Experimental Investigation on the Mechanism of Flow-Type Changes in Supersonic Cavity Flows

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Compressible flows over cavities with a series value of length-to-depth ratio (L/D) were investigated experimentally, with the objective being to elucidate the mechanism of the transition of types of cavity flows as their L/D increases or decreases. For open-type cavity flows, the freedom of backflow inside the cavity is found to be crucial in smoothing out adverse pressure gradient. The spreading of the shear layer and its gradual approach toward the cavity floor as L/D increases tend to suppress the freedom of backflow, causing the cavity flow to change from the open-type to the transitional-type. For closed-type cavity flows, the finite thickness of the upstream boundary layer leads to the presence of three kinds of characteristic lengths that correspond to the recirculation region, the deflection of the main flow and the recovery or the abrupt rise of the pressure, respectively. The compression fans at the foot of the impingement and the exit shock waves will approach each other well in advance of the possible merge of the vertices of the conventionally defined separation and recompression wakes. As the L/D of a closed cavity decreases, the reattached boundary layer on the mid-portion of the cavity floor will have less developing distance, thus it will be more susceptible to adverse pressure gradient and prone to separation. For the present two-dimensional cavity models, the critical values of L/D were found to be about 10 and 14 for the transition of cavity flows from the open- to the transitional-type and from the transitional- to the closed-type, respectively. The sum of the pressure lengths at the front and rear wakes agrees remarkably well with the second critical L/D .

Key Words: Supersonic, Turbulent, Cavity Flow, Flow Type Change

1. Introduction

Compressible flows over cavity like geometries such as grooves, wheel wells, and cutouts 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,^{1–36)} analytical,^{8,9,24,37–40)} and computational^{41–58)} investigations over the years. These studies largely concentrated on mean static-pressure distributions and/or unsteady-pressure spectra in cavities. Radiated acoustic pressure^{24,25,27,28)} and store separation characteristics^{18–23)} have also been obtained in some studies. A variety of control methods have been tested and their effects on the cavity flow field documented.^{1,9,31,36,54,55)}

Past researches have established that the defining parameter for these flows is their length-to-depth ratio (L/D). Closed flows occur for cavities with L/D of 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 of less than 10. The flow fields feature strong pressure

oscillations. Noise radiation, structural fatigue, and excessive heat transfer at the cavity trailing edge are problems associated with open cavity flows. For L/D from 10 to 13, transitional cavity flow occurs.

The effects of cavity width-to-length ratio (L/W) were investigated by Ahuja and Mendoza,²⁸⁾ Tracy and Plentovich,³⁰⁾ Stallings and Wilcox,²⁾ et al. Ahuja and Mendoza distinguished the cavity flow to be two-dimensional (2D) or three-dimensional (3D) depending on whether its L/W is less than or greater than 1. Tracy and Plentovich found that increasing the cavity width has the effect of significantly increasing resonant amplitudes. Stallings and Wilcox found that decreasing it resulted in a reduction of the critical values of L/D .

The characteristic (laminar or turbulent) and the thickness of the boundary layer (δ) just upstream of the leading edge of a cavity play an important role in determining the amplitude of the instability waves as they convect downstream and therefore the amplitude of feedback-related cavity tones. Heller et al.⁸⁾ observed experimentally that laminar upstream boundary layers produced louder cavity tones. Ahuja and Mendoza²⁸⁾ started out with a turbulent boundary layer and found that increasing the boundary layer thickness tends to eliminate most cavity tones. For static pressure, it was observed by Charwat et al.¹⁾ and Stallings and Wilcox²⁾ that an increase of δ/D brought about a decrease of pressure inside the cavity and the smoothing out of all pressure gradients. The effect is believed to be attributable to the decreased

momentum transfer to the cavity with increasing δ/D .

Although a freestream Mach number is found to have some effects on the value of $(L/D)_{cr}^{2,5)}$ and the spectrum of resonance,³⁰⁾ a Reynolds number does not appear to be an important parameter in defining the cavity flow field. Ahuja and Mendoza²⁸⁾ found that a Reynolds number based on cavity length had no effect on the nondimensional feedback frequencies of the cavity noise.

Analytical studies of cavity flow primarily concentrated on exploring the mechanism of self-sustained oscillation associated with open-type cavity flow. Although possible oscillatory frequencies can now be predicted analytically or semi empirically, it is beyond the reach of any existing model to predict the amplitude of the oscillations, since the full nonlinear equations are required to determine the absolute level of the oscillation intensity. For this reason, experimental and analytical work needs to be complemented with a numerical solution of unsteady Navier-Stokes equations.

Although it is well established that three distinct types of cavity flows exist and that the critical values of L/D have been well documented for flows ranging from subsonic to supersonic speeds, little effort has been directed toward understanding the mechanism of the cavity flow-type changes with L/D . The understanding of this mechanism is not only of profound academic interest; it will also be helpful in suggesting new ideas for the control of cavity flows. To the author's limited knowledge, no theory or explanation for the closing of the cavity is available in open literature. The mechanism for the opening of a closed cavity as the value of its L/D decreasing was proposed by Charwat et al.¹⁾ They suggested that the cavity opens when the vertices of the upstream recompression wake and the downstream separation wake merge and backflow occurs inside the cavity. Therefore the critical values of L/D for the opening of the cavity equals the separation distance of these two kinds of well-investigated wakes: $(L/D)_{cr} = (L_D + L_F)/D$. (Here the subscript D signifies the downward-facing step and F the forward-facing step.) However, Stallings and Wilcox²⁾ found that Charwat's formula under predicted the measured critical values throughout their test Mach number range. No explanation was given in Stallings and Wilcox's report.

The present work set out to investigate experimentally the supersonic cavity flows with a series value of L/D , with the objective of elucidating the physics of the transition of cavity-flow types as their L/D increases or decreases.

2. Test Apparatus, Instrumentation and Models

The tests were conducted in the supersonic wind tunnel of the Department of Aeronautics and Astronautics, the 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 being estimated to be about 8 mm.

Two-dimensional (2D) rectangular cavity models, with depths of 8 mm and values of L/D equal to 5, 7.5, 10, 12, 13.5, 13.75, 14, 14.5, 15, 17.5, and 20 were tested. The length of the cavity is adjusted by changing the position of the cavity's rear wall. The schematic of the model setup in the wind tunnel test section is shown in Fig. 1. A model for the rearward-facing step, formed simply by removing the rear plate of the cavity model, was also tested for comparison. It is instrumented with 55 pressure orifices, 0.5 mm in diameter, with locations shown in Fig. 2.

The total temperature and total pressure in the settling chamber were measured with a thermo couple and a Pitot tube, respectively. The static pressures along the cavity walls were connected with a scanning valve. The pressure transducers are products of Kulite Semiconductor. All the pressure transducers were referenced to atmosphere pressure, the value of which was read from a mercury manometer each time before a test run. The electronic signals from the thermo couple and the 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 a range of ± 10 V. 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 5 kg/cm² and an error of 0.1% of the reading. The calibrations were repeated several times during the entire experiment to account for the

Fig. 1. Schematic of model setup in wind tunnel test section.

Fig. 2. Pressure orifice locations. Linear dimensions are in millimeter.

variations of atmosphere temperature and humidity.

The 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 the Reynolds number per unit meter is 4.2×10^7 . Pressure coefficients at cavity walls are calculated with the following formula:

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

Schlieren visualization was taken during all the test runs. Oil flow visualizations using oil (500CS) mixed with TiO_2 were conducted for the three types of cavity flows.

3. Test Results and Discussion

3.1. Effects of length-to-depth ratio and $(L/D)_{cr}$

Figure 3 compares the longitudinal distribution of pressure coefficient among cavities with different values of length-to-depth ratio (L/D), the abscissa being normalized with respect to the cavity length. Cavity flow changes from the open- to the transitional-type, and then to the closed-type with the increase of L/D , confirming the general observations made by other investigators. Figure 4 shows the pressure distribution for cavities with L/D equal to 12, 13.75, 14, 14.5, and 15. Note the drastic change of pressure distribution for L/D equal to 13.75 and 14, which is typical for the transitional-type and closed-type cavity flow respectively. It seems that the $(L/D)_{cr}$ lies from 13.75 to 14. Yet quite surprisingly, the cavity with L/D equal to 14 changed from closed- to transitional-type in the oil flow visualization. Therefore the $(L/D)_{cr}$ for the present model configuration is judged to be 14.

The $(L/D)_{cr}$ for cavities with 3D configuration at Mach number of 2.0. were determined²⁾ to be 12.8–13.2, which is less than the present result. Two factors may be responsible for this. The first is that the width-to-depth ratio of the cavity in the present work is much greater than that in reference 2 and it was found²⁾ that an increasing cavity width resulted in

Fig. 3. Change of cavity flow types with L/D .

Fig. 4. Critical L/D for the change from transitional- to closed-type cavity flow.

an increase of $(L/D)_{cr}$. The second is the presence of the wind tunnel walls at the sides of 2D cavity models. It was found²²⁾ that the doors installed along the sidewalls of the cavity caused the recompression wake to extend upstream, thereby precipitating interaction between the separation and recompression wakes and increasing the value of $(L/D)_{cr}$.

The extent of the recirculation regions can be read out from the surface flow patterns. In oil-flow visualization, instead of using extremely viscous oil to ensure that the surface pattern will withstand the strong disturbance during the turning down of the operation and photographing the pattern after the test run, this work used less viscous oil to improve the traceability of the oil-dye mixture and videoed the development of the surface pattern during the test. The surface pattern was observed to begin taking shape during the start-up phase and to settle down quite stably as the external flow establishes. Visual inspection shows that the lines corresponding to recirculation boundaries quiver within a range of about 1 mm. The video pictures were printed out later and recirculation lengths were measured from them. For a closed-type cavity with $L/D = 16$, the lengths of the recirculation regions at the front and rear parts of the cavity were found to be about 2.75 and 2.88 times the depth of the cavity, respectively.

3.2. Lateral pressure distributions along front and rear faces

Lateral pressure distributions along the front and rear faces of the cavity for different values of L/D , covering about half the span of the cavity width centering at the centerline, are compared in Fig. 5. The following observations can be made from the Fig.: (1) As cavity flow changes from open- to transitional-type, the pressure at the front face decreases gradually, and the pressure at the rear face increases gradually. (2) A quantum jump of pressure occurs as the cavity flow changes from transitional- to closed-type. With a further increase of L/D , the pressure coefficients at the front face essentially remain at the same level, but there is a slight increase at the rear face. (3) The distribution of pres-

Fig. 5. Lateral pressure distributions at cavity front and rear faces.

Fig. 6. Surface flow patterns for three-types of cavity flows.

Table 1. Comparison of pressure coefficients near the front corner between inviscid model prediction and experiment measurement.

Mach angle (°)	31.03						
L/D	5	7.5	10	12	13.5	17.5	20
Shock angle (°)	33.32	32.8	31.8				
Fan angle (°)				2.76	3.95	22.9	24.73
Deflection angle (°)	2.7	2.09	0.95	-1.71	-2.46	-15.14	-16.4
C_p (inviscid model)	0.06	0.046	0.02	-0.03	-0.049	-0.229	-0.24
C_p (experiment)	0.059	0.046	0.02	0.012	-0.035	-0.228	-0.228

sure along the front face is nearly a straight line, suggesting essentially 2D flow at this region. (4) The distributions of pressure along the rear face are slightly curved, suggesting 3D flow at this region because of the finite width of the cavity and the presence of wind tunnel sidewalls. (5) All pressure distributions are relatively symmetrical about the longitudinal centerline, except the rear face pressure distribution for L/D equal to 20.

The surface flow pattern, as shown in Fig. 6, drawn from videos of oil flow visualization, indicated relatively weak 3D flows in open- and transitional-type cavities and a much stronger one in the closed-type cavity. The video of a closed-type cavity flow shows a pair of big vortices behind the exiting shock wave beside the two sidewalls, with the vortex axis somewhat perpendicular to the cavity floor. It reveals that the boundary layers over the wind tunnel sidewalls first thicken, then separate under the severe adverse pressure gradient associated with the impinging and exiting shock waves over the cavity.

3.3. Inviscid model for the prediction of C_p and wave structures

Although cavity flows are essentially viscous phenomena, the general wave structures can be closely reproduced with inviscid flow models. The front part of open-type cavity flow can be simplified to a weak oblique shock wave and a slip line that separates the deflected main flow from the recirculating flow inside the cavity. Both the shock wave and the slip line emanate from the leading edge. The pressure is constant across the slip line. The front part of transitional- and closed-type cavity flows can be simplified to an expansion fan and a slip line. The wave structures over the closed-type cavity flow can be simplified to two expansion fans emanating from leading and trailing edges and to impingement and exit shock waves generated at the floor. To close the inviscid models, additional parameters taken from experiments or empirical theories need to be supplemented.

To close the inviscid model for the front part of a cavity, the shock angles and the angles of the expansion fans

Fig. 7. Wave structures visualized in schlieren photographs and predicted with inviscid model.

were read from schlieren photographs. In Table 1, for cavities with increasing length-to-depth ratio, the pressure coefficients below the slip lines as predicted from the inviscid models are compared with the averaged values along the front face as obtained from the experiment. Although there is a certain amount of uncertainty in reading wave angles from schlieren photographs, the trend for the change of wave strength is beyond doubt. For open cavity flows, the shock wave becomes weaker as L/D increases. The change of flow types from the open to the transitional occurred at an L/D from 10 to 12. And it is signified by the disappearance of the shock wave and the emergence of expansion fan in the schlieren photographs, indicating the deflection of the main flow into the cavity. In some literature, a shock wave is depicted at the leading edge of a transitional cavity flow. The present investigation found this to be incorrect. For transitional- and closed-type cavity flows, the expansion fan becomes stronger as L/D increases. This is consistent with the experimental observations that pressure coefficient at the front part of the cavity decreases with increasing L/D .

For the closed-type cavity flows, the supplementary parameters for the inviscid model can be taken from the measured pressures at the separation and recompression wakes. In the separation wake, the pressure distribution has a flat region, and their average can be used to determine the strength of the expansion fan at the leading edge. The deflected mainstream strikes the cavity floor and redirects itself to generate the impingement shock wave. In the recompression wake, the plateau pressure over the central portion of the wake is identified with the pressure in the external flow after being turned by the exit shock wave, which emanates from the apex of the recompression wake.¹⁾ The mainstream redirects itself at the trailing edge of the cavity to follow the flat plate behind the cavity, emanating an expansion fan from the trailing edge. The wave structures generated through the inviscid model are compared with a schlieren photograph in Fig. 7. The C_{p1} and C_{p2} in the figure are the measured pressure coefficients at the flat region for the separation wake and the plateau region for the recompression wake. Salient features are well reproduced. Moreover, the reflected shock wave as a result of the intersection of impingement and exit shock waves, hardly visible in schlieren photographs, is also revealed from the inviscid model. In schlieren photographs,

the impingement shock wave curves slightly upstream because of its interaction with the expansion fan that emanates from the leading edge of the cavity. This effect is ignored in the inviscid model.

3.4. Mechanism for the opening of a closed-type cavity flow

The authors found that interesting behaviors of the two wakes in closed-type cavity flows as their L/D decreases

Fig. 8. Pressure distributions of closed cavity flows and step flow. Front corner aligned.

Fig. 9. Pressure distributions of closed cavity flows. Rear corner aligned.

Fig. 10. Characteristic lengths for closed-type cavity flows.

Fig. 11. Sketches of flow fields during the opening of the closed-type cavity flow.

could be revealed if the pressure distributions are plotted against the same reference length, the depth rather than the lengths of the cavity. Figure 8 compares the pressure coefficient distributions for closed-type cavity flows and the rearward-facing step flow, with the longitudinal distance being normalized with the depth and the origin set at the front corner. It is readily visible that the front portions of all the curves of closed-type cavity flows fall on that of the rearward-facing step. It indicates that the separation wake is essentially not affected by the approaching of the cavity rear face, even in the immediate vicinity of the $(L/D)_{cr}$. In contrast, the recompression wake is clearly affected by the approaching of the cavity front face, as shown in Fig. 9, where the origin is set at the rear corner. As L/D decreases, the pressure in the region ahead of the rear face decreases, suggesting a decrease in the strength of the exit shock wave. The location at which the pressure starts to rise abruptly moves slightly forward. The above observations are supported by the results of Stallings and Wilcox, with more evident upstream extension of the recompression wake.⁵⁹⁾ Three-dimensional cavity models were used in their investigation.

Previous investigations of step flows and closed-type cavity flows usually associated a single length with the separation wake or recompression wake. However, the authors found that three kinds of characteristic lengths can be identified in closed-type cavity flows because of the finite thickness of the upstream boundary layer. A recirculation length, associated with the extent of the recirculation region, can be defined from the surface oil flow visualization. A deflection length, corresponding to the intersection of the impingement and exit shock waves with the cavity floor, can be defined from the inviscid wave structures. A pressure length, corre-

sponding to the recovery of pressure at the front wake and the abrupt rise of pressure at the rear wake, can be defined from the plot of pressure distribution. While the abrupt rise of the pressure at the rear wake is clearly definable, the recovery of the pressure at the front wake is a gradual process. In this paper, the pressure length at the front wake is defined to the location where the pressure recovers to 95%. The flat slope of pressure distribution behind the impingement shock wave leads to a high uncertainty for the deduced pressure length Ld_3 , which is about $0.3D$. In Fig. 10, the left panel illustrates the definition of these three kinds of lengths. The right panel shows their values at different values of L/D . The disparate of the three lengths is clear. The deflection length here is actually the length that is conventionally associated with the step flows.

Table 2 lists the values of the deflection lengths, Ld_2 , Lf_2 , and the pressure lengths, Ld_3 , Lf_3 , and their sums at different values of L/D . Charwat's formula for the prediction of critical length to depth ratio is actually $(L/D)_{cr} = Ld_2 + Lf_2$. As discussed in a previous section, the critical length-to-depth ratio for the present model is determined to be 14. It is clear that Charwat's formula seriously under estimates the $(L/D)_{cr}$, and the sum of the pressure lengths agrees remarkably well with the experiment. The reason is quite simple. The pressure lengths are much longer than the deflection lengths. And the interaction between the two wakes begins when the apexes corresponding to the pressure lengths approach each other. Based on these results, the authors propose that the critical length-to-depth ratio may be predicted with the following formula:

$$(L/D)_{cr} = (Ld_3 + Lf_3)/D \quad (2)$$

The process of the opening of closed cavity flow can be

Table 2. Characteristic lengths for closed-type cavity flows.

L/D	Ld_2/D	Lf_2/D	$(Ld_2 + Lf_2)/D$	Ld_3/D	Lf_3/D	$(Ld_3 + Lf_3)/D$
14	3.77	4.54	8.31	6.53	7.13	13.66
14.5	3.77	4.49	8.26	6.64	7.00	13.64
15	3.77	4.44	8.21	6.60	6.88	13.48
17.5	3.69	4.22	7.91	6.85	6.87	13.72
20	3.63	4.09	7.72	6.80	6.87	13.67

Fig. 12. Effect of blocking of backflow with plate on longitudinal pressure distributions for cavity with $L/D = 5$.

described as follows (See Fig. 11). The black dots, the gray dots, and the open dots in the figure correspond to the apexes of pressure lengths, deflection lengths, and recirculation lengths, respectively.

- 1) When the L/D of a cavity is sufficiently large, the separation wake and the recompression wake are well separated, with a reattached boundary layer and main flow in between. Impingement and exit shock waves are generated because of the deflection of the main flow. The gradual change of the direction of the shear layer produces compression fans at the feet of the two shock waves. The pressure distribution along the floor features a flat region between two regions of dramatic rise.
- 2) As the value of L/D decreases, especially when the innermost edges of the two compression fans approach each other, the interaction between the two wakes begins. The reattached boundary layer has little distance to develop before it is subjected to the second compression fan. The ability of the boundary layer to withstand the adverse pressure gradient decreases, causing an upstream extension of both the separation region and the exit shock wave. For cavities with two-dimensional configuration, a slight further decrease of L/D will result in the drastic change of flow type to that of the transitional cavity flow.
- 3) The $(L/D)_{cr}$ for cavities with three-dimensional configuration will be less than that of a two-dimensional cavity, because the main flow has additional freedom in the lateral direction. According to the schlieren pho-

tographs and pressure coefficient distribution along the cavity centerline,²⁾ it appears that the length of the reattached boundary layer reduces to zero at a critical value of L/D of about 13; the shear layer impinges on the floor and separates again immediately. The impingement and exit shocks merge into a single shock. The flat region in the pressure distribution disappears accordingly, marking the change of flow from the closed to the transitional-closed type.

A more accurate model for the prediction of the critical length-to-depth ratio might be obtained by examining the behavior of a shear layer under the influence of the wave systems in a closed-type cavity flow.

3.5. Mechanism for the closing of an open-type cavity flow

For open-type cavity flows, it was found that the pressure near the cavity front corner is directly linked with the backflow inside the cavity.⁵⁹⁾ A plate was installed laterally near the mid portion of the cavity floor. The cavity had an L/D equal to 5. Two tests were taken, with the height of the plate being 2 mm and 4 mm respectively. Figure 12 compares their pressure distributions with that of the cavity with no plate installed. It is clear that the more the backflow is blocked, the lower the pressure at the front part and the higher the pressure at the rear part of the cavity floor.

Figure 13 shows the schlieren photographs for open-type cavities with L/D equal to 5, 7.5, and 10. For open-type cavity flows, the approaching of the developing shear layer over the cavity toward the cavity floor as the L/D increases acts

Fig. 13. Schlieren photographs for open-type cavity flows.

Fig. 14. Sketches of flow fields during the closing of the cavity flow.

just like a plate in hindering the backflow inside the cavity.

The upstream boundary layer separates at the cavity leading edge, entraining some amount of fluid beneath it inside the cavity and forming a mixing layer. The mixing layer becomes thicker as it moves downstream. When it strikes the trailing edge of the cavity, the loss of dynamic pressure of the intercepted fluid will increase the static pressure inside the cavity. The pressure above the mixing layer also increases. To balance this pressure, a shock wave is generated at the leading edge. The external flow is deflected away from the cavity near the leading edge.

For short cavities with $L/D = 5$, the mixing layer strikes the trailing edge directly before it approaches the cavity floor. Backflow occurs freely to replenish the depleted fluid near the front part. For cavities with $L/D = 7.5$ and 10, the spreading mixing layer approaches the cavity floor before it strikes the trailing edge. The free development of the lower side of the mixing layer is obstructed, causing the upper side of the mixing layer to curve upward on the one hand and blocking the backflow inside the cavity on the other. The curving up of the mixing layer further deflects the mainstream upward, generating a compression fan over the rear part of the cavity floor, whose strength increases as L/D increases. The blocking of the backflow makes it difficult to replenish the depleted fluid below the leading edge of the cavity, resulting in a further decrease of pressure there. The shock wave becomes weaker with increasing L/D , as evidenced by the decreasing of the shock angle. At the trailing edge, an expansion fan is generated as the main flow redirects itself to follow the plate behind the cavity.

Based on these observations, the mechanism of the closing

of cavity flows as L/D increases from a value corresponding to open cavity flows can be described as follows (Fig. 14):

- 1) For open-type cavity flow, the upstream boundary layer separates at the leading edge and entrains some amount of fluid beneath it inside the cavity, forming a mixing layer. The mixing layer becomes thicker as it moves downstream. When the L/D of a cavity is small, the separating shear layer strikes at the trailing edge of the cavity, increasing the pressure near the rear wall. The backflow occurs freely inside the cavity, since the mixing layer has yet to be sufficiently developed and the space between it and the floor is ample. A weak shock wave emanating from the leading edge is generated to adapt the freestream to the high pressure over the cavity.
- 2) At an increased value of L/D , the shear layer gets developed for a longer distance. The momentum with which it strikes the trailing edge increases, resulting in even higher pressure near the rear face of the cavity. As the shear layer grows thicker, it approaches the floor gradually. The presence of the floor hinders the free development of the lower part of the shear layer and pushes it upward. The main flow over the cavity gets deflected, producing a compression fan over the rear portion of the cavity. On the other hand, the space between the shear layer and the floor diminishes, and the momentum of the fluid flowing downstream in the shear layer increases, making it more and more difficult for the high pressure fluid at the rear part of the cavity to travel upstream. In fact, the streamlines inside the cavity, as predicted from numerical simulation, reveal

that the backflow is squeezed at the mid portion by the shear layer and the floor into a dumbbell-like shape.⁵⁹⁾ In the meantime, the air at the front part of the cavity is continuously scavenged by the shear layer above it, and the balance of mass flow causing the pressure there decreases. The shock wave at the leading edge weakens. The size of the recirculation near the front corner shrinks.

- 3) Further increasing the value of L/D , the shear layer approaches so close to the floor that the backflow is essentially separated into two parts. Two new recirculations, embedded in the backflow and linked with only a thin layer of fluid with upstream velocity just over the floor, are formed. Because of reduced air supplement, the pressure near the front corner decreases below that of the freestream. An expansion fan replaces the weak shock wave at the leading edge, and the external flow begins to deflect into the cavity, initiating the transitional-open type cavity flow. The compression fan over the rear portion of the cavity becomes strengthened.
- 4) At a critical value of L/D , the shear layer suddenly impinges onto the floor, cutting the backflow into two separate recirculations. The deprivation of air supplement through backflow from the rear part of the cavity causes the pressure near the front part to drop to a minimum. A strong expansion fan is formed at the leading edge. The deflection of the main flow at the floor produces a single shock wave that marks the transitional-closed type cavity flow.

4. Summary

Experimental investigation of compressible flows over cavities with a depth of 8 mm and a series value of length-to-depth ratio (L/D), at Mach number of 1.94 and Reynolds number per unit meter of 4.2×10^7 , found that the freedom of backflow inside the cavity is crucial in smoothing out adverse pressure gradient for open-type cavity flows. The spreading of the shear layer and its gradual approaching toward the cavity floor as L/D increases tend to suppress the freedom of backflow, causing the cavity flow to change from the open-type to the transitional-type.

For closed-type cavity flows, the finite thickness of the upstream boundary layer leads to the presence of three kinds of characteristic lengths that correspond to the recirculation region, the deflection of the main flow, and the recovery or the abrupt rise of the pressure, respectively. The compression fans at the foot of the impingement and exit shock waves will approach each other well in advance of the possible merge of the vertices of the conventionally defined separation and recompression wakes. As the L/D of a closed-cavity decreases, the reattached shear layer on the mid portion of the cavity floor will have less developing distance and will therefore be more susceptible to adverse pressure gradient.

For the present two-dimensional models, the change of

flow types from the open to the transitional is a gradual process and occurred at an L/D from 10 to 12. The change of flow types from the transitional to the closed shows an abrupt change in flow features and pressure distribution. The critical length-to-depth ratio was found to be about 14. The sum of the pressure lengths at the front and rear wakes agrees remarkably well with the second critical L/D .

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