Experimental investigation of initial shear-layer effect on the pressure oscillation in supersonic cavity flows

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Abstract

In the present study, features of oscillatory supersonic flows over a rectangular cavity are measured by changing the initial shear-layer property for the purpose of validating the numerical flow simulation perfomed as future work. In the experiments, two inlet flows having the same Mach number of 1.7 and different initial shear-layer properties are tested. The pressure oscillation is measured at the bottom wall of the cavity by use of the semiconductor-type pressure transducer by changing the length-to-depth ratio of the cavity at each condition. The instantaneous flow fields are also visualized by the schlieren method with a high-speed camera. As a result, it is found that the dominant oscillation frequency and the strength in pressure oscillation depend strongly not only on the length-to-depth ratio but also on the initial shear-layer property.

Key words: cavity flow, supersonic flow, flow oscillation, mixing enhancement

Introduction

Since the 1950s, a lot of investigations have been performed in order to understand the complicated flow structure of a supersonic flow over a rectangular cavity [1-6]. This flow is known to oscillate at certain predominant frequencies due to the feedback mechanism that involves shear layer instability and pressure wave propagation in the cavity. Such oscillations are possibly utilized to enhance supersonic mixing in the scramjet engine combustor [7-11] and chemical oxygen and iodine laser (COIL) [12].

In utilizing the cavity-induced pressure oscillation in the mixing enhancement, it is desirable that the flow keeps oscillating when the flow encounters a change in inlet conditions. If the flow encounters an inlet condition at which the flow oscillation becomes weakened, the flow should be controlled so as to keep oscillating, which might be achieved by adjusting the cavity depth. It is, therefore, important to predict the conditions at which the flow oscillates moderately. It is also important to understand the physical mechanism by which the oscillation is amplified or attenuated. In order to attain these, we have to rely on the computational fluid dynamics (CFD) because a lot of inlet conditions can be attempted in the numerical simulation more easily than in the experiment. In addition, the detailed flow behaviors by which the oscillation is amplified or attenuated may be found out in the numerical simulation. In contrast to such usefulness of CFD, the computational results should be checked carefully by the experimental results. However, it is difficult to validate the CFD results due to lack of experimental data.

The caivty-induced flow oscillation is expecded to sensitive to several parameters, such as inlet Mach number, Reynolds number, cavity length and depth, initial shear-layer property, and so on. The effect of inlet Mach number was investigated experimentally by Zhang and Edwards [5], who tested two inlet Mach numbers of 1.5 and 2.5 changing the cavity length L from L = 15 mm to L = 135 mm at the constant cavity-depth D (= 15 mm). According to their results, the flow at the Mach number of 1.5 osccilates more strongly than that at at the Mach number of 2.5 over all the tested L/D's.

Chandra and Chacravathy [6] measured the dominant oscillation frequenies by changing L and D at an inlet Mach number of 1.5. Their results reveal that the oscillation frequency is quite sensitive not only to L but also to D. Such a variation in frequency with respect to L/D is explained reasonably well by the oscillation model proposed by Handa and Masuda [7].

Upon reviewing the above studies, a question about supersonic cavity flows emerges. That is, how does the initial shear-layer property affect the characteristic of the cavity-induced flow oscillation? In order to answer this question, in the present study we test two inlet conditions with the same Mach number and the different initial shear-layer properties. In the experiments, the pressure oscillation is measured by changing the length-to-depth ratio of the cavity for both inlet conditions. The flow fields are also visualized by the schlieren method with a high-speed camera.

Experimental method

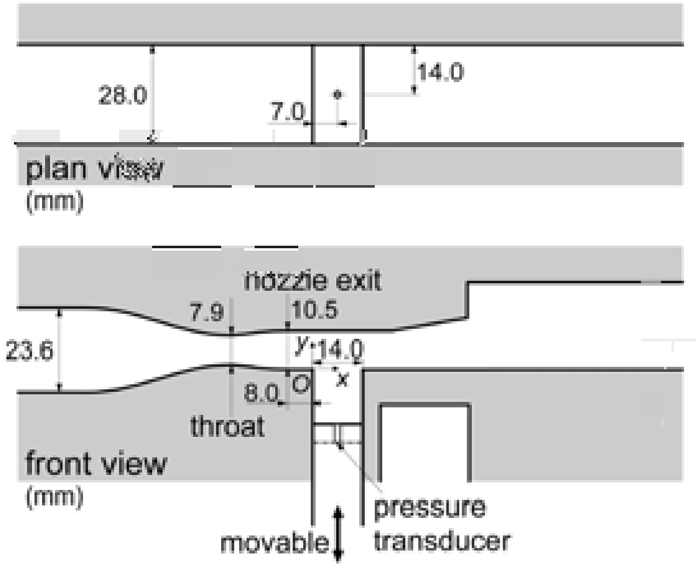
The experiments are carried out using a suction-type supersonic wind tunnel operated by dry nitrogen with atmospheric pressure and temperature. Before a tunnel run, the nitrogen is stored in the balloon that is connected to the stagnation chamber through a tube. This gas has a water content of less than 5ppm, and condensation in the duct is avoided by using this gas.

In order to investigate the effect of the initial shear-layer, two test ducts are designed as shown in Figures 1(a) and (b). Two symmetric contoured nozzles are designed using the method of characteristics. These are connected to the two test ducts, respectively. The Mach numbers at the nozzle exit are designed to be 1.7 and 2.0 for cases 1 (Fig. 1(a)) and 2 (Fig. 1(b)) respectively. However, the inlet Mach numbers can be set to the almost same value for both cases by making the distance from the nozzle exit to the leading edge of the cavity for case 2 longer than that for case 1. The inlet Mach numbers calculated from the static pressure measured at the location 6.0 mm upstream of the leading edge are 1.68 and 1.74 for case 1 and 2, respectively.

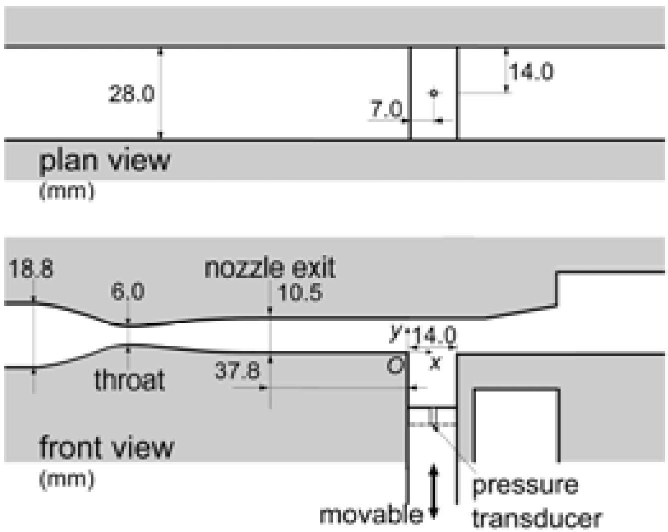
Both test ducts have the same rectangular cross-section whose height and width are 10.5 mm and 28.0 mm, respectively. The cavity length L is 14.0 mm and the cavity depth is adjustable. In the present experiments, the cavity depth is ranged from 4.7 mm to 28.0 mm (L/D = 0.5 − 3.0). Both test ducts have a section with a 10˚ divergence angle downstream of the cavity in order to avoid unstarting in the wind tunnel due to the boundary layer growth. The coordinate systems used to analyze the results are defined in Figs. 1(a) and (b), where x and y are the streamwise and height coordinates, respectively. The pressure and temperature in the stagnation chamber are maintained at 101 kPa and 301K respectively. The free-stream Reynolds number based on the duct height is 1.48×10^5.

The temporal variation of the static pressure is measured with a semiconductor-type pressure transducer (Kulite, XCQ-062-25SG). This transducer is mounted on the bottom wall of the cavity and is located 7.0 mm downstream of the front wall of the cavity and this is placed on the central plane of the duct. The temporal pressure signals are recorded by a digital oscilloscope (IWATSU DS-9121) at 1000k samples per second for a total of 16384 samples.

The oscillatory flow fields are visualized by the schlieren method. In the optical setup, two concave mirrors with focal lengths of 200 cm are used to collimate the light passing through the test section. The flow field is imaged through a single lens with a focal length of 100 cm and a diameter of 5 cm. Imaging scale is estimated to be ~0.6 for the present schlieren system. A camera with a fast frame rate (NAC Image Technology, ULTRA Cam HS-106E) is used to capture the schlieren images. The frame rate is set to 600,000 frames per second. The exposure time is set to 0.3 μs. One pixel on a digitized image corresponds to the physical size of 87.5 μm × 87.5 μm. The distance that the pressure wave propagates during the exposure time is estimated to be ~0.1 mm. This value indicates that the temporal resolution is high enough to capture the pressure waves in the flow field. The number of images captured per experimental run is 120. The light source is a xenon lump (Nissin



(a) case 1



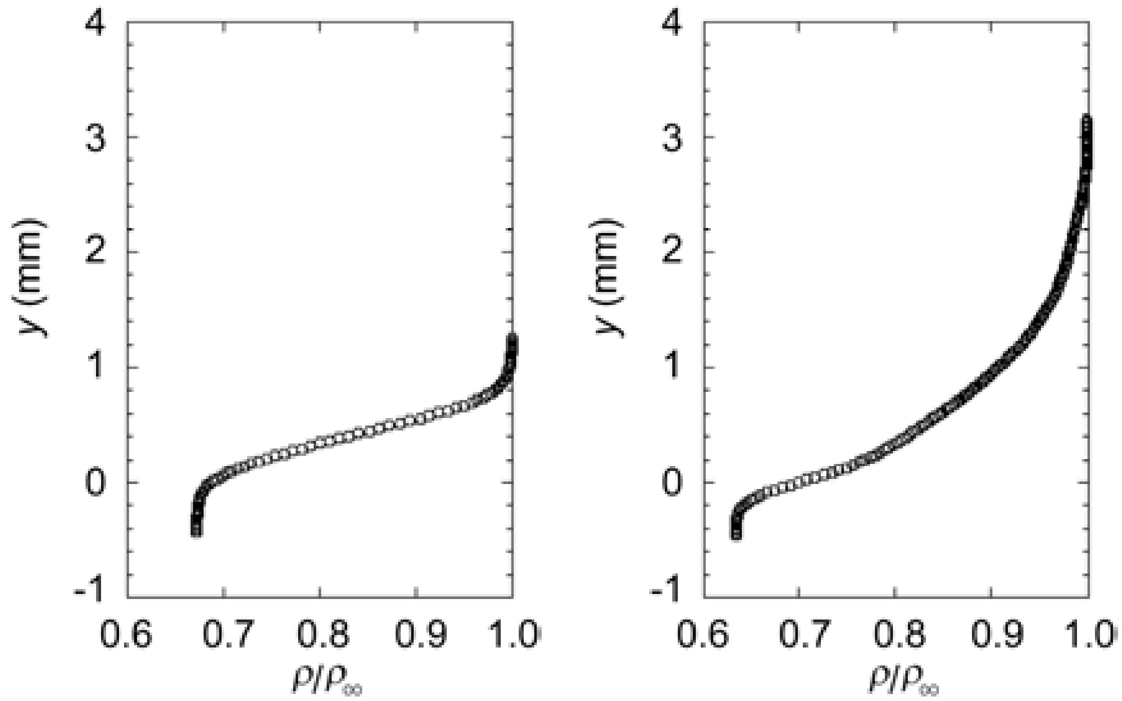
(b) case 2

Fig. 1 Test ducts

Electronic SAX-100H). The flash duration of this lump is ~1ms, and the light emission becomes stable 150 μs after the lump starts to flash. The capture of images, therefore, is started 150 μs after the flash.

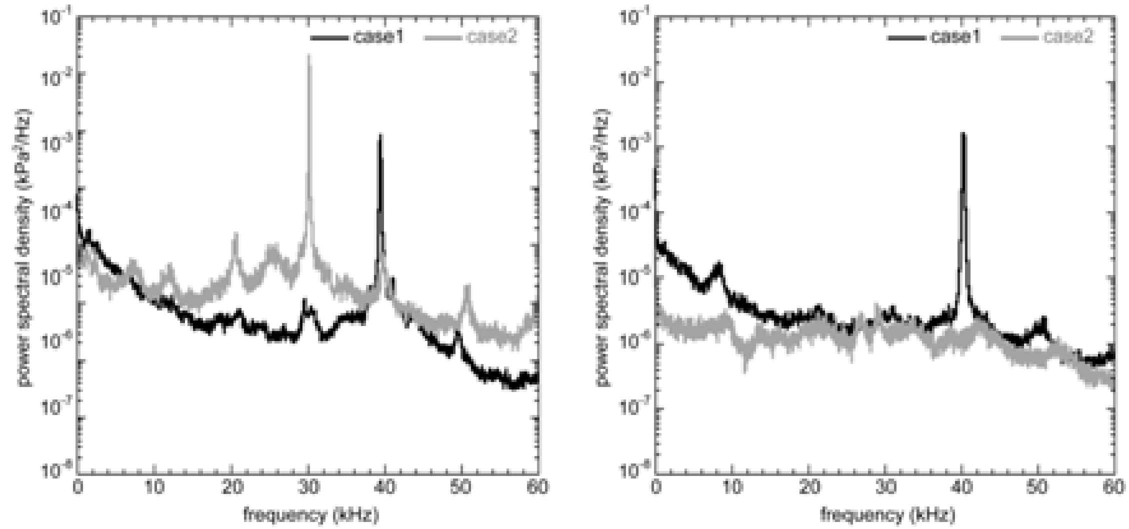
In order to measure the density profiles across the initial shear layer, another schlieren visualization is performed. In this visualization, a continuous light source (tungsten lump) is used with the same concave mirrors and lens as those used in the high-speed visualization. A charge coupled device (CCD) camera (Tokyo Electronic Industry, CS8310) is used to capture the schlieren images. The exposure time is set to 1/60 sec. One pixel on the digitized image captured in this camera corresponds to the physical size of 22.2 μm × 22.2 μm.

A density profile across the shear-layer is obtained by integrating the contrast of the digitized schlieren image along a *y*-direction from a point in the external flow to a point inside the cavity at which the flow is assumed to be stagnated. The density in the external flow is calculated from the time-averaged static pressure on the side



(a) case 1 **(b) case 2**

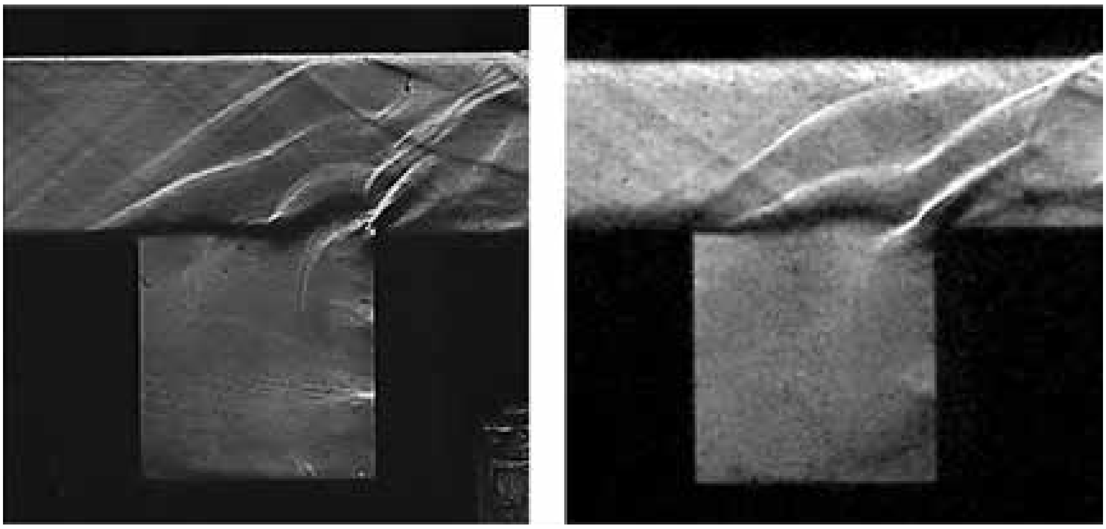
Fig. 2 Density profiles across the shear layer at *x*=1.0mm



(a) *L/D*=0.95 **(b) *L/D*=1.2**

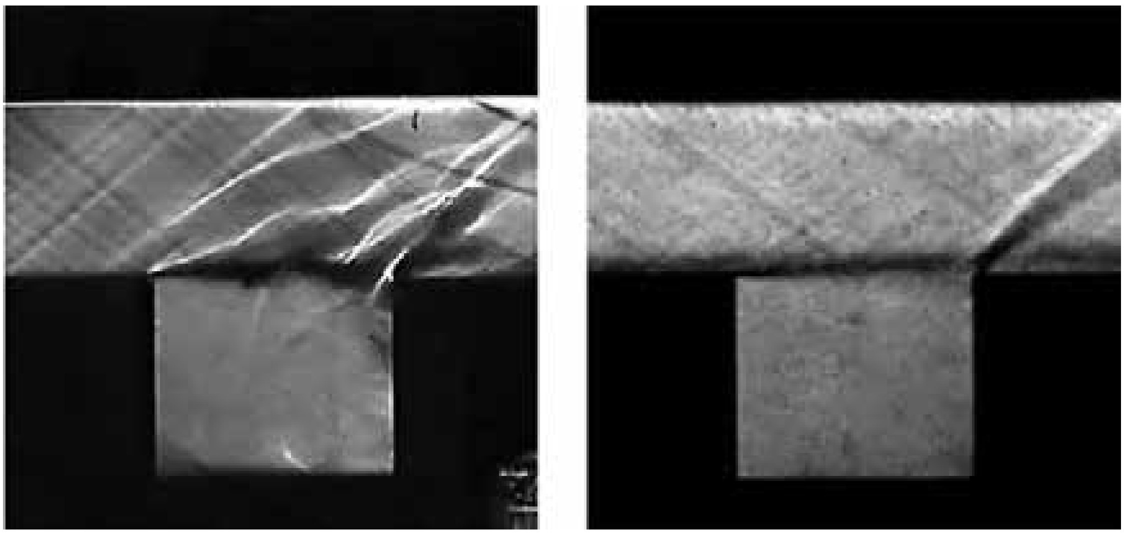
Fig.3 Power spectral density distributions

wall, the stagnation pressure and temperature in the prenum chamber. The density inside the cavity is calculated by assuming that the free-stream is stagnated adiabatically. The resulting density profiles at x = 1.0 mm are shown in Fig. 2. It is clear from this figure that the shear-layer for case 2 is thicker than that for case 1.



(a) case 1 **(b) case 2**

Fig. 4 Instantaneous schlieren images (*L/D*=0.95)



(a) case 1 **(b) case 2**

Fig. 5 Instantaneous schlieren images (*L/D*=1.2)

Results and Discussion

The power spectral density is calculated from the pressure signal measured on the bottom floor of the cavity for each *L/D*. The representative results are shown in Figs. 3(a) (*L/D* = 0.95) and (b) (*L/D* = 1.2). In Fig. 3(a), a sharp peak is observed for both cases 1 and 2. It is clear from these sharp spectral peaks that self-sustained oscillation occurs at *L/D* = 0.95 for both cases. However, the dominant frequencies are different between two cases at *L/D* = 0.95 (Fig. 3(a)). This implies that the initial shear-layer property strongly affects the dominant oscillation frequency. The flow oscillation is also recognized in the instantaneous schlieren images of Fig. 4. The pressure waves generated as a result of the oscillation are clearly observed above the cavity for both cases. The pressure waves are also seen clearly inside the cavity for case 1 (Fig. 4(a)), whereas not clearly seen for

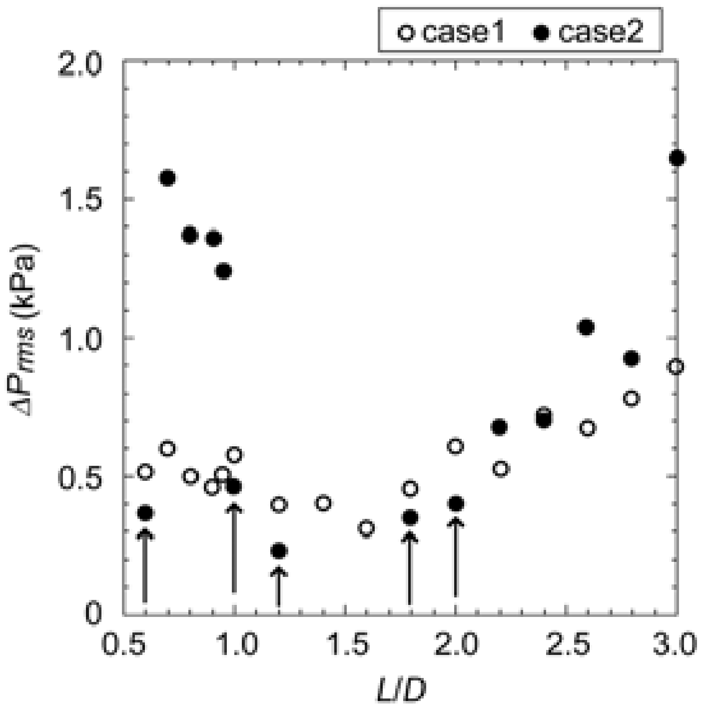


Fig.6 Plot of Δp_{rms} vs. *L/D*

case 2 (Fig. 4(b)). It is supposed that a three-dimensional flow might be formed inside the cavity for case 2. As a result of this three-dimensional flow, the pressure waves might have three-dimensional shapes. Therefore, it is concluded that the initial shear-layer property affects the three-dimensionality of the flow inside the cavity.

In Fig. 3(b) (*L/D* = 1.2), a sharp spectal peak is also seen only for case 1, whereas no remarkable peak is seen for case 2; i.e., the flow is quite steady for case 2. Such a steady flow is recognized in the instantaneous schlieren image of Fig. 5(b). No remarkable traveling pressure-waves are observed in this image. On the other hand, the pressure waves similar to those observed in Figs. 4(a) and (b) are also observed in Fig. 5(a). It is clear from the results for *L/D* = 1.2 that the initial shear-layer property affects the strength in flow oscillation because inlet flow parameters except initial the shear-layer profiles are the same between case 1 and 2.

The root-mean-square of the pressure fluctuation Δp_{rms} is calculated at each flow condition. The results are shown in Fig. 6. There are no data at *L/D*=1.4 and 1.6 for case 2 because unstarting occurs in the wind tunnel. It is found from the results that Δp_{rms} is strongly affected not only by the initial shear layer property but also by the length-to-depth ratio of the cavity. The results also reveal that there are several values of *L/D* at which a pressure oscillation for case 2 becomes much stronger than that for case 1, especially in deep-cavity flows, whereas, that there are also several values of *L/D* at which a flow is quite stable for case 2 (denoted by upward arrows). At present, we have no clear explanation for these phenomena. We have to rely on the computational fluid dynamics in order to clarify the reason why the flow is so selective in its oscillation even if the cavity length and inlet Mach number remain constant.

Conclusion

In the present study, features of oscillatory supersonic flows over a rectangular cavity are measured changing the initial shear-layer property for the purpose of validating the numerical flow simulation perfomed as future work. Two inlet flows having the same Mach number and different initial shear-layer properties are tested. The measurement results reveal that the initial shear-layer property strongly affects the dominant oscillation frequency and the strength in pressure oscillation especially in deep-cavity flows. At present, we have no clear reason why the dominant oscillation frequency becomes different between two flows produced under the same condition except the initial shear-layer properties, and why the flow selects, depending on the cavity depth, either an oscillatory state or a very quiet state even if the cavity length and inlet Mach-number remain constant. In order to clarify these reasons, the numerical flow simulation have to be performed and the resulting computational flow-fields have to be analyzed in detail.

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