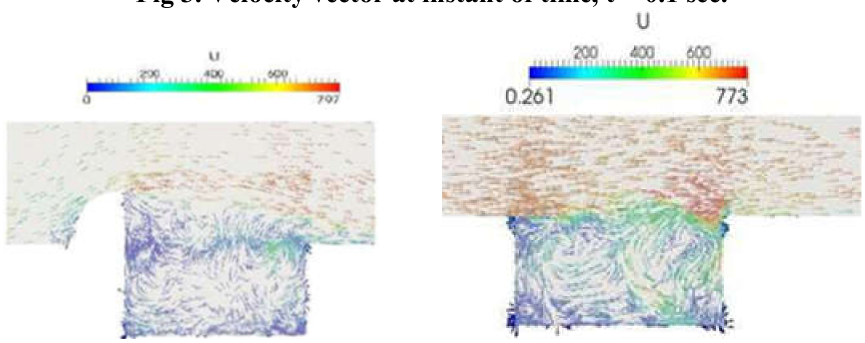
A. Velocity distributions with and without spoiler

The velocity vectors, at an instant of time t = 0.1 sec, for supersonic flow past an open cavity with and without the attachment of spoiler are revealed in the figure 3. The velocity vector indicates the recirculation within the open cavity. The flow performance past the open cavity with spoiler is unlike the open cavity flow without spoiler which may clearly be perceived from the velocity vectors. One shedding vortex is comprehended within the open cavity with spoiler at odds with two shedding vortices observed within the open cavity without spoiler. The recirculation regimes of both the open cavities are quite different from each other. The velocity vectors relating to supersonic flow past the open cavity with and without the attachment of spoiler, at an additional instant of time t = 0.3 sec, are also demonstrated in the figure 4. The distinctions in the flow behaviours may also be observed from both the stated figures portrayed at two different instants of times.



(a) With spoiler (b) Without spoiler

Fig 3. Velocity vector at instant of time, t = 0.1 sec.



(a) With spoiler (b) Without spoiler

Fig 4. Velocity vector at time, t = 0.3 sec.

B. Overall sound pressure level (OASPL) with and without spoiler

The OASPL distribution at the centreline of the aft wall of the open cavity with spoiler has been compared with that of without the attachment of spoiler. The comparison of both the said cases are presented in the figure 5. It is pragmatic that the OASPL is suppressed by approximately 18 dB and 14 dB at both aft and front walls of the stated open cavity, respectively. In addition, the OASPL distribution as observed at the centreline of the aft wall of the open cavity with spoiler attachment, remains almost uniform throughout.

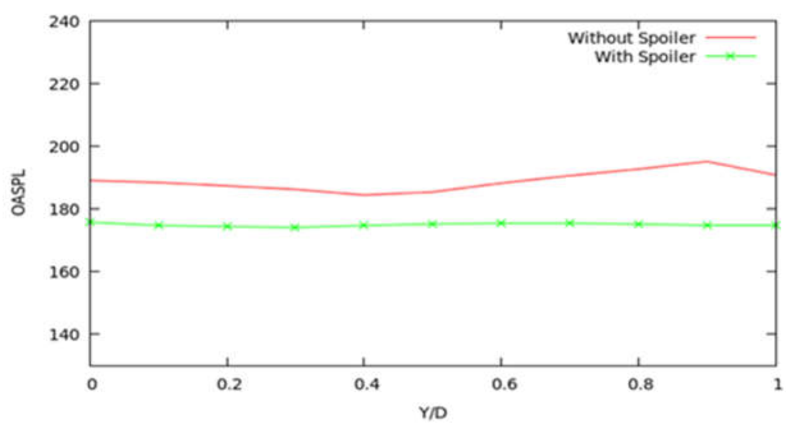


Fig 5. OASPL distribution at the aft wall with and without the use of spoiler.

5. Conclusion

In the current study, the numerical simulation has been accomplished for supersonic flow past an open cavity with and without the attachment of spoiler. The simulation is conducted with LES. The numerical results are obtained in the form of both cavity flow-field analysis as well as the aeroacoustic analysis epitomised by the overall sound pressure level at the centreline of the aft wall of the open cavity. The LES model is capable to ascertain all the core flow structures of the open cavity. The overall sound pressure level at the centreline of the aft wall of the open cavity with spoiler is compared with that of without the spoiler. There is both qualitative and quantitative agreement between the two. Nevertheless, with the attachment of spoiler, the sound pressure level is reduced by nearly 18 dB at the aft wall and also decreased by about 14 dB at the front wall of the stated open cavity. The trends of predictions for both the cavities are similar and therefore are comparable. In addition, the recirculation within the open cavity is also suppressed by use of spoiler which is also observed from the velocity vector. As a whole, in this investigation, a 3D model is developed for an open cavity and a spoiler is attached at its leading edge to study the flow structures and to suppress the recirculation and overall sound pressure level within the open cavity.

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