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Improved delayed detached-eddy simulations of sawtooth spoiler control before supersonic cavity

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ABSTRACT

Flows at $Ma = 1.5$ over a cavity with different leading-edge sawtooth spoilers were numerically studied using improved delayed detached-eddy simulation based on the two-equation shear stress transport model, coupled with the adaptive dissipation scheme. Transonic flow past M219 cavity was chosen as the validation case for numerical methods and mesh convergence. Comparison of predicted sound pressure levels and spectra against the measurements has proved that the major oscillation dynamics inside the cavity is captured numerically. Five sawtooth spoilers were then evaluated before the leading edge of a complex irregular cavity in a supersonic flow. It is found that the spoiler lifts the shear layer, preventing its reattachment on the cavity floor, and completely changes the cavity flow type. The presence of sawtooth is necessary to promote instability more upstream. All spoilers show significant reduction in pressure fluctuation. Pressure decrease on the cavity floor and rear wall contributes to overall drag reduction, despite the extra drag by the spoiler. The spoiler with height equal to the local boundary layer thickness and a 90° tooth angle achieves optimal and balanced performance in both drag reduction and noise suppression among the evaluated spoilers.

1. Introduction

Dynamic load or acoustic noise within a cavity at transonic or supersonic speed is an important research area in the field of fluid mechanics, especially in the weapon bay design of a stealth aircraft. When exposed to high speed free-stream flow, the cavity experiences an intense aero-acoustic environment. The flow past a cavity is accompanied by extremely unsteady and complex features, including boundary layer separation, shear layer instabilities, pressure oscillations, impingement to the rear wall and acoustic noise. Interactions among these features can result in damage to the cavity's internal equipment or the structure, or cause unexpected influence on store releasing. High acoustic noise levels can also limit the flight envelope when releasing stores inside the cavity. To this effect, it is extremely important to understand the flow mechanisms at work throughout the cavity and to find ways to reduce dynamic loads.

Cavity flows can be divided into three categories based on the length-to-depth ratio and free-stream Mach number: open, closed and transitional. Open cavity flow occurs for deep cavities such as a bomber's weapon bay, while closed cavity flow occurs for shallow cavities like a fighter's weapon bay. Transitional flows occurs between the boundaries of open and closed flow. Shear layer behavior differs most among the three categories. In an open cavity flow, the shear layer stretches straight across the cavity opening. In a closed cavity flow, the shear layer reattaches on the cavity floor and then separates again downstream. In a transitional cavity flow, shear layer behavior could be an alternate combination of the two above. For transonic or supersonic flows, different shear layer behaviors can lead to complex wave systems, both inside and outside the cavity.

Though cavity flows have been under research for more than sixty years, the flow mechanisms of complex geometries and related flow control strategies remain the focus of the scientific and industrial community. Numerical methods which provide both qualitative and quantitative insight into flow details are a satisfactory choice to facilitate cavity flow studies without the use of expensive wind tunnel tests. Interested readers may refer to the comprehensive review by Lawson and Barakos (2011) who systematically report on over 60 experimental and computational cavity flow studies before 2010. Early studies on cavity flows were typically conducted by solving Reynolds-Averaged Navier-Stokes (RANS) or unsteady RANS (URANS) equations with various turbu-

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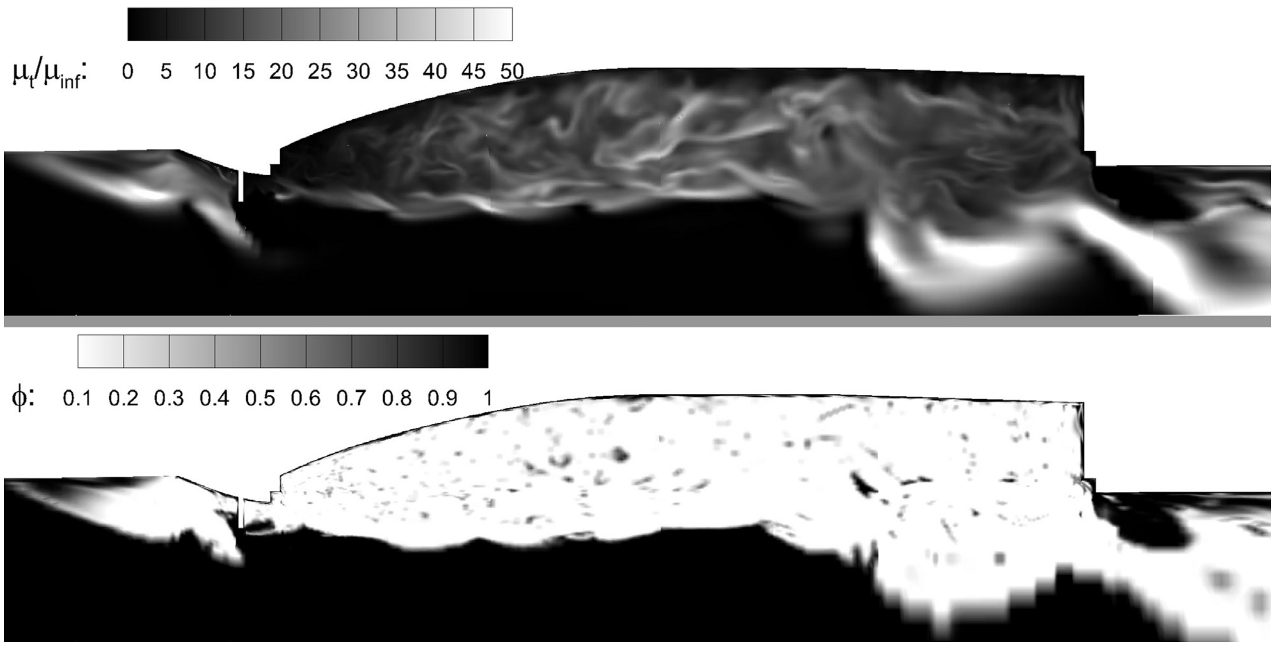

Fig. 1. Distributions of eddy viscosity and adaptive dissipation function in the cavity with a spoiler.

lence models. But recent studies (Peng, 2006; Liggett and Smith, 2011) have confirmed that they are incapable of simulating the high-frequency small scale turbulence that dominates in cavity flows, not to mention the acoustic tones or broadband noise. Thus only very few studies (Aradag et al., 2010) are still using traditional URANS now. On the other hand, direct numerical simulation (DNS) which resolves all the scales on a very fine grid, offers the highest accuracy. However it has limited application to cavity flows at high Reynolds number with computation resources currently available. Few studies using DNS (Gloerfelt et al., 2003; Bres and Colonius, 2007; Sun et al., 2014) were restricted to low Reynolds numbers or two-dimensional flows. Large-eddy simulation (LES) is affordable nowadays thanks to the growing computation power, and is being used in studies of cavity flows (Aybay et al., 2010; Li et al., 2013). Some of them are quite impressive. For example, Morton et al. (2012) studied a 1/15-scale F-22 main weapon bay model with interior details such as door hinges and rods by LES on an unstructured mesh. However its purpose was more of a code benchmark than a scientific investigation with flow details. But to accurately resolve a large range of turbulent scales in wall-bounded cavity flows, pure LES still suffers the same problem as DNS. For high Reynolds-number wall-bounded flow, special near-wall treatments like wall functions are usually necessary in LES computations.

Hybrid RANS-LES methods (HRLMs) use RANS for the near-wall flow and LES for the separated flow. Using RANS in near-wall regions is sometimes regarded as a unique LES near-wall treatment and saves computation resources. Typical HRLMs include detached-eddy simulation (DES; Spalart et al., 1997; Spalart, 2009), constrained LES (CLES; Chen et al., 2012), zonal DES (ZDES; Deck, 2005; 2012), partially-averaged Navier-Stokes (PANS; Girimaji, 2006; Chang et al., 2015a; 2015b) and scale-adaptive simulation (SAS; Menter and Egorov, 2010; Egorov et al., 2010; Davidson, 2006), as well as their combinations (Davidson and Peng, 2013; Davidson, 2014). Among those, DES and its variants are still the most popular in cavity flow simulation. In addition to the HRLM cavity studies summarized in the review of Lawson and Barakos (2011), a lot of HRLM studies have emerged since 2010 (Liggett and Smith, 2011; Temmerman et al., 2012; Wang et al., 2013; Arunajatesan et al., 2014; Luo and Xiao, 2015; Babu et al., 2015; Sheta et al., 2015; Hassan et al., 2016). Many researches have started dealing with complex geometries like realistic weapon bays and store release problems (Lawson and Barakos, 2010b; 2010a; Kannepalli et al., 2011; Khanal et al., 2011; Chaplin and Birch, 2012; Kim et al., 2015; Barone and Arunajatesan, 2016).

Many researchers have also explored methods of cavity flow control and improving the cavity environment. These control strategies can be roughly categorized as passive and active flow controls, according to the need for external energy input (Cattafesta et al., 2008). Passive control methods often have advantages of weight and complexity over active control methods, but are not as versatile over various flight conditions. Lawson and Barakos (2011) and Cattafesta et al. (2008) have summarized passive and active flow control studies respectively. Wind tunnel tests have been employed to test a wide array of control devices, most of which are leading edge modifications such as serration (Gai et al., 2015), block (Shaaban and Mohany, 2015), transverse rods (Dudley and Ukeiley, 2014) and sawtooth spoilers (Saddington et al., 2016a), as well as active blowing (Zhang et al., 2015; George et al., 2015) and plasma (Yugulis et al., 2014; de Jong and Bijl, 2014) controls. Leading edge devices generally are designed to drive the shear layer up and away from the cavity trailing edge, or to increase its instability and weaken large-scale impingement. Trailing edge modifications like the traditional trailing edge ramp control (Vikramaditya and Kurian, 2009) are less common, but have also proven effectiveness in suppressing pressure fluctuations. Recent experimental study (Saddington et al., 2016b) of both leading-edge and trailing-edge modifications on a cavity in transonic flow has reported that leading-edge control techniques are more effective at suppressing cavity tone amplitudes than trailing-edge modifications. Although wind tunnel tests are still currently the most popular method of researching, it is not easy for experimental studies to reach a balance of spatial and temporal resolution. A limited number of computations using advanced CFD methods (like LES or hybrid RANS-LES) are emerging, including leading edge rod (Comte et al., 2009), injection (Wang et al., 2013) and blowing (Zhang et al., 2015). Das Gupta and Roy (2014) designed a plasma actuated receptive channel that performs like a