Effects of Sidewalls and Leading-Edge Blowing on Flows over Long Rectangular Cavities

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The present work investigates sidewall effects on the characteristics of three-dimensional (3-D) compressible flows over a rectangular cavity with aspect ratios of $L/D = 6$ and $W/D = 2$ at $Re_D = 10^4$ using large-eddy simulations. For the spanwise-periodic cavity flow, large pressure fluctuations are present in the shear layer and on the cavity aft wall due to spanwise vortex roll-ups and flow impingement. For the finite-span cavity with sidewalls, pressure fluctuations are reduced due to interference to the vortex roll-ups from the sidewalls. Flow oscillations are also reduced by increasing the Mach number from 0.6 to 1.4. Furthermore, secondary flow inside the cavity enhances kinetic energy transport in the spanwise direction. Moreover, 3-D slotted jets are placed along the cavity leading edge with the objective of reducing flow oscillations. Steady blowing into the boundary layer is considered with momentum coefficient $C_w = 0.0584$ and 0.0194 for $M_m = 0.6$ and 1.4 cases, respectively. The three-dimensionality introduced to the flow by the jets inhibits large coherent roll-ups of the spanwise vortices in the shear layer, yielding 9–40% reductions in root mean square (rms) pressure and rms velocity for both spanwise-periodic and finite-span cavities.

Nomenclature

| Symbol | Definition |
|--------|------------|
| $C_p$  | pressure coefficient |
| $C_{m_p}$ | momentum coefficient |
| $d$    | distance from slot center to cavity leading edge |
| $f_n$  | frequency of nth Rossiter mode |
| $L, W, D$ | cavity length, width, and depth |
| $l_s$  | slot width (streamwise extent) |
| $l_z$  | slot length (spanwise extent) |
| $M$    | Mach number |
| $m$    | aggregated mass flow rate |
| $p$    | pressure |
| $P$    | integrated pressure |
| $Re_D$ | $Q$-criterion |
| $S_{th}$ | depth-based Reynolds number |
| $u, v, w$ | streamwise, transverse, and spanwise velocity |
| $x, y, z$ | streamwise, transverse, and spanwise directions |
| $\alpha$ | specific heat ratio |
| $\gamma$ | initial boundary-layer thickness at cavity leading edge |
| $\delta$ | averaged convection speed of disturbance |
| $\lambda$ | distance between adjacent slot center |
| $\nu_{jet}$ | transverse velocity of slotted jet |
| $\rho$ | density |
| $\tau$ | Reynolds stress |
| $\omega_x, \omega_y, \omega_z$ | streamwise, transverse, and spanwise vorticity |
| $\infty$ | freestream quantity |
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I. Introduction

Flow over a rectangular cavity has been a fundamental research topic for several decades due to its pervasive nature in many engineering applications, such as landing-gear wells and weapon bays of aircraft. In open-cavity flows [1], a shear layer emanating from cavity leading edge amplifies disturbances as they advect downstream. Large spanwise vortical structures roll up and impinge on the cavity aft wall, resulting in intense pressure fluctuations and acoustic waves. As these waves propagate upstream, new disturbances are induced near the leading edge, which forms a feedback process and makes the oscillation self-sustained [1–3]. For unsteady cavity flows, strong resonance is observed. Rossiter [4] first predicted these resonant frequencies through a semi-empirical formula, whose modes are referred to as Rossiter modes.

The characteristics of cavity flow can be affected by various factors including cavity aspect ratio along with hydrodynamic and acoustic features of the incoming flow [5–10]. As such, a large number of experimental and computational studies have been performed to examine influence of cavity geometry, freestream Mach number, Reynolds number, and other parameters [3,7,11,12] on cavity flow behaviors. The review paper by Lawson and Barakos [1] have summarized the studies on turbulent cavity flow for both experiment and simulation efforts from the past few decades. Recently, global stability analysis [13–15] has been adopted to identify the instabilities present in cavity flows. These studies found that Rossiter modes are two-dimensional oscillations stemming from Kelvin–Helmholtz instabilities [16,17], whereas three-dimensional modes are associated with centrifugal instabilities [18–22], which were also observed in experiments [19,23].

In the aforementioned cavity flow studies, the influence of cavity sidewalls was generally neglected by using a full-span model for wind-tunnel tests and a periodic boundary condition for numerical simulations. However, because a cavity with sidewalls (finite-span cavity) better represents practical engineering configurations, some
research has examined the complicated influence of the sidewall on the flow. In the experimental work by Zhang and Naguib [24], an axisymmetric cavity model was used to consider cavity flows that are free from sidewall influence. Then, they examined how the flow behaviors are affected by adding sidewalls. Because rectangular cavities are more widely used in engineering applications, Crook et al. reported the characteristics of incompressible flow over a rectangular shallow cavity with sidewalls from experiments [25]. Later, influence of compressibility is also considered while analyzing sidewall effects. A joint work of experiments and simulations was conducted by Arunjatesan et al. [6] to investigate effects of finite width on transonic cavity flows. Analysis of hypersonic finite-span cavity flows was performed by Ohmichi and Suzuki [26] with a focus on flow structures and heating augmentation. Moreover, triglobal stability analysis [27] has also been carried out by Liu et al. [20] to uncover three-dimensional instabilities of incompressible flow over a finite-span cavity. As additional findings on sidewalls effects are revealed, it becomes necessary and valuable to assess the appropriateness of spanwise-periodic cavity flow as a suitable model for practical cavity flows. Hence, in the present numerical study of cavity flows, we examine sidewall effects by considering both spanwise-periodic and no-slip boundary conditions for the spanwise setup.

In addition to exploring fundamental physics of open-cavity flows, numerous flow control studies have been performed, with the objective of suppressing flow oscillations, because the intense fluctuations may damage cavity structures and lead to high-level noise emission. In general, flow control is classified as passive or active. Passive control is achieved by techniques including modifying object geometry, adding a spoiler, or introducing ramps [28–30], which does not require actuator energy input to the base flow. The drawback of passive flow control strategy is its potential performance degradation when the flow condition deviates from the original design condition. For cavity flows, especially in aerospace applications, a robust control strategy is required for different flight conditions, hence calling for active flow control that introduces external energy input through actuators. Active control strategies provide an adaptable capability [31–34] over a wide range of operating conditions. The review paper by Catciftesa et al. [35] summarizes efforts in active flow control techniques applied to unsteady cavity flows in experiments.

Nonetheless, there have not been clear control guidelines that can be applied to cavity flows in a general manner. Rizzetta and Visbal [36] have performed large-eddy simulation (LES) on controlled cavity flow at $M_{∞} = 1.19$ using two-dimensional mass injection. However, numerical studies of three-dimensional steady actuations for cavity flow have been rarely discussed in past studies. In recent companion experimental efforts [37,38] of controlling cavity flow oscillations via introducing steady jets along the cavity leading edge, we found that three-dimensional actuation suppresses pressure fluctuations more effectively than spanwise uniform (two-dimensional) injection. To obtain a better understanding of this control mechanism, we further examine three-dimensional controlled flows using LES to resolve unsteadiness of the flows and near-wall physics. Moreover, the sidewall effects that were mentioned previously are also considered while analyzing the controlled flows in the present work.

In this paper, we examine the sidewall effects by analyzing spanwise-periodic and finite-span cavity flows at $R e_D = 10^4$. Both subsonic ($M_{∞} = 0.6$) and supersonic ($M_{∞} = 1.4$) flow conditions are considered. Moreover, we examine the effectiveness of active flow control (three-dimensional steady jets) for the baseline cases with the objective of suppressing pressure fluctuations. The choice of control parameters are guided from experimental work [37–39]. The present numerical study will offer insights into how momentum injection influences the base flow and ultimately attenuates flow oscillations under different flow conditions. This paper is organized as follows. The numerical approach is described in Sec. II. Results are described in Sec. III, where sidewall effects on baseline flow characteristics are presented in Sec. III.A, whereas control effects are discussed in Sec. III.B. Finally, concluding remarks are provided in Sec. IV.

II. Numerical Approach

Three-dimensional LES has been performed to examine the flow over a cavity with aspect ratios of $L/D = 6$ and $W/D = 2$ at $R e_D = 10^4$ using the compressible flow solver CharLES [40–42], where $L$, $W$, and $D$ are cavity length, width, and depth, respectively. The solver uses a second-order finite-volume discretization and a third-order Runge–Kutta time integration scheme to numerically solve the Navier–Stokes equations. The Vreman model [43] is implemented for the subgrid-scale model in LES, and the Harten–Lax–van Leer contact [44] scheme is used to capture shocks for supercritical flows.

The computational setup is presented in Fig. 1. A Cartesian coordinate is used, with origin placed at the spanwise center of cavity leading edge. We consider two Mach numbers of $M_{∞} = 0.6$ and $1.4$ to examine compressibility effects on the flow characteristics. To model an incoming turbulent boundary layer, perturbations are added to the inlet turbulent velocity profile given by the one-seventh power law via superposing random Fourier modes [45,46]. The initial boundary-layer thickness $δ_{∞}/D$ at the leading edge is set to $0.167$ based on our companion experiments [37,38]. No-slip and adiabatic conditions are specified at the floor and the cavity walls. Sponge zones are applied in the far-field and outflow regions spanning $2D$ from boundaries of the computational domain to damp out exiting wave structures [47]. The influence of the sidewall is investigated by specifying spanwise-periodicity and no-slip walls at $z/D = ±1$ as depicted in Figs. 1a and 1b, respectively. For the finite-span cavity shown in Fig. 1b, slip condition is prescribed for the far-field side boundaries. In the cavity region of $\{x, y, z\}/D \in [-1, 1] \times [-1, 1] \times [-1, 1]$, structured grids with 488,000 x 200 x 128 are used for $x$, $y$, and $z$ directions. A nonuniform and slowly stretched mesh is adopted with the minimum grid size near cavity surfaces having wall-normal $y^+ = 1$. For the upstream and downstream floor ($y/D = 0$) meshes, $x^+ = 15$ and $y^+ = 1$ are ensured to resolve the boundary layer and flowfields. There are approximately 14 million volume cells in the computational domain for the spanwise-periodic case. For the finite-span cavity flows, the number of volume cells increases to 24 million grid points due to a larger domain with additional no-slip sidewalls.

We will also analyze the influence of active flow control through steady slotted jets in addition to the sidewall effects on the flows. Active control of the cavity flows with slotted jets has been examined for the objective of reducing pressure fluctuations on the cavity surfaces in our companion experimental studies by Zhang et al. [37], George et al. [38], and Lusk et al. [39]. From their work, segmented slots are more effective to reduce flow oscillations compared to jets spanning the entire cavity width. Hence, we select effective slot configurations [37–39,48] and investigate the control effectiveness taking compressibility and sidewall influences into consideration. In the computational domain, three slots are evenly placed along the cavity leading edge with their centers at $z/D = 0$ and $±0.67$. The slot spanwise extent is $l_s/D = 0.17$, the streamwise extent is $l_f/D = 0.014$, the distance of adjacent slot centers is $z/D = 0.67$, and the distance between slot centers and the cavity leading edge is $d/D = 0.07$, as shown in Fig. 1c. Steady slotted jets introduce transverse blowing into the boundary layer with a velocity boundary condition of $(u, v, w) = (0, v_{bl}, 0)$ specified on slot areas. The control input is characterized by the number of slots, spatial duty cycle $l_s/l$, spanwise wavelength $\lambda/D$, and momentum coefficient:

$$C_{m_{\text{jet}}} = \frac{\dot{m}_{\text{jet}}}{(1/2) \rho_{\infty} u_{\infty}^2 \delta_{\lambda}}$$ (1)

where $\dot{m}_{\text{jet}}$ is the aggregate mass flow rate, $v_{bl}$ is the steady velocity of the slotted jet, $\rho_{\infty}$ is the density, and $u_{\infty}$ is the freestream velocity. We use the actuator configurations that are found effective from our companions experiments [37,38] as listed in Table 1. The grids around the slotted jets are further refined to resolve the actuator jets and their interactions with the incoming flow. Each region around the slot is finely discretized with $50 \times 80 \times 50$ grid points. A hyperbolic tangent function is adopted for the blowing velocity profile to smooth the
velocity discontinuity at slot edges. The pressure and density on the slot areas are prescribed as the reference values from freestream as approximate boundary conditions.

The numerical results of the baseline flow at $M_\infty = 0.6$ and $Re_D = 10^5$ have been compared to the results from the experiments at $Re_D = 3.3 \times 10^5$. Good agreement is found concerning the properties of Rossiter modes as reported in the study by Zhang et al. [37] (not shown here). Moreover, the time- and spanwise-averaged streamlines and Reynolds stress flowfields from the present work and those from midspan of the experiments exhibit qualitative agreement as shown in Fig. 2.

### III. Results and Discussions

In this section, we discuss sidewall effects on the baseline flows and then examine the underlying mechanism of flow control. The compressibility effects are also investigated for the subsonic ($M_\infty = 0.6$) and supersonic ($M_\infty = 1.4$) cavity flows.

#### Table 1 Slotted-jet configuration in the present study (this setup is used for both spanwise-periodic and finite-span cavity flows)

| $M_\infty$ | Number of slots | $l_\lambda$ | $\lambda/D$ | $C_p$ | $v_{jet}/u_\infty$ |
|------------|-----------------|-------------|-------------|-------|------------------|
| 0.6        | 3               | 0.25        | 0.667       | 0.0584| 1.20             |
| 1.4        | 3               | 0.25        | 0.667       | 0.0194| 0.70             |

#### A. Sidewall Effects

We first describe the flows at $M_\infty = 0.6$ for spanwise-periodic versus finite-span cavities. Representative visualizations of the flowfields are shown in Fig. 3. We use isosurfaces of the $Q$-criterion [49] to identify vortical structures and color them with instantaneous pressure coefficient $C_p$, which reveals intense pressure fluctuations in the baseline flows.

In the spanwise-periodic baseline flow shown in Fig. 3 (left), the shear layer rolls up into large spanwise aligned vortices after the flow passes over the leading edge and convects downstream. Smaller-scale turbulent vortical structures appear around the primary spanwise vortices. As these vortices advect downstream, the large structures lose coherence around $x/D \approx 4$. Large pressure fluctuations are prominent in two regions: one is in the shear-layer region ($1 \leq x/D \leq 4$), where the intense fluctuations are carried by the spanwise coherent vortex, and the other one is near the cavity trailing edge, where the large-scale vortical structures impinge on the aft wall.

For the finite-span cavity flow shown in Fig. 3 (right), the shear layer rolls up into large spanwise aligned vortices after the flow passes over the leading edge and convects downstream. Smaller-scale turbulent vortical structures appear around the primary spanwise vortices. As these vortices advect downstream, the large structures lose coherence around $x/D \approx 4$. Large pressure fluctuations are prominent in two regions: one is in the shear-layer region ($1 \leq x/D \leq 4$), where the intense fluctuations are carried by the spanwise coherent vortex, and the other one is near the cavity trailing edge, where the large-scale vortical structures impinge on the aft wall.

For the finite-span cavity flow shown in Fig. 3 (right), the spanwise coherent vortices roll up near the cavity leading edge, similar to that observed for the spanwise-periodic case. However, the sidewall edges bend these large spanwise vortices near the sidewalls and instigate the breakdown of the large coherent structures earlier. Investigation of numerous instantaneous snapshots indicate that the large vortical structures rarely appear after $x/D \approx 3$ compared to the spanwise-periodic case. Moreover, the presence of the sidewalls
results in the formation of streamwise vortices that spread out away from the cavity. We also observe a reduction in instantaneous pressure fluctuations in the shear-layer region and on the aft wall of the finite-span cavity flow compared to the spanwise-periodic case. Detailed discussion on rms pressure is provided later to illustrate these reductions in the finite-span case.

For cavity flows at $M_\infty = 1.4$, compressibility plays a larger role in affecting the flow characteristics. As shown in Fig. 4 (left) for $M_\infty = 1.4$, large density gradient magnitudes $|\nabla \rho|$ on the midspan $z/D = 0$ are captured above the cavity, indicating strong compression waves as seen in Fig. 4b. These waves are generated due to either the obstructions caused by the spanwise vortex roll-up in the shear layer or their impingement on the aft wall. Because of the emission of these compression waves, the normalized pressure fluctuations above the trailing edge become more intense than in the case of the subsonic flows. This is depicted from the rms pressure discussion presented later.

For the finite-span cavity flow at $M_\infty = 1.4$, the development of spanwise coherent structures is hindered because of the sidewalls, and streamwise vortical structures are formed from the lateral edges, in a manner similar to those observed from the subsonic cases. It is noteworthy that once the shear-layer roll-ups are weakened, the source of the compression waves in the shear-layer region is diminished. Hence, the density gradient magnitudes above the cavity in the finite-span cavity flow are lower than those in the spanwise-periodic cavity flow, as shown in Fig. 4b. The discussion on rms pressure presented later further supports this observation.

A global view of the normalized rms pressure is shown in Fig. 5. It is noted that all the reported pressure quantities are normalized by freestream dynamic pressure $((1/2)\rho_\infty u_\infty^2)$. To reveal locations of most intense pressure fluctuations, we choose the midspan $z/D = 0$ for the finite-span cases as a reference plane where the largest $p_{\text{rms}}$ in the shear layer is observed compared to the other $x$-$y$ planes. In the spanwise-periodic cases, the $p_{\text{rms}}$ distribution in the shear layer is nearly uniform in the spanwise direction; as such, the $z/D = -1$ plane is visualized. For both $M_\infty = 0.6$ and 1.4 cases, large values of rms pressure are observed mainly in the shear-layer region and near the trailing edge. However, because the sidewalls of the finite-span cavities hinder the development of spanwise roll-ups, the maximum rms pressure in the shear layer is reduced by 9 and 30% for $M_\infty = 0.6$ and 1.4, respectively, compared to the spanwise-periodic cases. Moreover, the regions of large pressure fluctuations $p_{\text{rms}}/((1/2)\rho_\infty u_\infty^2) > 0.2$ in the shear layer verify that the shear-layer roll-ups are weakened in the finite-span cases compared to that of the spanwise-periodic ones. We also integrate the rms pressure on the aft wall, denoted as $\bar{p}_{\text{rms}}$, and list their values in Table 2. In the baseline flows, $\bar{p}_{\text{rms}}$ in the finite-span cases are smaller than those in the spanwise-periodic cases by 30 and 21% for $M_\infty = 0.6$ and 1.4, respectively, indicating a reduced strength of the flow impingement on the aft wall. The controlled results are also provided in the table here for comparisons, which will be discussed later in Sec. III.B.

In addition to the large rms pressure in the shear layer and on the aft wall, pressure fluctuations are intense in the region above the trailing edge at $M_\infty = 1.4$ in the spanwise-periodic cases because of the compression waves generated around the trailing edge in the supersonic flow. However, these wave-induced fluctuations decrease in the finite-span cavity flow due to the lack of presence of spanwise coherent structures as revealed from the instantaneous flowfields.

Fig. 3 Isosurfaces of instantaneous $Q(D/u_\infty)^2 = 14$ colored by $C_p = (p - p_\infty)/((1/2)\rho_\infty u_\infty^2)$ from the baseline flowfields at $M_\infty = 0.6$: a) perspective, b) side, and c) top views of the spanwise-periodic and finite-span cavity flows.
such as that shown in Fig. 4b. With an increase in Mach number from $M_\infty = 0.6$ to 1.4 for both spanwise-periodic and finite-span cases, we further notice a stabilizing effect due to compressibility [15] that the roll-up of the shear layer is delayed. The maximum normalized rms pressure is reduced, and its location moves farther downstream in the supersonic case. This stabilizing effect of compressibility has also been observed in the experimental work by Beresh et al. [7].

Strong resonances in velocity and pressure fluctuations for cavity flows are known as Rossiter modes with a semi-empirical formula [4]. Heller et al. [28] further modified the expression to better predict the resonant frequencies observed from simulations and experiments as shown next:

$$S_{\text{L}} = \frac{f L}{u_\infty} = \frac{n - \alpha}{1/\kappa + M_\infty/\sqrt{1 + (\gamma - 1)M_\infty^2/2}}$$

where the empirical constant $\kappa (\approx 0.65)$ is the average convective speed of disturbance in the shear layer, $\alpha (\approx 0.38)$ is the phase delay [37], $\gamma = 1.4$ is the specific heat ratio, and $n = 1, 2, \ldots$

| $M_\infty$ | Spanwise boundary condition | Baseline | Controlled | Reduction, % |
|-------------|----------------------------|---------|------------|-------------|
| 0.6         | Spanwise-periodic          | 0.401   | 0.228      | -43.1       |
| 0.6         | Finite-span                | 0.281   | 0.213      | -24.2       |
| 1.4         | Spanwise-periodic          | 0.383   | 0.314      | -18.0       |
| 1.4         | Finite-span                | 0.305   | 0.277      | -9.2        |

Table 2 Integrated pressure fluctuations

$$\bar{p}_{\text{rms}} = \int_{S_{\text{aftwall}}} (\rho_{\text{rms}}/(1/2\rho_\infty u_\infty^2)) \, dS$$

on the aft wall in all the cases considered (the reduction is evaluated as $(\bar{p}_{\text{rms, controlled}} - \bar{p}_{\text{rms, baseline}})/\bar{p}_{\text{rms, baseline}} \times 100\%$)

Fig. 4 Isosurfaces of instantaneous $Q(D/u_\infty)^2 = 14$ colored by $C_p$ from the baseline flowfields at $M_\infty = 1.4$: a) perspective, b) side, and c) top views of the spanwise-periodic and finite-span cavity flows. The contours of density gradient magnitude $|\nabla \rho|$ on the midspan ($z/D = 0$) are shown in the side views.

Fig. 5 Normalized pressure fluctuations $p_{\text{rms}}/(1/2\rho_\infty u_\infty^2)$ of baselines for the spanwise-periodic and finite-span cavity flows at $M_\infty = 0.6$ and 1.4. Pressure time series are collected from the probe as illustrated in the plot.
denotes the nth Rossiter mode. We use Welch’s method [50] with 75% overlap and Hanning window to calculate the power spectra of the pressure time series collected from a probe located in the middle of the aft wall [x, y, z]/D = [0.6, 0.5, 0]. Non-dimensional power spectral density (PSD) over Strouhal number St_L is shown in Fig. 6. The shaded areas indicate uncertainty bounds representing 95% confidence. The resonant tones revealed from the spectra agree well with frequencies predicted by Eq. (2). For spanwise-periodic case at M∞ = 0.6, the dominant and subdominant Rossiter modes based on the measurement from the aft wall are modes II and I, respectively. This phenomenon is also observed in experimental work from Zhang et al. [37] with a higher Reynolds number for M∞ = 0.6 cavity flow. However, the peaks of these two modes are significantly suppressed in the finite-span case. For the spanwise-periodic case at M∞ = 1.4, the dominant Rossiter mode is III, and the subdominant modes are modes II and IV. In the finite-span case, Rossiter mode II is dominant, but its amplitude is smaller than the value from the spanwise-periodic case. The change of dominant Rossiter mode due to different cavity geometry has also been reported in studies by George et al. [38]. From their experimental study on cavity flow with Reynolds number of order ~O(10^7) at M∞ = 1.4, the dominant Rossiter mode shifts from Rossiter mode III to II when the cavity model is changed from spanwise-periodic to finite-span. Hence, the emergence of Rossiter modes is affected by the sidewalls for both cases at M∞ = 0.6 and 1.4. It should, however, be noted that the characteristics of the Rossiter modes, such as their dominance and amplitudes, are dependent on the location of the probe. The discussion here on Rossiter modes on the aft wall is treated as a representative but its amplitude is smaller than the value from the spanwise-periodic case. The change of dominant Rossiter mode due to different cavity period from spanwise-periodic to finite-span. Hence, the emergence of Rossiter modes is affected by the sidewalls for both cases at M∞ = 0.6 and 1.4. This phenomenon is also observed in experimental work from Zhang et al. [37] with a higher Reynolds number for M∞ = 0.6 cavity flow. However, the peaks of these two modes are significantly suppressed in the finite-span case. For the spanwise-periodic case at M∞ = 1.4, the dominant Rossiter mode is III, and the subdominant modes are modes II and IV. In the finite-span case, Rossiter mode II is dominant, but its amplitude is smaller than the value from the spanwise-periodic case. The change of dominant Rossiter mode due to different cavity geometry has also been reported in studies by George et al. [38]. From their experimental study on cavity flow with Reynolds number of order ~O(10^7) at M∞ = 1.4, the dominant Rossiter mode shifts from Rossiter mode III to II when the cavity model is changed from spanwise-periodic to finite-span. Hence, the emergence of Rossiter modes is affected by the sidewalls for both cases at M∞ = 0.6 and 1.4. It should, however, be noted that the characteristics of the Rossiter modes, such as their dominance and amplitudes, are dependent on the location of the probe. The discussion here on Rossiter modes on the aft wall is treated as a representative but should not be considered as the global behavior of the flow.

Based on the preceding results, the sidewalls in the finite-span cavity appear to hinder the development of the shear-layer roll-ups, which leads to the modification of pressure fluctuation level and Rossiter mode behavior. Moreover, the lateral edges of the sidewalls can introduce three-dimensionality into the flow as streamwise vortices are generated along the lateral edges, as shown in Figs. 3 and 4. Here, we use isosurfaces of helicity \( \hat{u} \cdot \hat{w} \) to visualize the streamwise vortices aligned with the direction of the flow. Helicity is adopted to visualize streamwise vortices without highlighting the dominant spanwise vortices and the near-wall vorticity in the boundary layers. As shown in Fig. 7, for both M∞ = 0.6 and 1.4, large regions of helicity appear along the lateral edges. Because the flow is predominant in the streamwise direction, the opposite sign of helicity on the side faces of the lateral edge suggests that streamwise vortices develop near the lateral edges and rotate in opposite directions around the corner from each side edge. As shown in the zoomed-in subplot of time-averaged \( \hat{v} - \hat{w} \) velocity flowfield at slice x/D = 4 from the left sidewall edge, the flow outside of the cavity near the horizontal surface is directed into the cavity, forming a negative streamwise vortex, whereas the flow inside the cavity and close to the sidewall moves upward, inducing a positive streamwise vortex. The formation of the streamwise vortices due to the lateral edges is similar in both subsonic and supersonic cases. This streamwise-aligned vortices have also been captured from an experimental study by Crook et al. [25] and numerical work by Ohmichi and Suzuki [26]. For the spanwise-periodic flows, there are no prominent helicity structures due to absence of the cavity sidewalls; hence, the analogous helicity visualizations of spanwise-periodic cases are not shown here.

Thus far, we have discussed the shear-layer behavior driven by the two-dimensional Kelvin–Helmholtz instability. However, a strong variation in the spanwise direction is observed from the rms pressure distribution on the aft wall in the spanwise-periodic cavity flow at M∞ = 0.6 in Fig. 5. We speculate that there is a secondary motion present in the flow in addition to the nominally two-dimensional shear-layer flow over the cavity. Three-dimensional streamlines derived from time-averaged velocity flowfields are visualized in Fig. 7. The starting points of the streamlines are placed inside the cavity and integrated in both time directions. Only representative streamlines are plotted for visualization clarity, from which we observe that the majority of the flow moves out near the center of the trailing edge for M∞ = 0.6. For M∞ = 1.4, the flow moves out near the two corners of the trailing edge. The arrows near the trailing edges in Fig. 7 indicate these locations where the majority of the flow inside the cavity exits. The different paths of streamlines are likely affected by the flow motion inside the cavity. Hence, we further plot the \( \hat{v} - \hat{w} \) velocity flowfield at x/D = 5.5 (≈90% of cavity length in streamwise direction) to reveal the internal flows in Fig. 8. Only half of the flowfield is presented due to the symmetry of the flows about the midspan. In Fig. 8, the dotted black lines indicate the cavity midspan, whereas the dashed
blue lines indicate the periodic boundaries. The red dot highlights a contour line of $\bar{u} = 0$. As shown in Fig. 8b at $M_{\infty} = 0.6$, the flow moves upward near the midspan, lifting the shear layer. In contrast, for $M_{\infty} = 1.4$ in Fig. 8d, the flow moves downward near the midspan. This difference explains the aft locations from which the flow leaves the finite-span cavities at $M_{\infty} = 0.6$ and 1.4. This secondary motion is most prominent in the rear part of the cavity, which has also been observed in past studies. Crook et al. [25], George et al. [51], and Zhang [52] have experimentally found a strong spanwise motion located near the cavity aft wall using particle image velocimetry and oil-flow visualization. Global instability analyses on cavity flows [18,20] have also captured centrifugal modes that possess spanwise motion, which mainly reside in the aft part of the cavity.

To examine the influence of the sidewalls on the secondary motion, the spanwise-periodic cases are also visualized in Figs. 8a and 8c for comparison. It should be noted that the flow direction near the spanwise-periodic case at $M_{\infty} = 0.6$ and 1.4, the streamwise velocity fluctuation $u_{rms}$ is integrated on the $x/D = 5.5$ for the baseline flows.

![Fig. 8 Contours of time-averaged streamwise velocity $\bar{u}/u_{\infty}$ (dashed lines for negative values) with an increment of $\Delta \bar{u}/u_{\infty} = 0.1$, and quiver of time-averaged velocities $\langle \bar{u}, \bar{w} \rangle/u_{\infty}$ colored by $\bar{v}/u_{\infty}$ at $x/D = 5.5$ for the baseline flows.](Image)

momentum transport under the influence of the sidewalls based on velocity fluctuation and Reynolds stress. Each component of velocity fluctuations (rms) is integrated on the $y-z$ planes with $-1 \leq y/D \leq 1$ and $-1 \leq z/D \leq 1$ to consider the overall fluctuations along the streamwise direction without being biased at a specific $y$ or $z$ location. As shown in Fig. 9 for the spanwise-periodic cavity flows at $M_{\infty} = 0.6$, the streamwise velocity fluctuation $u_{rms}$ is the largest component and keeps increasing as the flow approaches the trailing edge. The transverse velocity fluctuation $v_{rms}$ saturates after $x/D \approx 3$. Although the spanwise velocity fluctuation $w_{rms}$ is smaller than $v_{rms}$ at each location, it reaches a comparable magnitude to $v_{rms}$ around $x/D \approx 5$. In the finite-span case, a similar trend is observed but with reduced magnitudes in the velocity fluctuations. Analogously, we further examine the Reynolds stress by integrating their absolute values $|\tau_{ij}|$ as shown in Fig. 9 (right). In the spanwise-periodic case, the Reynolds stress $|\tau_{xy}|$ is the largest component because the primary oscillations in the velocity flowfields are due to the shear-layer roll-up. The integrated value of $|\tau_{xy}|$ increases until $x/D \approx 3$ and saturates, where the roll-ups break into small-scale structures. As the flow approaches the trailing edge, the Reynolds stresses in the other directions, $|\tau_{zz}|$ and $|\tau_{yy}|$, grow due to turbulent mixing, but their magnitudes are almost negligible compared to the primary Reynolds stress $|\tau_{xy}|$. For the finite-span case, the sidewalls interfere with the development of spanwise coherent structures, causing the Reynolds stress $|\tau_{xy}|$ to be relatively smaller than that of the spanwise-periodic case. However, slight increases in $|\tau_{zz}|$ and $|\tau_{yy}|$ are observed in the finite-span cavity flow, which are caused by the enhanced mixing of the flows near the lateral edges.

The preceding analysis of rms velocity and Reynolds stress over the cavities integrates the variation of the flow in the spanwise direction. Hence, representative $x-y$ planes are visualized in Fig. 10 to reveal spatial distributions of these quantities. For the spanwise-periodic cavity flow at $M_{\infty} = 0.6$, $\tau_{xy}$ is the dominant component, whereas the other two Reynolds stresses are almost negligible along the midspan ($z/D = 0$). However, along the plane at $z/D = 0.5$, $\tau_{xy}$ decreases slightly, whereas $\tau_{zz}$ and $\tau_{yy}$ increase.

![Fig. 9 Integrated rms velocity $u_{rms}/u_{\infty}$ (left) and Reynolds stress $\tau/\bar{u}^3$ (right) on $y-z$ planes for the baseline flow of spanwise-periodic (solid line) and finite-span (dashed line) cases at $M_{\infty} = 0.6$.](Image)
In other words, the momentum fluctuations carried by the shear layer are transported to the spanwise direction significantly at the location where the spanwise motion is prominent. Therefore, the secondary motion discussed previously enhances the turbulent mixing inside the cavity. For the finite-span case, because the secondary motion is similar to the spanwise-periodic cavity flow, large Reynolds stress $\tau_{xz}$ on offset plane at $z/D = 0.5$ is also captured inside the cavity.

For both $M_\infty = 1.4$ cases, the most significant change in velocity fluctuations is the decrease in

$$\int_{S_{zc}} |\tau_{yz}|/u_\infty^2 dS$$

before $x/D = 3$, as shown in Fig. 11 (left), compared to the subsonic cases (Fig. 9, left). The integration area is the same as that used in Fig. 9. This compressibility effect on stabilizing transverse velocity fluctuations has also been reported in the experimental work by Beresh et al. [7]. Because of the reduced fluctuation in transverse velocity, large Reynolds stress

$$\int_{S_{zc}} |\tau_{yz}|/u_\infty^2 dS$$

in Fig. 11 (right) emerges slightly downstream compared to the subsonic flows in Fig. 9 (right).

The enhancement of turbulent flow mixing via secondary motion is also seen in supersonic flows, which is that kinetic energy is transferred from the primary shear-layer oscillation into the spanwise direction. In Fig. 11, the integrated $|\tau_{xz}|$ and $|\tau_{yz}|$ of the finite-span cases are approximately double their respective values from the spanwise-periodic flows. Because there is a lack of significant secondary motion present in the spanwise-periodic cavity flow at $M_\infty = 1.4$ (in Fig. 8), $|\tau_{xz}|$ and $|\tau_{yz}|$ are thus mainly generated from turbulent mixing, and yet their values are still almost negligible compared to $|\tau_{yz}|$. However, in the finite-span case, the sidewalls induce prominent secondary motion inside the aft part of the cavity, which leads to increases in $|\tau_{xz}|$ and $|\tau_{yz}|$ at $z/D = 0.5$, as seen in Fig. 12. Hence, the phenomenon that secondary motion increases turbulent mixing is also observed in the supersonic flow.

### B. Control Effects

With the insights and findings obtained from studying the baseline flows, let us further discuss the influence of flow control applied for the purpose of reducing the pressure fluctuations in the cavity flows. In the controlled flows, three spanwise aligned slotted jets are evenly placed along the cavity leading edge, introducing steady transverse blowing into the boundary layer, as described in Table 1.

Instantaneous visualizations of the controlled flows are presented in Fig. 13 for $M_\infty = 0.6$. For the spanwise-periodic case, three
streaks are created from the slotted-jet control input, hindering the formation of large-scale spanwise coherent vortices near the cavity leading edge and enhancing the shear-layer mixing. The structure of the spreading shear layer appears more linear compared to the intermittent feature from baseline flows (Fig. 3b). The streaks visualized by instantaneous $Q$ can be observed up to $x/D \approx 2$, after which the flow becomes well mixed in the spanwise direction. Moreover, there are no prominent large vortex cores present over the cavity. As a consequence, the large pressure fluctuations induced by the shear-layer roll-ups in the uncontrolled case (Fig. 3) are expected to be reduced. Here, only a representative snapshot is displayed; however, an examination of multiple snapshots reveals similar behavior of the flows described previously. The observation of reduced fluctuations with control will be further verified from the rms pressure plot shown later.

In the controlled finite-span case, similar changes to the shear-layer behavior are observed compared to the spanwise-periodic cavity flow shown in Fig. 13. The absence of large spanwise vortical structures is expected to lead to the attenuation of streamwise vortical structures formed from the lateral edges. The sidewall effects on the instantaneous flow do not appear as significant as in the baseline cases. Once the effects of the slotted jets break large vortical structures into small-scale ones, the influence of the sidewalls on the flow structures weakens such that the flow features from the spanwise-periodic and the finite-span controlled cases are nearly indistinguishable over the cavities.

As shown in Fig. 15 for the controlled spanwise-periodic cavity flow at $M_{\infty} = 1.4$, similar streaks from slotted jets are observed and prevent the formation of spanwise coherent vortical structures. Moreover, shocks are pinned at the leading edge, as shown in Fig. 15b compared to the baseline flows in Fig. 4. Because of the diminishment of the formation of the shear-layer roll-ups, the compression waves generated from spanwise coherent structures are attenuated. Although a large density gradient magnitude is captured at the location of the slotted jet where the shocks are formed, this local increase in $\nabla \rho$ is negligible compared to the overall changes in the flows. Analogous to the discussions for the subsonic cases, the sidewall effects appear insignificant in the finite-span controlled case because there are no large-scale structures present in the flow. The observations from the spanwise-periodic controlled case also apply to the finite-span cavity flow.

A global view of rms pressure is presented in Fig. 14 for the controlled flows. Because of the diminishment of the large-scale shear-layer roll-ups, there are significant reductions of pressure fluctuations in the entire flowfields, especially in the shear-layer region and on the cavity aft wall compared to the rms pressure of baseline flows shown in Fig. 5. The values of integrated rms pressure $p_{\text{rms}}$ are listed in Table 2. In a comparison of $p_{\text{rms}}$, between the spanwise-periodic and finite-span controlled cases, there is no significant difference in their values for both Mach numbers. This further verifies the observation from the instantaneous flowfields that the sidewall effects do not play an important role in the controlled flows. The margin of reduction with flow control is relatively smaller in the finite-span case than in the spanwise-periodic case due to the lower baseline fluctuations in the finite-span cavity flows. Moreover, the rms pressure is reduced above the cavity trailing edge in the supersonic cases as the compression waves are suppressed.

Power spectra of pressure time histories on the cavity aft wall are reported in Fig. 16 for the controlled flows with the same setting used for the baseline flows (Fig. 6). At $M_{\infty} = 0.6$, for the spanwise-periodic case, the power of all the Rossiter modes decreases in Fig. 16a compared to the baseline results (Fig. 6). The prominent peak in the controlled case is associated with Rossiter mode I, and the power of the dominant Rossiter mode II from the baseline is reduced by 126%. In the finite-span controlled case, the powers of almost all the Rossiter modes are reduced compared to those in the baseline flows (Fig. 6).

For $M_{\infty} = 1.4$, in the spanwise-periodic case shown in Fig. 16b, although the powers of Rossiter modes I, II, and III are still comparable to the baseline results (Fig. 6b), the overall spectral levels are reduced, especially for the high-frequency components with $St_{\lambda} > 1.5$, which leads to a global reduction in the pressure fluctuations. In the finite-span controlled flow, Rossiter modes II and III are prominent, and all the powers of Rossiter modes are suppressed with the control compared to the baseline flows (Fig. 6).

From the baseline flow results (Fig. 8), we noticed the presence of secondary motion in the flows and its interaction with the shear layer toward the rear of the cavity. To further investigate its role in controlled flows, we visualize the mean velocity flowfield along the $x/D = 5.5$ plane in Fig. 17, in which we follow the same approach used for Fig. 8 to visualize the flowfields for comparison. The dot-dashed black lines indicate the cavity midspan, whereas the dashed blue lines indicate the periodic boundaries. The red dot highlights a contour line of $u = 0$. In Fig. 17, there is one prominent...
Fig. 14 Normalized pressure fluctuations \( \frac{p_{\text{rms}}}{(1/2) \rho_\infty u_\infty^2} \) of controlled cases for the spanwise-periodic and finite-span cavity flows at \( M_\infty = 0.6 \) and 1.4.

Fig. 15 Isosurfaces of instantaneous \( Q(D/u_\infty)^2 = 14 \) colored by \( C_p \) from the controlled flowfields at \( M_\infty = 1.4 \) with \( C_p = 0.0194 \): a) perspective, b) side, and c) top views of the spanwise-periodic and finite-span cavity flows. The contours of density gradient magnitude \( \| \nabla \rho \| \) on the midspan \( (z/D = 0) \) are shown in the side views.

Fig. 16 Power spectral analysis of pressure \( p/(1/2) \rho_\infty u_\infty^2 \) on the aft wall for the controlled flows at \( M_\infty = 0.6 \) and 1.4. Spanwise-periodic case (blue) and finite-span case (red) with dashed lines indicating baseline results. The predicted Rossiter mode frequencies using Eq. (2) are denoted by gray dashed lines.
feature observed in all cases. The flow near the midspan moves downward with a spanwise motion near the cavity floor toward the sides. For $M_\infty = 0.6$ shown in Figs. 17a and 17b, the flows are modified to move downward near the midspan rather than upward as captured in the baseline flows shown in Figs. 8a and 8b. However, for $M_\infty = 1.4$ in Figs. 17c and 17d, the flow motions inside the cavity remain similar to the baseline flows except that there is a larger secondary motion appearing in the spanwise-periodic case (Fig. 17c). In the control cases, three slots are placed evenly along the leading edge, but flows around $x/D = 5.5$ do not present any features related to the slot placement, and there is no apparent connection between the spanwise locations of the primary downward motion. Based on the discussions of the instantaneous flowfield in Figs. 13 and 15, the three-dimensionality introduced by the slotted jets decays as the flow convects downstream. The sustained extent of these three-dimensionality from the jets is dependent on the momentum coefficient $C_\mu$, which has been reported in the work by Zhang et al. [37]. The jets affect the development of the shear layer and then indirectly change the secondary motion present in the rear part of the cavity.

To evaluate the control performance, we integrate the absolute value of $\tau_{xy}$ at various $x-y$ planes with $0 \leq x/D \leq 6$ and $-1 \leq y/D \leq 1$ because this area covers the primary motion of shear-layer roll-up. As shown in Fig. 18, the spanwise-averaged values denoted by dashed lines reveal significant reductions in Reynolds stress $|\tau_{xy}|$ with control. In the spanwise-periodic cases, 30 and 28% reductions are achieved for $M_\infty = 0.6$ and 1.4, respectively. In the finite-span cases, 23 and 21% reductions are achieved for $M_\infty = 0.6$ and 1.4, respectively. Moreover, in the controlled cases, the locations of the integrated $|\tau_{xy}|$ maxima almost correspond to the slotted-jet locations indicated by short horizontal lines in Fig. 18.

As discussed previously, control mitigates the effects of the sidewalls. As such, the integrated rms velocity and Reynolds stress are very similar in the spanwise-periodic and the finite-span controlled cases, as shown in Figs. 19 and 20 for $M_\infty = 0.6$ and 1.4, respectively. For $M_\infty = 0.6$ (Fig. 19, left), the introduction of the slotted jets increases all components of velocity fluctuation $u_{\text{rms}}$ before $x/D = 2$ compared to the baseline results (Fig. 10, left). However, decreases in $u_{\text{rms}}$ are observed after $x/D = 2$. Accordingly,
Fig. 20 Integrated rms velocity $u_{rms}/u_{in}$ (left) and Reynolds stress $\tau/u_{in}^2$ (right) on $y-z$ planes for the controlled flow of spanwise-periodic (solid line) and finite-span (dashed line) cases at $M_{in} = 1.4$.

Fig. 21 Reynolds stress $\tau/u_{in}^2$ on x−y planes at $z/D = 0$ (midspan in line with a slot center) and 0.5 (in between two slots) for the controlled flows at $M_{in} = 0.6$.

Fig. 22 Reynolds stress $\tau/u_{in}^2$ on x−y planes at $z/D = 0$ (midspan) and 0.5 for the controlled flows at $M_{in} = 1.4$. The same analysis for baseline flows is referred to Fig. 12.

$|\tau_{xz}|$ increases significantly before $x/D = 2$ and decreases downstream ($x/D > 2$) as shown in Fig. 19 (right).

The Reynolds stresses $\tau/u_{in}^2$ on $x-y$ planes are visualized in Fig. 21 for $M_{in} = 0.6$. The locations of the $x-y$ planes are chosen to be aligned with the slot center ($z/D = 0$) and in between ($z/D = 0.5$) the slots. For both spanwise-periodic and finite-span cases, large values in $\tau_{xz}$ are captured at $z/D = 0.5$ because streamwise vortices are formed from the edges of the jets. These induced streamwise vortices remain coherent up to $x/D \approx 3$ and gradually vanish. From the work of Zhang et al. [37], higher values of the momentum coefficient $C_p$ are shown to sustain the spanwise signature of 3-D vortices. $C_p$ is too low, the three-dimensionality added into the flow from the jets attenuates too fast, which could lead to the reemergence of shear-layer roll-ups and yield large fluctuations in the aft part of the cavities. Detailed discussions on the effects of $C_p$ and Mach number on the control performance can be found in our companion studies [37,38].

The influence of the slotted jets on the coherent structures is concentrated in the front half of the cavity, which is the critical region for the shear layer to roll up into spanwise coherent structures. We also find that the turbulent motion is weakened in terms of a reduced Reynolds stress of $|\tau_{xz}|$ in the spanwise period of the controlled flows at $M_{in} = 0.6$. However, the Reynolds stress in the baseline flows are generated by the boundary layer motion that enhances turbulent mixing in the rear part of the cavity. Moreover, control effort decreases $|\tau_{xz}|$ by 50% at $x/D = 5.5$ for both spanwise-periodic and finite-span controlled flows (Fig. 19, right) compared to the baseline flows. Hence, the slotted jets alter the shear-layer roll-ups and further weaken the secondary motion inside the rear part of the cavities.

The cavity flow at $M_{in} = 1.4$ presents similar features compared to those at $M_{in} = 0.6$. In the controlled cases, there are increased velocity fluctuations in the front part of the cavity and decreased fluctuations due to the absence of shear-layer roll-ups, as shown in Fig. 19 (right). Moreover, in the finite-span case denoted by dashed lines in Fig. 20 (right), the Reynolds stress $|\tau_{xz}|$ after $x/D \approx 3$ is reduced compared to the baseline flows results (Fig. 11, right). This observation is similar to the subsonic cases in which the turbulent mixing via the secondary motion is weakened in the controlled flows. In the spanwise-periodic case, there is no apparent secondary motion present in the baseline flows. However, the secondary motion is present in the supersonic controlled flow, and the Reynolds stress $|\tau_{xz}|$ in the rear part of the cavity is slightly higher than that in the baseline flow. The Reynolds stress $\tau/u_{in}^2$ on different $x-y$ planes are shown in Fig. 22, in which an increase...
in $\tau_{sc}$ is captured between the adjacent slots at $z/D = 0.5$, but a significant reduction of the spanwise Reynolds stress $\tau_{sc}$ is achieved.

IV. Conclusions

In this study, the characteristics of 3-D compressible flows over rectangular cavities with aspect ratios of $L/D = 6$ and $W/D = 2$ at $Re_M = 10^5$ for baseline and controlled flows were investigated using LES. This work focuses on the influences of spanwise boundary condition and compressibility on both baseline and controlled flows.

For the baseline flows, large-amplitude pressure fluctuations are present in the shear-layer region and the cavity aft wall due to the spanwise vortex roll-ups and the flow impingement, respectively. For the supersonic flows at $M_a = 1.4$, strong compression waves can further induce fluctuations above the cavity. However, the overall pressure fluctuations in the flows are reduced once the sidewalls are added to the cavity in place of a periodic boundary condition. The formation of large spanwise coherent structures is hindered by the presence of the sidewalls, which leads to a reduction in the pressure fluctuations from the shear-layer region as well as on the aft wall. Compression waves generated from the shear-layer roll-ups are also weakened due to the absence of large spanwise coherent structures. It is further noticed that the reduced fluctuations of the flow with increasing the Mach number from 0.6 to 1.4 based on normalized quantities, which is in agreement with past experimental work [7]. Moreover, secondary motions are found in the flow inside the cavity, which are influenced by the sidewalls or 3-D instabilities [15] depending on the flow conditions. This secondary motion enhances the turbulent mixing, from which the kinetic energy in the shear layer is converted from the streamwise and transverse directions into the spanwise direction.

For controlled flows, steady slotted jets are introduced along the cavity leading edge based on the companion experimental work [37–39]. In the controlled flows, three-dimensionality imposed by three slotted jets inhibits the formation of the shear-layer roll-ups for both spanwise-periodic and finite-span cavity flows. With the shear-layer roll-ups inhibited by the control input, the pressure fluctuations are reduced significantly in the shear-layer region and cavity aft-wall. For the supersonic flows, the compression waves are also suppressed in the controlled cases.

The present work leverages 3-D LES to reveal the sidewall effects on the characteristics of the cavity flows, which brings valuable knowledge and insights for the conventional numerical studies with spanwise-periodicity assumption as well as practical engineering setups in experiments. Furthermore, these high-fidelity simulations uncover the control mechanisms that can provide insights for design of more effective control strategies in the future.

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