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A Study of the Pressure Oscillation in a Supersonic Cavity Flow and Its Control

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Abstract
For the development of supersonic to hypersonic transports with high flight performance, a great interest has been taken in understanding the supersonic cavity flow features and associated unsteady phenomena during last several decades. According to the previous investigations, the pressure oscillation generated in the supersonic cavity flow is considered to be a severe source doing harm to overall performance and stable operation of aerodynamic and industrial applications, and it depends on the configuration of cavity, flow Mach number and Reynolds number. The present study describes unsteady flow phenomena generated in a supersonic flow passing over a rectangular cavity and suggests a way of control of the pressure oscillation. The three-dimensional, unsteady, compressible Navier-stokes equations are numerically solved based on a fully implicit finite volume scheme and large eddy simulation. The cavity flow is simulated with and without control methods, including a triangular bump and blowing jet installed near the leading edge of the cavity. The results show that the pressure oscillation can be attenuated by both control techniques, especially near the trailing edge of the cavity.

INTRODUCTION

A cavity system installed in a supersonic flow has a number of aerodynamic and industrial applications, and great interest has been taken in this research field during the last several decades[1-4]. For instance, cavity systems are applied to supersonic air intakes of aircraft, which address normal shock-related problems occurring in the final step of supersonic compression, consequently leading to the improvement of starting characteristics and engine efficiency. In the presence of a cavity system, however, strong pressure oscillation generated inside the cavity interferes in safe system operation[5]. For this reason, the design of cavity system should play a key role to improve overall system performance, and a systematic investigation needs to be carried out in order to devise control techniques to attenuate the pressure oscillation.

A typical supersonic cavity flow includes a shear layer generated from the leading edge of cavity, recirculations inside the cavity, an oblique shock wave induced by the shear layer developed from the leading edge of the cavity, and a bow shock/expansion wave system generated ahead of the trailing edge of the cavity. The inherent unsteadiness of cavity flow is concerned mainly with a time-dependent variation of shear layer structure, which leads to significant change in wave interaction with the shear layer and cavity walls, and recirculation characteristics in the cavity. These flow features result in severe pressure oscillation which may do harm to flight performance and stability, and the reduction of the oscillation has been one of the major considerations for aerodynamic applications with supersonic cavities.

The previous studies on the supersonic cavity flow have generally been conducted to examine external flow problems[6-8], primarily focused on reducing the aerodynamic drag of aircraft wings[9]. Researches regarding internal flow applications have been relatively limited, and in spite of considerable efforts made to offer an understanding of cavity flow physics to date, the detailed flow mechanism resulting in pressure oscillation has not been explained clearly yet. In addition, the main stream of cavity flow control has been active methods like a blowing jet, which require additional devices and energy to produce a jet flow, leading to an increase in payload and extra cost for flow control.

The present study aims at investigating the detailed mechanism of pressure oscillation inside the cavity, and developing a passive cavity flow control technique to overcome the defects of active control. The supersonic cavity flow is simulated with and without control methods, including a triangular bump installed near the leading edge of the cavity. The effectiveness of this method is examined with the results obtained using a bleed jet.

NUMERICAL METHODS

The present study adopted a commercial computational code, FLUENT 6, in order to analyze the unsteady characteristics of a supersonic cavity flow. The three-dimensional, unsteady Navier-Stokes equations governing the flow field in a rectangular cavity were discretized by an implicit finite volume scheme spatially and a multi-stage Runge-Kutta scheme temporally. Large Eddy Simulation (LES) using the Smagorinsky-Lilly model[10] is carried out to properly simulate the turbulent features of cavity flow.

Fig.1 shows the schematic diagram of the testing model used in the present computation. A rectangular cavity with a depth(D) of 20mm, a length(L) of 40mm

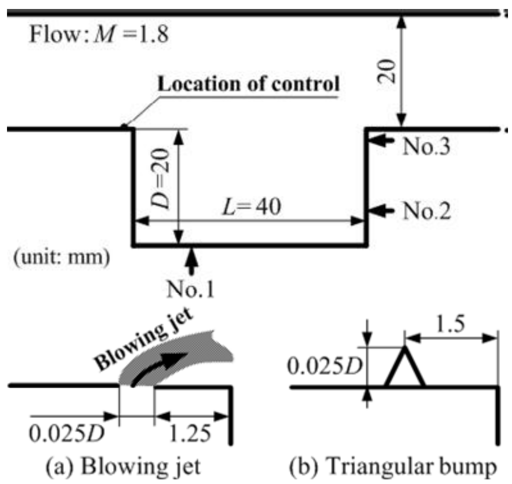


Fig. 1 Schematic diagram of the present cavity model (unit: mm)

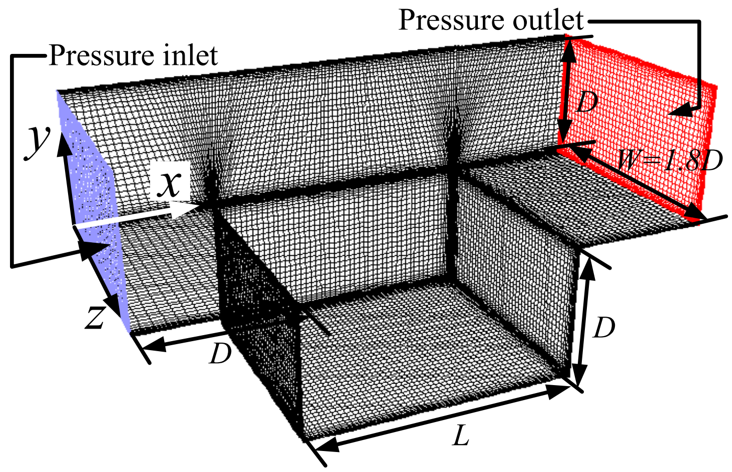
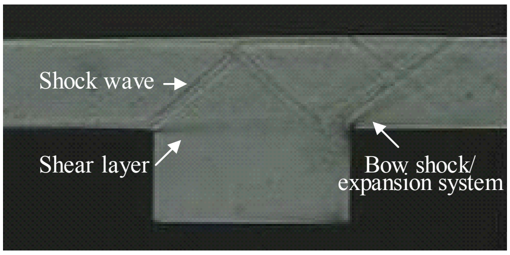


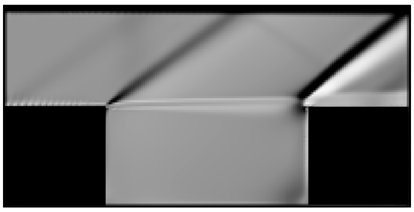
Fig.2 Computational grid system and boundary conditions

and a span (W) of 36mm is placed at a location of 20mm downstream of the nozzle exit. A blowing jet slit and a triangular bump to control pressure oscillation are installed at a location of 1.25 mm upstream from the leading edge. Mach number of main flow over the cavity is 1.8. Static pressure values along the cavity wall are measured at three points as shown in the figure(No.1~3), and then data obtained are analyzed by frequency analysis using FFT transform.

Fig.2 schematically illustrates the present computational domain and boundary conditions with grids. The length and height of computational domain are defined by 4D and 2D, respectively. A structured grid system with 700,000 nodes is considered. Grids are clustered in the regions where a large pressure gradient to be formed, is expected like near the wall region, jet slit, triangular bump, shear layer, and shock waves. Regarding the boundary conditions, at the inlet boundary, total pressure and temperature are used, while at the outlet boundary, static pressure is applied. No slip



(a) Shadowgraph



(b) Computed image

Fig. 3 Typical supersonic cavity flow (L/D=2 and M=1.8)

conditions are applied to all wall boundaries. The mass flow inlet condition is used for the case with a blowing jet, where a mass flow rate value of 0.0067kg/sec is applied at the exit of the blowing jet.

RESULTS AND DISCUSSION

Fig 3 gives the comparison between experimentally and numerically obtained results at M=1.8 and L/D=2. In the shadowgraph, it can be observed that, a shear layer is generated from leading edge of the cavity, an oblique shock wave is induced by the shear layer rear the leading edge of the cavity, and a bow shock/expansion wave system is formed in front of the trailing edge of the cavity. In comparison with the computed image, the angle of the oblique shock wave is slightly larger. This means that the flow Mach number in the experiment is lower than the computation. Excluding this feature, the present computation predicts the flow structure obtained from the experiment well.

Fig. 4 shows time-dependent density and pressure contours with corresponding velocity vectors to find the generation mechanism of pressure oscillation inside the cavity without control. In the figure, the non-dimensional time t' is defined as the ratio of computational flow time to the period concerned with the dominant frequency of pressure oscillation. The dominant frequency in the computation is predicted as about 11 kHz, and therefore the period is 9.09×10^{-5} sec. At t'=0, due to the region with an alternate change in high and low pressure, the shear flow horizontally generated from the leading edge of the cavity becomes more complicated towards the downstream, and the low pressure region with a downward flow occurs in the

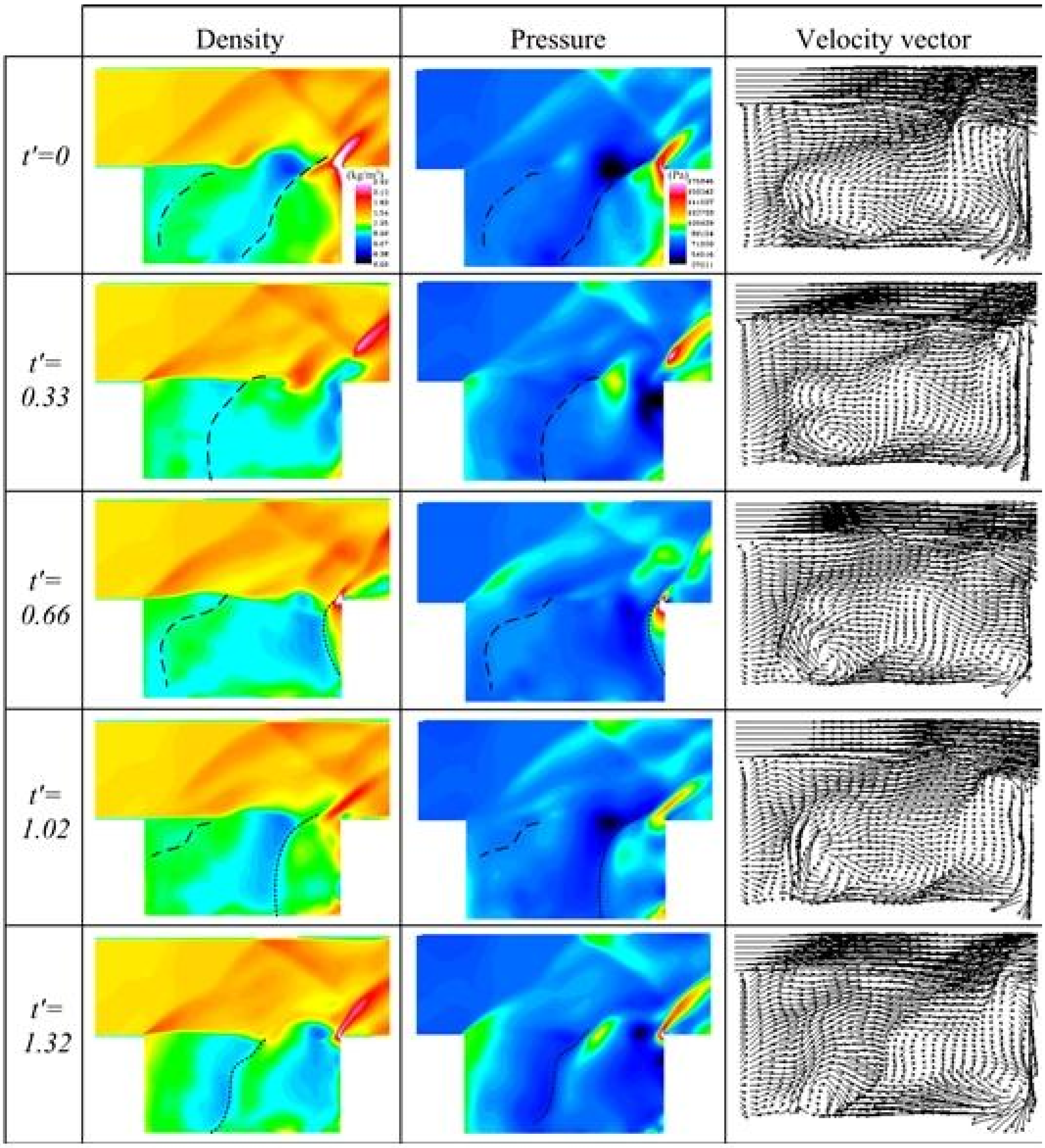


Fig. 4 Generation mechanism of pressure oscillation (x-y plane and z/D=0.9)

downstream of the shear layer. At t'=0.33, the flow in the vicinity of the rear wall region of the cavity is expanded by the low pressure region in the shear flow. At t'=0.66, the compression wave generated by the high pressure region near the rear wall of the cavity propagates upstream. Therefore, high and low pressure regions occur locally in the cavity. This phenomenon occurs periodically due to the cyclic pressure oscillation in the cavity. At t'=1.32, in the region of the leading edge of the cavity, the shear layer moves up and down due to the increase and decrease in static pressure by the propagation of the pressure wave. A low and high pressure region is generated by the fluctuating shear layer near the rear wall of the cavity. In addition, a shock wave is generated by a local supersonic flow in the high pressure region in the

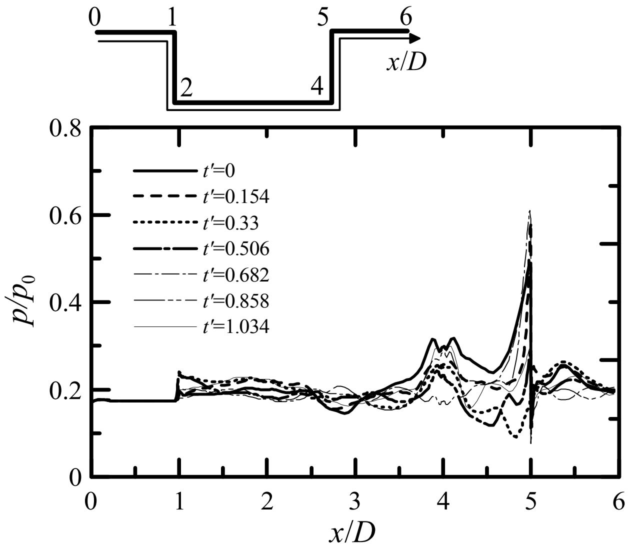


Fig. 5 Generation mechanism of pressure fluctuations (x-y plane and z/D=0.9)

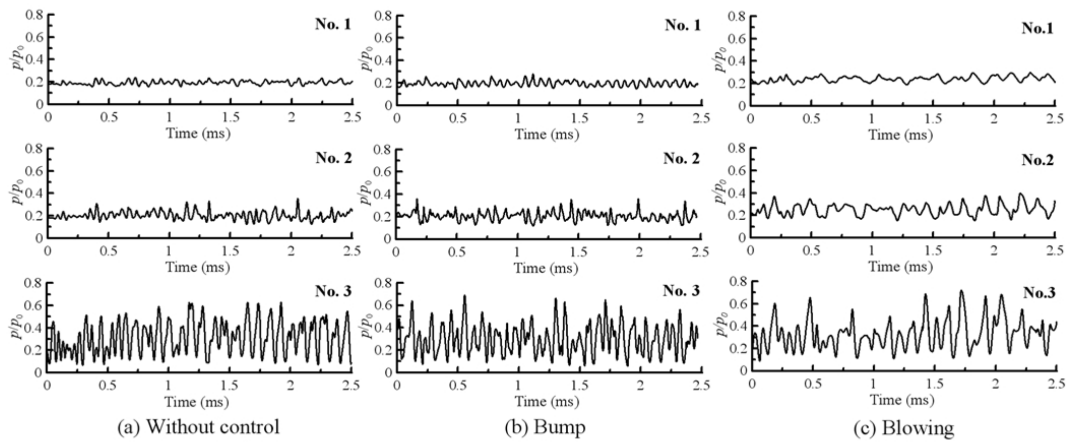


Fig. 6 Pressure oscillation at the cavity wall with and without control

shear flow. Therefore, the pressure oscillation in the cavity is attributed to the propagation of the compression wave from the rear to front wall of the cavity and the high and low pressure region along the shear flow.

Fig. 5 shows static pressure distributions along the cavity wall for about one cycle. In the figure, x/D is the axial distance normalized by the depth of cavity D. As time increases, the wall static pressure oscillates in the region of $x/D > 1$. For $4 < x/D < 5$, the range of fluctuation of wall static pressure is extremely large. At $x/D = 5$, which corresponds to the leading edge of the cavity, there is a sudden increase in static pressure, reaching the maximum value. The result implies that this region is considerably affected by the high and low pressure regions along the shear flow.

Fig. 6 shows the pressure oscillation at the cavity wall with and without control elements like a triangular bump or blowing jet. Closer is the location to the rear wall

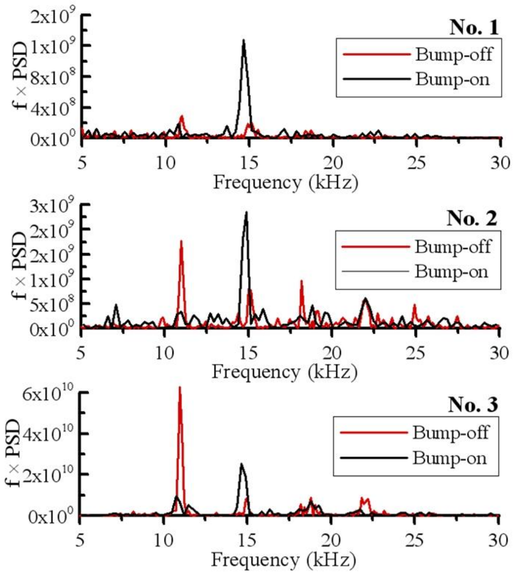


Fig. 7 Pressure spectra at the cavity with and without a bump

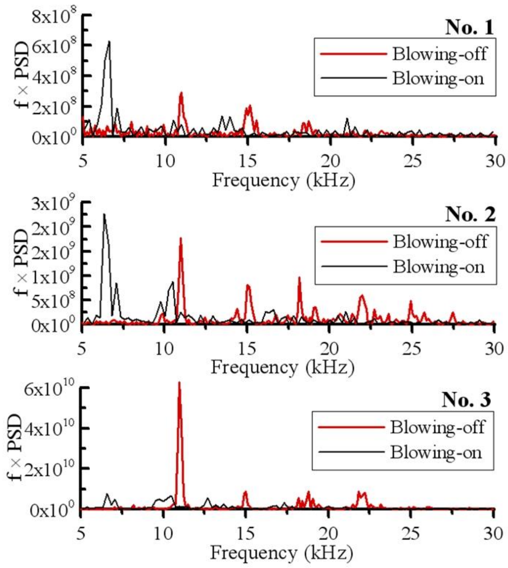


Fig. 8 Pressure spectra at the cavity wall wall with and without blowing

of cavity(No.3), larger is the wall static pressure fluctuation observed. In Fig 6(b), it is seen that RMS values for No.1 and No.2 increases though not by a great deal. But RMS value for No.3 decreases by about 9.5% when compared with that of the case with the triangular bump. In addition, for all the cases tested, the amplitude is similar at all points but frequency decreases by a considerable amount.

Fig. 7 and 8 shows the result of frequency analysis for static pressure values obtained on the cavity wall. When a triangular bump is used, the dominant frequency increases, compared with the bump-off case. Pressure spectra of No.1 and No.2 increase but those of No.3 decrease. Considering the pressure oscillation at No.3 is shown to be dominant, it implies that the overall cavity flow oscillation can be attanuated by using the passive mean. With the blowing jet, pressure spectra are dense in a low frequency range below 15 kHz and the dominant frequency becomes lower. Especially, the pressure oscillation near the rear wall of the cavity is significantly reduced. It is therefore considered that the overall pressure oscillation can be weakened by both control methods.

CONCLUSIONS

The present study describes computational work to develop an effective control technique of the supersonic cavity flow oscillation. The present study investigates the effect of a triangular bump and blowing jet installed in front of a cavity on the characteristics of flow oscillation. The computational results showed that:

1. The pressure oscillation at the rear wall of the cavity was dominant compared with those of other locations.
2. Flow control by installing a blowing jet in front of the cavity was slightly more effective than the case with a triangular bump.
3. With the triangular bump, the overall pressure oscillation but the usefulness of this control method was not clear. To effectively control the pressure oscillation, a systematic study is required regarding the size and location of the bump

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