# CONTROL OF CLOSED-TYPE SUPERSONIC CAVITY FLOWS

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## Abstract

*Three types of devices were tested for their effects in reducing the strong adverse pressure gradient in a closed-type cavity with a depth of 8mm and length-to-depth ratio of 15. The first type of control device embedded arrays of tubes longitudinally along the two sides of the cavity. It sought to move the high-pressure air at the recompression wake to the separation wake by creating a passage. The second type of control device installed a baffle plate laterally near the shock impingement line or the mid-part the cavity floor. It aimed at changing the wave structure of the cavity flow through interfering with the reattaching or reattached boundary layer. The third type of control device tried to increase the base pressure by supplementing external fluid with downstream blowing through side-holes along a lateral tube placed at the front corner of the cavity.*

*Of the three types of control devices, the installation of tubes along the two sidewalls of cavity was found to be most effective in reducing adverse pressure gradient along the cavity centerline. Of the four combinations of plate installed laterally on the cavity floor, the 4mm-high plate installed near the middle of cavity was found to be most effective. The relative ineffectiveness of downstream blowing near the cavity front corner is believed to be a result of the low blowing rate.*

*Unsteady pressure measurement at two locations for rearward-facing step, cavity of basic configuration and cavity with control device installed found that (1) Cavity flow were much noisier than step flow; (2) Arrays of tubes along two sidewalls produced the greatest reduction of peak powers and overall SPL at the rear location; (3) Discrete pressure oscillations were induced only in the case of 4mm-high plate installed at the front location. (4) Blowing at cavity front corner, although ineffective in mitigating the adverse pressure gradient, is very effective in suppressing the pressure oscillations in the cavity..*

## 1 Introduction

Compressible flows over cavity-like geometries such as grooves, wheel wells, and cutouts, etc., occur widely in aerospace and aeronautical vehicles. The flow field features boundary layer separation, shear layer instability, vortex flow, acoustics radiation, shock/expansion wave and shock-boundary-layer interactions, and self-sustained pressure oscillations. The co-presence of and interaction among these features in such a simple configuration and their potential hazardous effects on the performance, integrity and stability of the vehicles present a challenging problem and have stimulated extensive experimental, analytical, and computational investigations over the years.

Past researches[1,2] have established that the defining parameter for such flows is their length-to-depth ratio (L/D). Closed flows occur for cavities with L/D greater than 13. The pressure distribution along the cavity floor centerline features strong adverse gradient, resulting in large pressure drag for the vehicles. Open flows occur for cavities with L/D less than 10. The flow fields feature strong pressure oscillations. Noise radiation, structural fatigue, and excessive heat transfer at the cavity trailing

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edge are problems associated with open cavity flows. For L/D between 10-13, transitional cavity flow occurs.

As understanding of the cavity flows accumulates, efforts have also been taken to search for ways of controlling the cavity flow fields. By varying the rear wall from rectangular to circular and to ramp, Charwat et al[1] investigated the effect of downstream cavity edge geometry on compressible, closed-type cavity flow. They found that the geometry of the recompression step did not essentially modify the pressure distribution in the cavity, and the length L of the cavity should be defined to the reattachment of the free-streamline.

For incompressible, open-type cavity flows, Pereira and Sousa[3] found that different downstream cavity edge geometry (sharp, nose-shape, and round) did not alter the corresponding value of Strouhal number, despite the fact that the recirculating flowfield inside the cavity was markedly influenced by the downstream corner geometrical detail. Attenuation of the fluctuation peak magnitudes was observed for nose-shape impingement edge.

After trying various ways to affect the oscillation process in open cavity flow, Heller and Bliss[4] concluded that introduction of vorticity into the shear layer through spoilers installed ahead of the cavity leading edge, and provision of a slanted trailing edge bulkhead had a stabilizing effect on the external free shear layer and helped to reduce oscillating amplitudes. No oscillation amplitudes reduction was observed by the forced entrainment of boundary layer fluid into the cavity at the leading edge, by tilting the leading- and /or trailing-edge bulkheads, by implementation of an upstream "spoiler cavity", or by cavity internal transverse spoilers and baffles.

The effect of a passive-venting system, consisting of a porous floor with a vent chamber beneath it, was investigated by Wilcox[5]. This arrangement, allowing high-pressure air from the rear of the cavity to vent to the forward part of the cavity, was found to be extremely effective in modifying the flow field over a cavity with closed-type flow at supersonic speeds. The type of the flow field changed from that of closed to that of transitional, with the drag reduced by a factor of approximately 3. Covering the porosity near the cavity midlength with tape did not significantly reduce the effectiveness.

In addition to experimental researches, numerical simulation has also been employed to examine various ideas for their effects on cavity flows. The effect of a small jet, placed within an open-type cavity just below the front lip, was examined by Lamp and Chokani using two-dimensional time-accurate Navier-Stokes simulation[6] with Baldwin-Lomax turbulence model. The forcing of the jet on the shear layer was found to be effective in reducing the large pressure oscillations. The effectiveness of the suppression was found to strongly depend on the amplitude and frequency of the jet and weakly depend on the phase angle and duty cycle of the jet. Zhang et al[7] investigated the effects of leading edge compression ramps, expansion surfaces and mass injection on supersonic shallow cavity flow oscillations, through solutions of Short-time Reynolds-Averaged Navier-Stokes equations with the turbulence modeled by a two-equation k-□ model.

The focus of the present work is the control of supersonic cavity flow of closed type which features strong longitudinal pressure gradient along the floor. This strong pressure gradient is undesirable in that it produces a nose-up pitching moment during the separation of store and that it increases the drag of the vehicles significantly. It is found[5] that the cavity experiences an abrupt rise in drag as the flow changes from the transitional to the closed type. Therefore, it is highly desirable to find ways to change the flow of a cavity that would have supported closed-type to that of transitional type. In the mean time, no self-sustained oscillation of open-type cavity flow should occur or be significant as that would lead to structure fatigue. Furthermore, for a control device to be practical, it should be both effective and simple, not incurring excessive weight or drag penalty, and not reducing usable cavity volume significantly. The present work seeks to investigate three types of devices for their effects in reducing the strong adverse pressure gradient associated with closed-type cavity flow, based on the understanding of the mechanism for the change of cavity flow types as their L/D changes.

It was found in the first author's Ph. D work[8] that the freedom of the backflow inside the cavity is the key factor in shifting the mass balance at the front corner of the cavity, thereby determining the change of cavity flow type as its length-to-depth (L/D) ratio increases. When the backflow is completely blocked, the cavity flow settles to a stable closed-type. The first type of control device tested is arrays of tubes embedded longitudinally along the two sides of the cavity. The idea is to facilitate the backflow by providing a passage for the high-pressure fluid at the rear part of the cavity to vent into the low-pressure front region of the cavity.

It was also found[8] that closed-type cavity flow changes to that of transitional-type as L/D decrease when the reattached boundary layer separates under the increased adverse pressure gradient when the front expansion wake and the rear recompression wake approach each other. The second device tested is a baffle plate laterally installed near the shock impingement line or the mid-part the cavity floor. It is hoped that by interfering with the reattaching or reattached boundary layer and forcing it to separate, the wave structure of the cavity flow might change.

The third device tested is external fluid addition by downstream blowing through side-holes along a lateral tube placed at the front corner of the cavity. External fluid addition near the front corner will certainly delay the change of flow to the closed-type (elevating the critical length-to-depth ratio). However, it is unclear how external fluid addition will affect the cavity flow when its L/D is much larger than the critical value.

## 2 Test apparatus, instrumentation and models

The tests were conducted in the supersonic wind tunnel of Department of Aeronautics and Astronautics, University of Tokyo. The test section has a rectangular cross section of 80 by 140 mm2. A nozzle with design Mach number 2 was used in the current work. The boundary layer just upstream of the position where cavities are to be installed was measured and judged to be of turbulent, its thickness estimated to be about 8mm.

Two-dimensional (2D) rectangular cavity models, with depth of 8mm and values of L/D equal to 15, with and without control device installed, were tested. The model is instrumented with 24 pressure orifices, 0.5mm in diameter, along the floor centerline. The installation of control devices on the cavity is shown in figure 1.

The total temperature and total pressure in the settling chamber were measured with thermo-couple and Pitot tube, respectively. The static pressures along the cavity walls were connected with a scanning valve. Three unsteady pressure orifices were opened near the centerline of cavity floor, with the distance from the front wall being 15, 30, and 75mm, respectively. The pressure transducers are products of Kulite Semiconductor Company. All the pressure transducers were referenced to atmosphere pressure, the value of which was read from a pressure meter each time before test run. The electronic signals from thermo-couple and pressure transducers, amplified with voltage amplifiers, were input to a computer through an A/D converter. The A/D converter has a capacity of 12 bits, and was set to work in range of +/-10V. The maximum sampling rate of the converter is 200MHz. The thermo-couple was calibrated against a thermometer. The static pressure transducers were calibrated against a mercury U-tube manometer. The total pressure transducers were calibrated against a pressure gauge, which has a range of 5kg/cm2 and an error of 0.1% of the reading. The calibrations were repeated several times during the entire experiment to account for the variations of atmosphere temperature and humidity.

Freestream Mach number, calculated from freestream total pressure and static pressure at the wind tunnel wall opposite to the cavity using isentropic relation, has a value of 1.94, and Reynolds number per unit meter is 4.2×107.

Pressure coefficients at cavity walls are calculated as follows:

$$C_p = \frac{2}{\gamma M_\infty^2}\left(\frac{p}{p_\infty}-1\right) \qquad (1)$$

Schlieren visualization was taken during all of the test runs. Oil flow visualizations using oil (500CS) mixed with TiO2 were conducted.

## 3 Test result and discussions

### 3.1 Tubes along two sidewalls of cavity

Plastic tubes, 96mm long and with a diameter of 6mm, were embedded longitudinally along the two sides of the cavity. Two cases were tested. In the first case, three tubes were patched together and pasted on the floor along each sidewall of the cavity. In the second case, only one tube was pasted on each side. The tubes were placed near the mid-portion of the cavity, with its one end opening to the front part of the cavity and the other end to the rear part. It was expected that by creating a passage for the high pressure air in the recompression wake to vent into the low pressure separation wake, the pressure at the front region would increase, the expansion of the main flow at the leading edge would be weakened, and the flow would change to that of transitional type.

Figure 2 compares the pressure coefficient distribution of the cavity with tubes installed with that of the basic cavity. The left and right panel corresponds to the three tubes and one tube at each side, respectively. Both cases were effective in changing the cavity flow to the transitional-open type, with the three-tube case was more effective, as more air could be vented upstream.

Schlieren photographs confirmed the change of concentrated impingement and exit shock wave system to that of spread compression wavelets. As the flow fields were highly three-dimensional when the tubes were installed, caution should be exercised in interpreting the schlieren photographs.

Oil flow visualization showed surface streakline pattern that is completely different from that of basic configuration. There was backflow not only inside the tubes, but also near the cavity centerline. Between the centerline and the tubes, the limiting streamline flowed downstream. See right panels of figure 5.

### 3.2 Plate installed laterally over the cavity floor

The effect of lateral plate at two locations over the cavity floor was tested. The plate had a thickness of 1mm and height of 2mm and 4mm. The front and rear location was 21mm and 61mm from the front face, respectively. Four combinations of the plate heights and locations were tested. In the first case, a 4mm high plate was installed at the front location. It was hoped that the plate would intercept some amount of air from the separating shear layer, thereby increasing the pressure in the region ahead of it. In the second case, a plate was placed at the same location but had a height of 2mm. In the third case, a 4mm high plate was installed at the rear location. It was hoped that a plate near the middle of the cavity would separate a long cavity of closed type into two short cavities of open type. In the fourth case, a 2mm high plate was placed at the rear location. The height may be too small to separate the long cavity into two. However, it was hoped that the short plate might force the attached boundary layer near the mid-portion of the cavity to separate, thereby facilitating the formation of backflow.

Figure 3 compares the pressure coefficient distributions of the cavities with plate installed with that of the basic cavity. Following observations can be made:

- The 4mm-high-plate installed near the middle of the cavity was most effective in changing the cavity flow to the transitional-open type. There was only a small kink near the location of the plate.
- The second effective case was the 4mm-high-plate installed near the front face. There was violent variation of pressure near the plate.
- For the 2mm-high-plate installed near the front face, the base pressure increased slightly and the recompression wake

pressure decreased slightly, but the cavity flow type remained the same.

- For the 2mm-high-plate installed near the middle, the base pressure at the separation wake and the subsequent pressure rise was nearly identical to that of the basic cavity, except that the pressure did not level off to a plateau in the middle portion of the cavity, but rather continued to rise nearly linearly up to the location of the plate. Behind the plate, there was an abrupt drop in pressure, followed by gradual rising. The pressure at the recompression wake was considerably lower than that of the basic cavity.

Following observations can be made for each case from schlieren visualizations:

- For the high plate at middle, the strength of the expansion at the leading edge was dramatically reduced, and the shock wave system changed to the compression fan.
- For the high plate at front, the expansion at the leading edge was considerably weakened; extended compression fan replaced the original shock system.
- For the low plate near the middle, the strong expansion and impingement on the floor remained the same. A compression fan was generated ahead of the plate, followed by expansion and then compression again.
- For the low plate near the front, wave pattern remained essentially the same, except that the region between the impingement and exit shocks changed from that of nearly uniform density to that of compression.

Oil flow visualizations were conducted for the three relatively more effective cases. Sketches of the surface flow pattern for 4mm-high plate are shown in the left panels of figure 5. Following observations can be made:

- For the high plate at middle, extensive back flows occur in both shorter cavities. The streakline pattern in each cavity resembles that of open-type cavity flow. The flow is essentially two-dimensional for most part of the cavities.
- For the high plate at front, strong recirculation occurs in the front cavity, indicating that the plate does intercept considerable amount of air from the separating shear layer. In the rear cavity, the main flow reattaches on the floor and separates again before the rear face.
- For the low plate at front, the surface streaklines resemble that of the basic cavity.

## 3.3 Downstream blowing along front corner

Blowing from side-holes in a tube embedded at the front corner of the cavity sought to actively increase the pressure at the separation wake through introducing external air into it. Two cases with different flow rates were tested. In the first case, the tube was connected to the atmosphere. The resulting volume flow rate was about 5.17´10-4m3/s (31SL/min). In the second case, the tube was connected to the high-pressure source of the wind tunnel. The volume flow rate, after conversion to the standard value, was about 3.3´10-3m3/s (200SL/min).

Figure 4 compares the pressure coefficient distribution of the cavity with blowing tube installed with that of the basic cavity. There is essentially no change for the low blowing rate. For the high blowing rate, the base pressure increases slightly and the pressure distribution changes from that of closed-type to that of transitional-closed type.

Schlieren visualization shows essentially no change of wave pattern for the low blowing rate. For the high blowing rate, the impingement and exit shocks are linked with a compression region.

To put the effect of blowing into perspective, the ratio of mass flow rate between the blowing and the external flow across an area equal to that of the cavity front face was calculated and was found to be about 2×10-3 for the low flow rate, and 1.3×10-2 for the high flow rate. It is expected that blowing can be more effective if the blowing flow rate is further increased.

## 3.4 Unsteady effects of the control devices

The spectra of unsteady pressure signals indicated that new discrete pressure oscillations emerged when the 4mm-high plate was installed at the front location. The peak frequencies matched approximately the predicted values from Rossiter's[9] modified formula, the distance from the front wall to the plate being used as the cavity length. No discrete pressure oscillations were detected in other cases and when other control devices were installed.

Table 1 compares the peak power and overall sound pressure level (SPL) at two locations near the foot of impingement and exit shock waves, for rearward-facing step, cavity of basic configuration and cavity with arrays of tubes, plate, or blowing device installed. Model for the rearward-facing step is formed simply by removing the rear plate. Following observations can be made:

- Cavity flows are much noisier than step flow. There is considerable increase of both overall SPL and peak powers in cavity flow compared with step flows. Due to the presence of exit shock wave in the cavity flow, the peak power at the rear sensor increases by about 26dB.
- Arrays of tubes along two sidewalls produce the greatest reduction of peak powers and overall SPL at the rear sensor.
- For the installation of plates, the peak powers at the rear sensor reduce by 8-13dB, while the peak powers at the front sensor and overall SPL at both sensors remain essentially unchanged. Power spectra indicate that discrete pressure oscillations are induced only in the case of 4mm-high plate installed at the front location.
- Blowing at cavity front corner, with very low flow rate, is very effective in reducing the pressure oscillations in the cavity, although not being effective in mitigating the adverse pressure gradient. It reduces the peak powers at the front sensor by 8-10dB, the overall SPL by 6-7dB. It reduces the peak powers at the rear sensor by 8-14dB, the overall SPL by 3dB.

## 4 Summary

Three types of devices were tested for their effects in reducing the strong adverse pressure gradient in a closed-type cavity with a depth of 8mm and length-to-depth ratio of 15. The first type of control device embedded arrays of tubes longitudinally along the two sides of the cavity. It sought to move the high-pressure air at the recompression wake to the separation wake by creating a passage. The second type of control device installed a baffle plate laterally near the shock impingement line or the mid-part the cavity floor. It aimed at changing the wave structure of the cavity flow through interfering with the reattaching or reattached boundary layer. The third type of control device tried to increase the base pressure by supplementing external fluid with downstream blowing through side-holes along a lateral tube placed at the front corner of the cavity.

Of the three types of control devices, the installation of tubes along the two sidewalls of cavity was found to be most effective in reducing adverse pressure gradient along the cavity centerline. Of the four combinations of plate installed laterally on the cavity floor, the 4mm-high plate installed near the middle of cavity was found to be most effective. The relative ineffectiveness of downstream blowing near the cavity front corner is believed to be a result of the low blowing rate.

Unsteady pressure measurement at two locations for rearward-facing step, cavity of basic configuration and cavity with control device installed found that (1) Cavity flow were much noisier than step flow; (2) Arrays of tubes along two sidewalls produced the greatest reduction of peak powers and overall SPL at the rear location; (3) Discrete pressure oscillations were induced only in the case of 4mm-high plate installed at the front location. (4) Blowing at cavity front corner, although ineffective in mitigating the adverse pressure gradient, is very effective in suppressing the pressure oscillations in the cavity.

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| Flow Type | | step | Cavity (L/D=15) | Tubes 3+3 | Tubes 1+1 | 4mm plate middle | 4mm plate front | 2mm plate middle | 2mm plate front | blowing, 31SL/min | blowing 200SL/min |
|---|---|---|---|---|---|---|---|---|---|---|---|
| front sensor | peak power | 132 | 138 | - | - | 137 | 137 | 136 | 136 | 130 | 128 |
| | overall SPL | 158 | 164 | - | - | 163 | 164 | 164 | 164 | 158 | 157 |
| rear sensor | peak power | 127 | 153 | 132 | 138 | 140 | 143 | 145 | 143 | 145 | 139 |
| | overall SPL | 153 | 163 | 158 | 159 | 163 | 163 | 163 | 161 | 160 | 160 |

**Table** 1 Comparison of peak power and overall SPL for rearward-facing step and cavity flows(sampling frequency 20kHz)

Fig. 1 Schematic of cavity models with control device installed

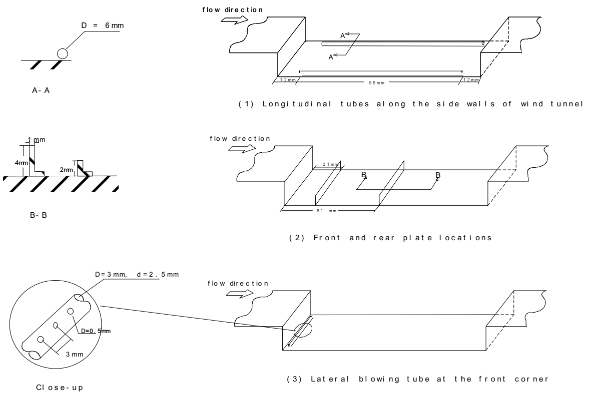


Fig. 2 Effects of venting tubes on pressure distribution (L/D = 15)

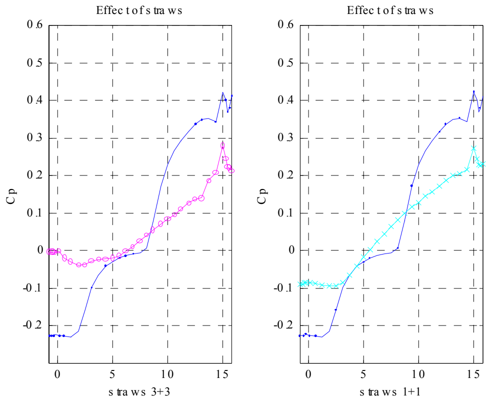


Fig. 3 Effects of baffle plate on pressure distribution (L/D = 15)

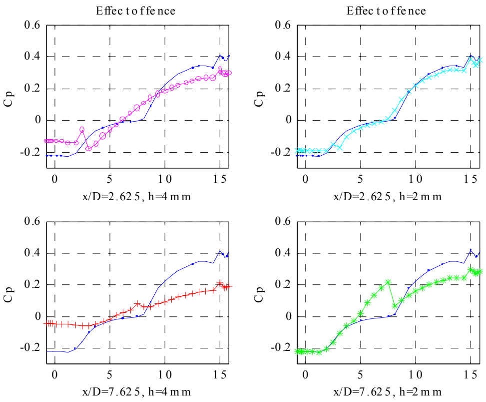


Fig. 4 Effects of external mass addition on pressure distribution (L/D = 15)

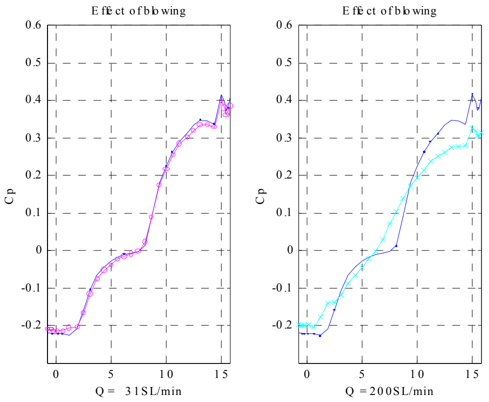
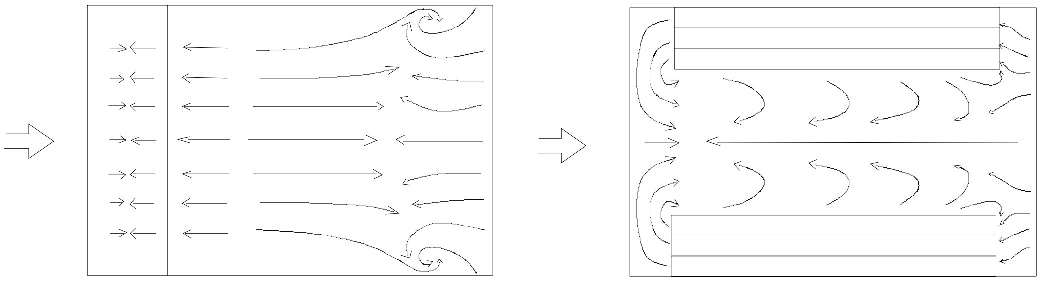
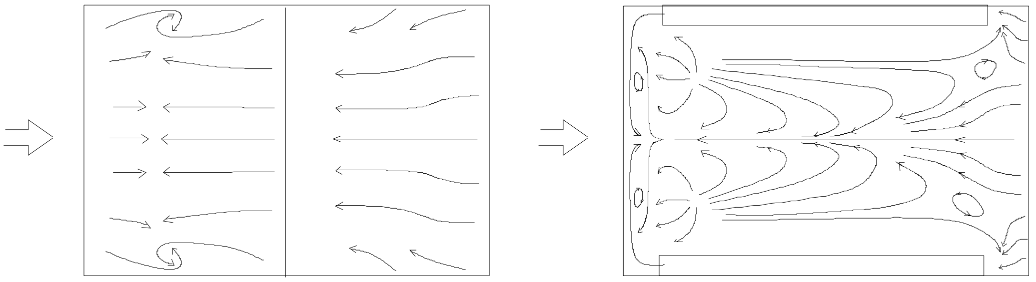


Fig. 5 Surface flow patterns for cavities with control devices installed



4mm-high-plate at front

three tubes along each side



4mm-high-plate at middle

one tube along each side