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Numerical investigation of the passive control of cavity flow oscillations by a dimpled non-smooth surface

Yiping Wang [a,b,c,*], Shuai Li [a], Xue Yang [c]

[a] Hubei Key Laboratory of Advanced Technology of Automotive Parts, Wuhan University of Technology, Wuhan 430070, China
[b] Hubei Collaborative Innovation Center for Automotive Components Technology, Wuhan University of Technology, Wuhan 430070, China
[c] Wuhan Ordnance Noncommissioned Officers School, Wuhan 430075, China

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ABSTRACT

Computational investigations are conducted to determine the effectiveness of a passive control technique, which was employed to decay the pressure oscillations induced by a subsonic flow over a cavity. This work focuses on a cavity with a small opening but a large volume. The passive control technique is employed by introducing a dimpled non-smooth surface, which is installed at the upstream of the cavity. Large eddy simulation is used to investigate the flow field and flow instability around the cavity for the smooth and non-smooth cases. Experiments are conducted in an acoustic wind tunnel for the smooth case to validate the computational scheme. Flow visualizations revealed that the dimpled surface located upstream effectively suppresses cavity flow oscillations. Finally, the control mechanism of cavity oscillation with the dimpled non-smooth surface is also determined based on the comparison of the flow field structure between the smooth and non-smooth cases.

1. Introduction

Oscillation in the flow over a cavity is an important benchmark problem for aeroacoustics and has been the focus of considerable interest over the past few decades because of its high academic and practical significance. Despite numerous investigations on this area, the basic physical mechanism underlying oscillation and control over a wide range of flow conditions have not been examined adequately. At present, the most difficult problem for researchers of fluid dynamics and aeroacoustics is determining how to model the noise source and the disturbances that cause oscillations accurately. For researchers of flow control, the most significant challenge is to achieve suppression in various modes of oscillations. These and several other issues make flow-induced cavity oscillations a typical problem in flow control.

Various control strategies for cavity oscillation suppression have been tested in the past years. These approaches can be classified into two types, namely, passive control and active control. Active flow control can suppress noise and can be adjusted adaptively according to various conditions. However, finding a suitable and stable control approach is still a challenging task [1,2]. Compared with the active methods, passive control techniques, such as spoilers, mass injection, and modification of the cavity leading and/or trailing edge, are the easiest to implement and the most inexpensive. Most of these concepts were proven to be effective in reducing the dynamic pressure levels. Heller and Bliss [3] are two of the earliest researchers who experimentally and analytically evaluated the effectiveness of several control devices, such as slanting the trailing edge, upstream vortex generators, or spoilers, and the results revealed that several of the proposed devices were useful in substantially suppressing the oscillations. Shaw [4] conducted wind tunnel tests to determine the effectiveness of the leading edges in suppressing oscillations, and the results showed that the slanted trailing edge was effective in controlling the cavity tones; however, the spoilers were not fully successful. Wang et al. [5] conducted experimental and numerical analyses to investigate the noise induced by a subsonic flow over a cavity and proposed a vented spoiler, which showed superiority in noise reduction by modifying the flow structure of the shear layer. Chokani and Kim [6] conducted a numerical investigation to determine the effectiveness of a passive control technique in suppressing the oscillations in an open cavity exposed to a supersonic flow. They observed that the passive pneumatic control substantially suppressed the amplitude of the low-frequency oscillations. Sarno and Franke [7] determined the effect of static and oscillating fences and steady and pulsating flow injections at the leading edge

* Corresponding author at: Hubei Collaborative Innovation Center for Automotive Components Technology, Wuhan University of Technology, Wuhan 430070, China.
E-mail address: wangyiping@whut.edu.cn (Y. Wang).

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on cavity sound pressure levels. They observed that static fences were the most efficient approach. Stallings et al. [8] conducted an experimental study at subsonic and transonic speeds to investigate the effects of several passive venting techniques on the pressure distributions in shallow and deep cavities. Their test results demonstrated that the porous floor and the porous floor combined with slot vents had the greatest effect on the distribution of shallow cavity pressures. Zhang et al. [9] investigated the effects of leading edge compression ramps, expansion surfaces, and mass injection on supersonic cavity flow oscillations. Ukeiley et al. [10] examined a leading-edge fence with a cylindrical rod, which was suspended in the approaching boundary layer parallel to the leading edge. They determined that this device played an important role in the level of surface pressure suppression. Alam et al. [11] employed a passive control technique by modifying the cavity geometry with two flat plates attached to the front wall of a square cavity in the horizontal and vertical positions. Their results showed that this approach was effective in reducing cavity pressure oscillations. Li et al. [12] conducted a numerical investigation to explore the mechanism and efficiency of noise control in supersonic cavity flow with steady mass injection at the upstream. They observed that the strong interaction between the upstream boundary layer and the injection flow could force the shear layer to lift up. The lifting up of the shear layer could weaken the large-scale vortices impinged on the trailing edge. Although the passive control techniques proposed by the aforementioned researchers can attenuate cavity-induced pressure oscillations, most of these control devices do not perform well within the wide range of flow conditions and do not successfully suppress multiple acoustic modes simultaneously.

Based on the literature review, the passive approaches could be classified into two categories: one type destroys Rossiter's feedback loop, and the other type changes the flow structure of the upstream boundary layer. The investigation related to the influence of the boundary layer on cavity noise generation [13–15] revealed that the pressure fluctuation induced by a turbulent boundary layer was weaker than that induced by a laminar boundary layer. According to Krishnamurthy [13], for a given Reynolds number, a minimum cavity length exists in the flow direction. When the length of the cavity is less than the critical length, the shear layer would traverse over the cavity so that oscillations were not induced. However, for a given cavity, the dimension of the minimum length was not provided. In subsequent experiments, Sarohia [16] introduced a nondimensional length, expressed as follows:

$$D = (L/\delta_0) \times (Re_{\delta 0})^{1/2},$$

where L is the span length of the cavity, δ_0 is the thickness of the boundary layer, and $Re_{\delta 0}$ is the Reynolds number, and determined that oscillations will not be induced when the nondimensional length is less than 0.29×10^3. In other words, for a given L and velocity, the critical condition can be easily obtained when δ_0 is thick. Generally, the thickness of the turbulence boundary layer is approximately several times thicker than that of the laminar boundary layer. The investigation conducted by Chang et al. [17] determined that, when the incoming boundary layer was laminar, the growth of the three-dimensional instabilities originating at the leading edge induced deformations of the cores of the spanwise vortices that were shed quasi-regularly in the separated shear layer. However, for the turbulence boundary layer, quasi-regular shedding was not observed because of the strong interaction between the incoming turbulent eddies and near-wall region upstream of the cavity. At present, many passive approaches for controlling cavity oscillation, such as deflector [5] and sub-cavity [18], are based on this principle. However, the introduction of a deflector will increase drag and cost, and structure reliability must also be considered. The presence of a sub-cavity in the streamwise direction will lead to the accumulation of particles and dirt, and the need for cleaning or servicing must be considered.

Therefore, one issue that needs to be resolved is how to use an economic approach to obtain a turbulence boundary layer and increase its thickness while avoiding the increase of drag. In the past decade, dimpled non-smooth surfaces were introduced to reduce the pressure drag and friction drag [19,20]. For a non-smooth surface, the entire boundary layer will be turbulent and a more forward momentum will be obtained; thus, the boundary layer resists the adverse pressure gradient relatively longer before it separates from the surface [21]. Therefore, in the current research, dimpled non-smooth surfaces are introduced to promote a turbulent boundary layer and increase the thickness of the upstream boundary layer.

2. Dimpled non-smooth surface and cavity model

The study object is a rectangular box with a large volume and a small top-opening. The box has a spanwise width of 300 mm, length of 400 mm, and depth of 290 mm. The opening has a spanwise width of 240 mm and a streamwise length of 100 mm. The cavity center was aligned with the center of the rectangular opening (Fig. 1). The dimpled non-smooth surface was located on the leading edge of the opening with a spanwise width of 245 mm and a streamwise length of 145 mm. The dimple distribution is a rectangular array, and the spacing between two dimpled units is 5 mm along the direction of the width and length. For the dimpled unit, the print diameter (D) is 20 mm and the depth (h) is 6 mm (see Fig. 1), which correspond to a ratio of depth to print diameter of $h/D = 0.3$.

In the current research, two cases were considered for the computation. The first case involves a smooth surface at the leading edge, which was used to validate the computational scheme, and the second case involves a dimpled non-smooth surface at the leading edge.

3. Computational method

3.1. Turbulence model

Assuming a weak compressibility effect for a low Mach number flow without heat sources, a set of nondimensional equations were obtained as follows [22]:

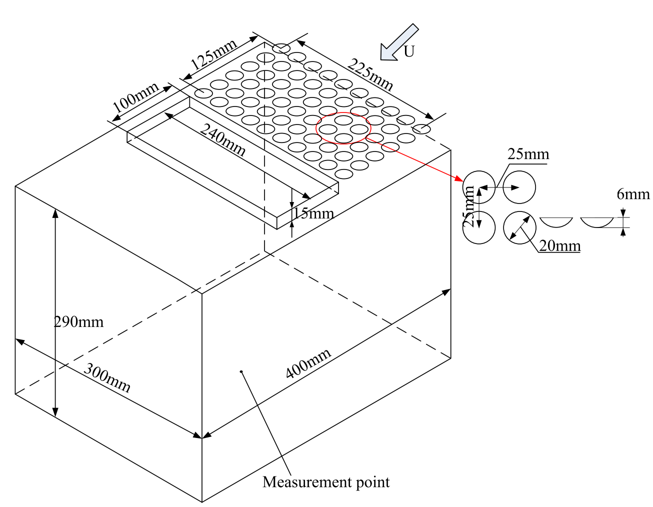

Fig. 1. Schematic representation of dimpled non-smooth surface and cavity model.