Computers and Fluids 121 (2015) 1–10

Contents lists available at ScienceDirect

Computers and Fluids

journal homepage: www.elsevier.com/locate/compfluid

Detached eddy simulation of weapons bay flows and store separation

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ARTICLE INFO

Article history:
Received 12 October 2014
Revised 2 June 2015
Accepted 23 July 2015
Available online 6 August 2015

Keywords:
Detached eddy simulation
Cavity flow
Flow unsteadiness
Pressure fluctuation
Store separation
Steady blowing

ABSTRACT

When internal weapons bay is exposed to free-stream, highly unsteady flow-field is formed over and inside the bay. The pressure fluctuation may cause damages on the surrounding structures, and increases noise. The complicated aerodynamic characteristics inside the weapons bay also affect the behavior of the stores released from the weapons bay. In the present study, numerical investigations of the unsteady flow-fields inside a weapons bay were conducted by using a three-dimensional compressible flow solver based on unstructured meshes. The effects of fluctuating flow inside the cavity on the aerodynamic loads of the store were also studied. Then simulations of the stores separating from the cavity were carried out, and the effect of flow unsteadiness on the store trajectory was examined. Finally, steady blowing was applied to suppress the pressure fluctuation and to help stabilizing the store separation. It was shown that flow unsteadiness inside the cavity is mainly caused by the detaching and reattaching process of the shear layer. It was found that the results of the *SST–DES* simulation are in better agreement with experiment in predicting high frequency flow contents than those of the k–ω *SST* turbulence model. When the store is located inside the cavity or at the shear layer, the pressure on the store oscillates in time. As a result, the trajectory of the store during the initial separation stage is significantly affected depending on the release point in time. It was demonstrated that steady blowing is an effective mean for mitigating the pressure fluctuation and stabilizing the store separation.

1. Introduction

Recently, internal weapons bay system is widely used in modern military aircrafts because of its advantages of reducing aerodynamic heating, drag, and radar cross-section. However, when the doors of weapons bay are open for releasing stores and the bay is exposed to free-stream, a highly-unsteady fluctuating flow-field, so called cavity flow, develops. The pressure fluctuation inside the cavity may cause damages on surrounding structures, and may increase noise. The pressure fluctuation can also influence the trajectory of released stores by changing the forces and moments acting on them. In this regard, detailed understanding of the flow characteristics inside the internal weapons bay is essential for the design of advanced weapon systems in the future.

A significant number of studies about the flow characteristics inside cavity were previously conducted with different cavity configurations for a broad range of Mach number and Reynolds number through wind-tunnel testing [1–4]. Numerical studies about the cavity flows have also been performed using different levels of turbulence model. At the early stage of the study, Reynolds-averaged Navier–Stokes (RANS) equations were mostly used. However, it was found that RANS simulations are not capable of predicting high frequency contents of the flow near the cavity corner by excessively over-estimating the eddy viscosity. Because of this reason, large eddy simulations (LES) and detached eddy simulations (DES) have been more widely used in the recent studies [5,6].

Nowadays, the stores are getting smaller and lighter, and therefore, when a store is released from the cavity, the trajectory of the store can be affected considerably by the surrounding unsteady aerodynamics. Studies about the effects of the flow inside the cavity on the trajectory of separating stores have been previously performed. Johnson [7] and Westmoreland [8] showed the theoretical, computational and experimental evidences that the flow unsteadiness inside the cavity can alter the trajectory of the stores depending on the time of release. Davis [9] carried out parametric studies to assess the sensitivity of the trajectory deviation due to the various store release parameters.

To suppress the unsteady pressure fluctuation and noise inside cavity by reducing the interaction between the aft wall and the shear layer, studies about adopting flow control devices have also been carried out. The flow control mechanism can be divided into either passive or active. Passive flow control adopts devices such as rod or spoiler, or modifies the configuration of cavity to change the behavior of the flow. Active flow control can be classified into open- and closed-loop approaches. The main difference between the two

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http://dx.doi.org/10.1016/j.compfluid.2015.07.022
0045-7930/

approaches is in the fact whether the control includes a feedback loop or not. Smith [10] conducted experiments by installing rods with various sizes at different locations. Nayyar [11] showed that the flow characteristics can be changed depending on the locations of spoiler and jet blowing.

In the present study, numerical simulations of the unsteady flow features inside a cavity were conducted using an unstructured mesh flow solver. Then, the effect of store presence on the flow characteristics was studied by its location. Also, variation of the store trajectories depending on the point of release time was investigated. Next, the effects of steady blowing as a mean of flow control to affect the trajectory of separating stores were also examined. For this purpose, the weapons internal carriage and separation (WICS) cavity bay with a length-to-depth ratio of 4.5 was chosen as the baseline geometry. The free-stream Mach number was set to 0.95, and the Reynolds number was 3.75×10^6. The unsteady turbulent flow over the rectangular cavity was simulated by using the k–ω *shear stress transport* (*SST*) turbulence model [12] and also with the *detached eddy simulation* (*DES*) based on the k–ω *SST* [13] to test the effect of turbulence model. The results were compared with available experimental data [3] for validation.

2. Methodology

2.1. Numerical method

The numerical simulations were performed by using a three-dimensional compressible flow solver based on an unstructured mesh technique [14]. The governing equations were discretized using a vertex-centered finite-volume method. The convective terms were discretized using Roe's flux-difference splitting scheme, while the viscous flux terms were computed by adopting a central-difference method. An implicit time integration algorithm based on the linearized second-order Euler backward differencing was used to advance the solution in time. Dual-time stepping was also adopted to minimize the error involved in the linearization. The linear system of equations was solved at each time step by using a point Gauss–Seidel method. The k–ω *SST* turbulence model and the *DES* based on the k–ω *SST* turbulence model were used to estimate the turbulent eddy viscosity. The flow solver was parallelized by partitioning the computational domain into several subdomains using the MeTis library [15]. Communication of the data between the processors was achieved using the message passing interface (MPI) library.

2.2. Turbulence models

To include the effect of turbulence, the k–ω *SST* turbulence model and the *DES* based on the k–ω *SST* turbulence model were applied. The k–ω *SST* turbulence model is constructed with blended functions of k–ω and k–ε models as follows:

$$\frac{\partial}{\partial t}\begin{bmatrix}\rho k\\ \rho\omega\end{bmatrix}+\frac{\partial}{\partial x_j}\begin{bmatrix}\rho u_j k\\ \rho u_j\omega\end{bmatrix}-\frac{\partial}{\partial x_j}\begin{bmatrix}(\mu_l+\sigma_k\mu_t)\frac{\partial k}{\partial x_j}\\ (\mu_l+\sigma_\omega\mu_t)\frac{\partial \omega}{\partial x_j}\end{bmatrix} = \begin{bmatrix}\tau_{ij}S_{ij}-\beta'\rho k\omega\\ \frac{\alpha}{\nu_t}\tau_{ij}S_{ij}-\beta\rho\omega^2+2(1-F_1)\frac{\rho\sigma_{\omega 2}}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j}\end{bmatrix} \quad (1)$$

The turbulent length scale L_t is defined by transforming the destruction term in the k -equation:

$$\beta'\rho k\omega = \rho\frac{k^{3/2}}{\sqrt{k}/(\beta'\omega)} = \rho\frac{k^{3/2}}{L_t} \quad (2)$$

In the *SST–DES*, the length scale is replaced by the *DES* length scale:

$$\beta'\rho k\omega \bullet \max\left(\frac{L_t}{C_{DES}\Delta}, 1\right) \quad (3)$$

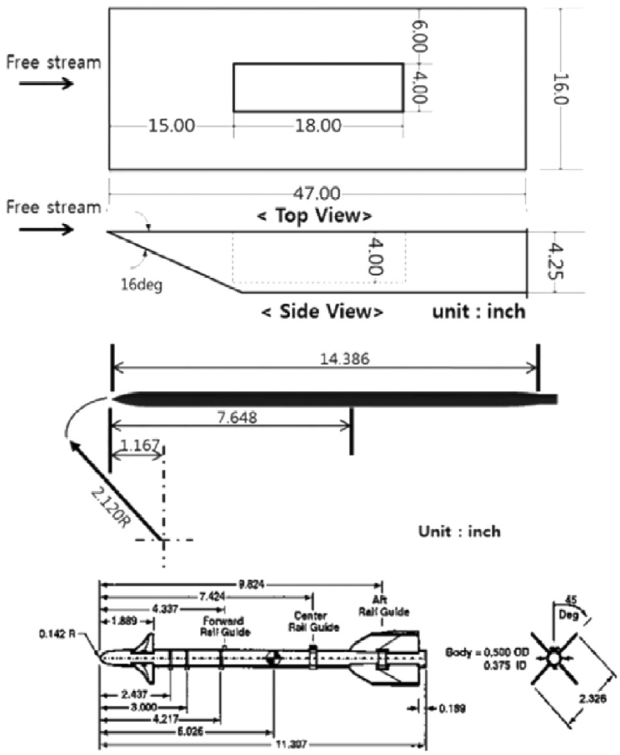

Fig. 1. Configuration of weapons bay and stores.

Table 1
Mesh topology for the calculations.

Cavity	# of nodes	Surface cell size	Store	# of nodes
Coarse	576, 552	0.022*L*	GMPM	266, 522
Medium	1, 903, 550	0.011*L*	AIM-9L	861, 721
Fine	3, 871, 460	0.0055*L*		

In the present study, the constant C_{DES} was set to 0.95. The filter size Δ was determined by doubling the maximum distance from the center of each cell to the faces of the cell of the unstructured mesh.

2.3. Configuration and mesh

The WICS wind-tunnel experiment [3] conducted in the Arnold Engineering Development Center (AEDC) was used as the baseline data for comparison. The weapons bay with a length-to-depth ratio of 4.5 was chosen for the cavity geometry in the present study. As the store configuration, the Generic Missile Pressure Model (GMPM) was chosen to test the effect of the presence of store by its location. For the store separation simulations, the AIM-9 L store configuration was used. Fig. 1 shows the geometry of the WICS cavity, GMPM store, and AIM-9 L store. Fig. 2 and Table 1 show the computational mesh and the boundary conditions applied. The mesh is presented for the case when the store is installed inside the cavity. It is shown that small cells are distributed mostly inside and over the cavity such that the detailed cavity flow behavior and its influence on the store can be captured more accurately. Inside the boundary layer, 25 layers of prism cells are packed on the cavity and store surfaces. The initial thickness of the prism cell is 7.99×10^{-6}, which is normalized by the reference length, L, of the cavity length. The y+ value at the first prism layer is approximately one.