6th European Conference on Computational Mechanics (ECCM 6)
7th European Conference on Computational Fluid Dynamics (ECFD 7)
11 – 15 June 2018, Glasgow, UK

ACTIVE CONTROL USING MOVING BOTTOM WALL APPLIED TO OPEN CAVITY SELF-SUSTAINED OSCILLATION WITH MODE SWITCHING

TAKASHI YOSHIDA[1] AND TAKASHI WATANABE[2]

[1]Shinshu University, Department of Mechanical Engineering Systems
4-17-1 Wakasato, Nagano-shi, 380-8553, Japan
yoshi-t@shinshu-u.ac.jp

[2]Nagoya University, Graduate School of Informatics
Furo-cho, Chikusa-ku, Nagoya-shi, 464-8601, Japan
watanabe@i.nagoya-u.ac.jp

Key words: Open Cavity Flow Oscillation, Flow Control, Moving Bottom Wall, Incompressible Flow, Two-dimensional Direct Numerical Simulation.

Abstract. The self-sustained oscillations of open cavities with cavity aspect ratios of 2.0, 2.5, 3.0, 3.5, and 4.0 were studied with and without an active control using moving bottom wall. The studies were conducted by using 2D incompressible direct numerical simulations. Self-sustained oscillatory regimes of shear layer without control were classified into mode II, mode III and wake mode as the cavity aspect ratio increases. The results showed that the self-sustained oscillations were completely suppressed by our control method using suitable moderate moving velocities of the bottom wall for all oscillatory modes.

1 INTRODUCTION

Flows over open cavities occur in a wide variety of aerospace and engineering applications, for example, the landing gear wheel well of aircrafts, aircraft cargo bays, car sunroofs and windows, and spaces between 2 train wagons, etc. Cavity flow is of very interest, because the presence of cavity causes self-sustained oscillations of the separated shear layer by a complex feedback mechanism, despite its geometrical simplicity. Self-sustained oscillating flow over the cavity has been a fluid dynamics phenomenon of interest since the 1960s. Rockwell and Naudascher [1] have described the fluid-dynamic excitation mechanism. The nature of flow-induced oscillations in the open cavity is illustrated in Figure 1 where the length of the cavity is L and the depth of the cavity is D. The separated shear layer at the leading edge of the cavity develops from its initial perturbations and the Kelvin-Helmholtz instability of the mean shear layer profile. The vortical structure of the shear layer travels the length of the cavity and ultimately reattaches near the trailing edge of the cavity. The periodic pressure disturbances are produced at the trailing edge of the cavity and are fed back to the origin of the unstable shear layer near the leading edge of the cavity. The pressure disturbances feedback periodically forces the separated shear layer and enhances its coherent structure, so that regular large-scale vortices are produced. The interaction of these vortices with the reattachment surface induces the pressure disturbances. While the open cavity flow has been investigated by the numerical method (Vinha *et al*. [2]) and the experimental method (Immer *et al*. [3], Kumar and Vaidyanathan [4]), the characteristic of the flow is not still cleared. In this study, the oscillation of the flow is studied and the 2D direct numerical simulation is carried out to show that the oscillation is suppressed by the active control using a moving wall.

It is well known that the primary frequency of the shear layer oscillations varies with the cavity length. Many experimental studies have been carried out to reveal the characteristics of the frequency variation (Sarohia [5], Knisely and Rockwell [6], Gharib [7], Gharib and Roshko [8]). The general feature of the variation of the dominant frequency represented by the Strouhal number St with the cavity aspect ratio L/D is shown in Figure 2. A minimum cavity aspect ratio is required for the initiation of self-sustained oscillation. The onset of the oscillation is associated with the decrease in St as the cavity aspect ratio increases. This flow regime is referred as “shear layer mode”. The shear layer mode is characterized by the roll-up of vorticity in the shear layer. In the shear layer mode, the decrease in St with the increase in the aspect ratio is interrupted by the sudden jump-up. The flow mode before and after the jump-up are called the mode II and the mode III, respectively. As the cavity aspect ratio increases further, there is a substantial change in the pattern of the cavity oscillations. Gharib and Roshko [8] observed a wake-like flow, so they called this flow regime as “wake mode”. The wake mode is characterized by a large-scale vortex shedding from the cavity leading edge. From the computational point of view, some studies about the mode switching phenomena have been conducted. Rowley *et al*. [9] investigated the mode switching of the shear layer mode and the wake mode by using 2D compressible direct numerical simulation. Rubio *et al*. [10] investigated the mode switching by using 2D compressible large eddy simulation. However their simulation have been changed at coarse intervals of cavity aspect ratio. Yoshida and Watanabe [11] investigated the mode switching by using a series of 2D incompressible direct numerical simulation at the cavity aspect ratio from 1.0 to 4.0 with an interval of 0.1. The results showed the mode switching among non-oscillation mode, shear layer mode (mode II and mode III), and wake mode and the relationship between the cavity shear layer oscillation modes and recirculating vortices in the cavity.

The control of the cavity flow oscillations is one of the challenging topics in flow control

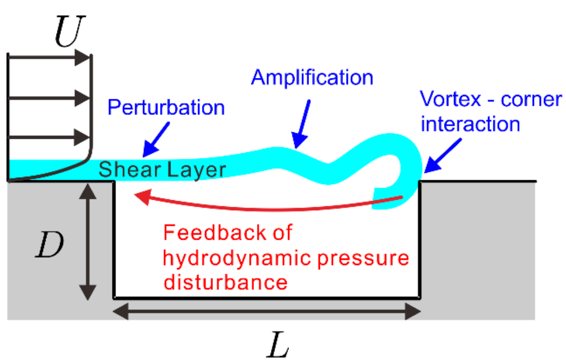


Figure 1: Schematic illustrating flow-induced cavity oscillation.

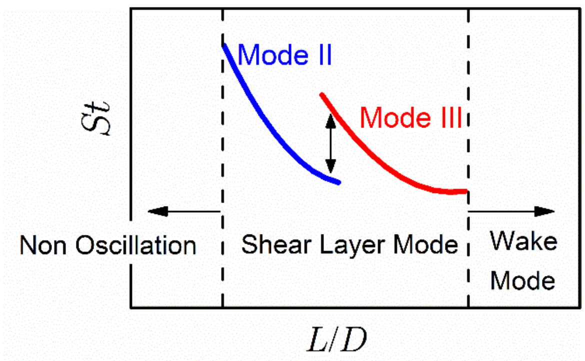


Figure 2: Schematic of Strouhal number variation and the definition of oscillation modes.

problems. The suppression of the cavity flow oscillations has received considerable attention in recent years. The control of cavity oscillations has been reviewed by Rowley and Williams [12] and Cattafesta *et al.* [13]. Numerous workers have used various control devices, for example, microjet injection, pulsed blowing actuators, synthetic jets, oscillating spoilers, piezoelectric flaps, piezoelectric bimorph actuators, plasma actuators and others. They reported the suppression of the oscillations in the separated shear layer by the control using these devices.

Yoshida *et al.* [14] developed a new active control method for the suppression of the cavity flow oscillations. We focused on the role of the recirculation vortices in the cavity in the shear layer oscillations. The interaction between the recirculating flow field and the shear layer oscillations has been neglected in most previous studies. Our control method is to drive the bottom wall of the cavity with a constant tangential velocity, which is similar to the method used in the lid-driven cavity flow problem. The moving bottom wall produces a shear stress in the fluid and changes the recirculating vortices in the cavity. We presented that the suppression of the cavity oscillations is achieved by applying our control method using 2D direct numerical simulations for the cavity aspect ratio L/D = 2. However, the effect of our control method on the flows at different cavity aspect ratios and different oscillatory modes is not obvious.

The major aim of this investigation is to reveal the effect of our new control method to different cavity aspect ratios and different modes. 2D incompressible direct simulations with our control method are performed for the flows at the cavity aspect ratios L/D = 2.0, 2.5, 3.0, 3.5 and 4.0. The mode II appears at L/D = 2.0, 2.5 and 3.0. The mode III emerges at L/D = 3.5. At L/D =4.0, the flow is in the wake mode. We demonstrate that the oscillations of the mode II, mode III, and wake mode are suppressed using our control method.

2 NUMERICAL METHOD AND CONTROL METHOD

The numerical method of this study is the same as the one used by Yoshida and Watanabe [11]. Figure 3 shows a sketch of the computational domain and indicates several system

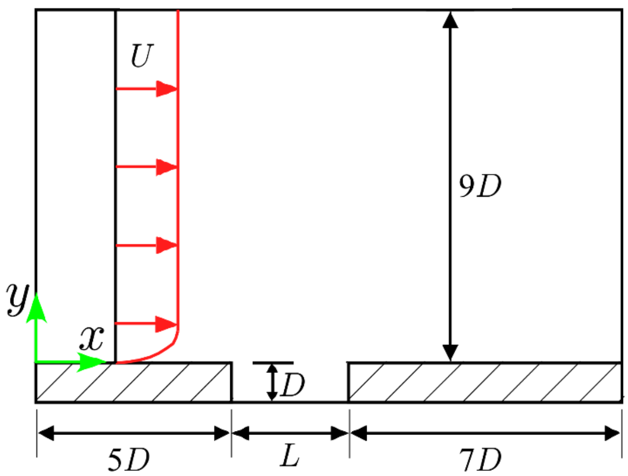


Figure 3: Cavity configuration and computaional domain.

parameters. The governing equations are the two-dimensional, unsteady, incompressible Navier-Stokes equations and the equation of continuity in Cartesian coordinates. All variables are nondimensionalized by using the cavity depth D and the freestream velocity U. These equations are integrated in time by using the P2 pressure correction method by Armfield and Street [15]. The momentum equations are discretized by using the second order Adams-Bashforth method for the convective terms and the Crank-Nicolson method for the diffusive terms. These equations are solved by fractional step method to enforce the solenoidal condition. The pressure correction term is used with Kim and Moin type boundary condition [16] in order to reduce the projection error and recover the second-order accuracy in time. Nonuniform staggered grid systems, which cluster node points in the boundary layer, the shear layer, the cavity bottom, and the cavity edges, are used for the spatial descretization. The second order fully conservative finite difference scheme by Morinishi *et al*. [17] is used for the convective terms and the second order central difference scheme was used for the other terms in the spatial discretization. The dimension of the computational domain is similar to that used in the 2D direct numerical simulations of Rowley *et al*. [9]. The laminar Blasius boundary layer is specified in the inflow boundary at $x = 0$. A free-slip condition is applied to the normal boundary. A no-slip boundary condition is applied to the wall. At the outflow boundary, we use the Sommerfeld radiation condition, which is also called the convective outflow condition. The convective velocity in this condition is set equal to the free-stream velocity U. This boundary condition allows the vortices to smoothly pass across the computational domain. The Reynolds number based on the freestream velocity U and the cavity depth D is 6,000. The boundary layer momentum thickness θ at the upstream cavity edge is 0.0322 for L/D = 2.0. The Reynolds number Re_θ based on U and θ is 193.6. This

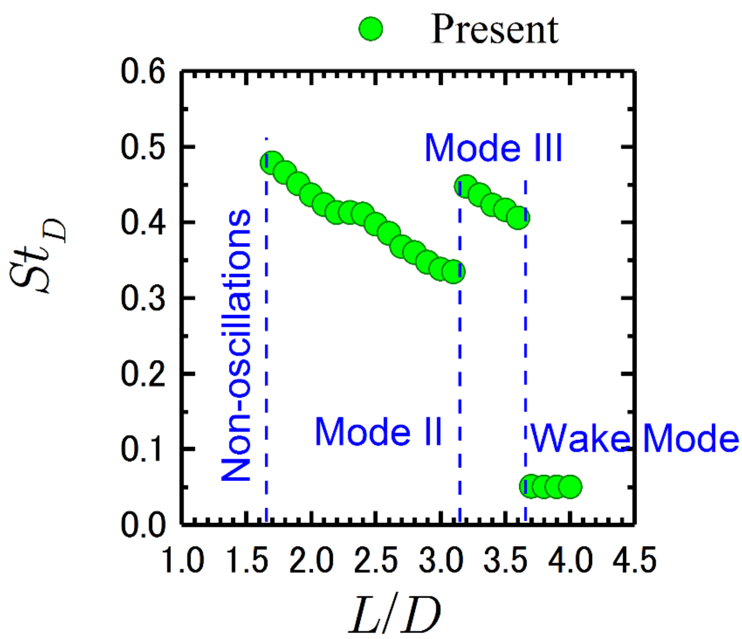


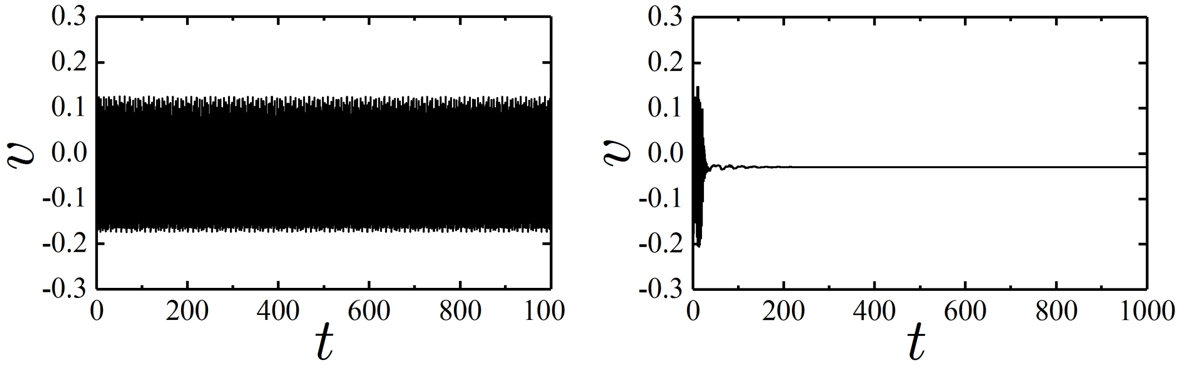
Figure 4: The Strouhal number variation with cavity length.

condition is similar to that of the experiment by Knisely and Rockwell [6], where $Re_\theta = 190$.

3 RESULTS

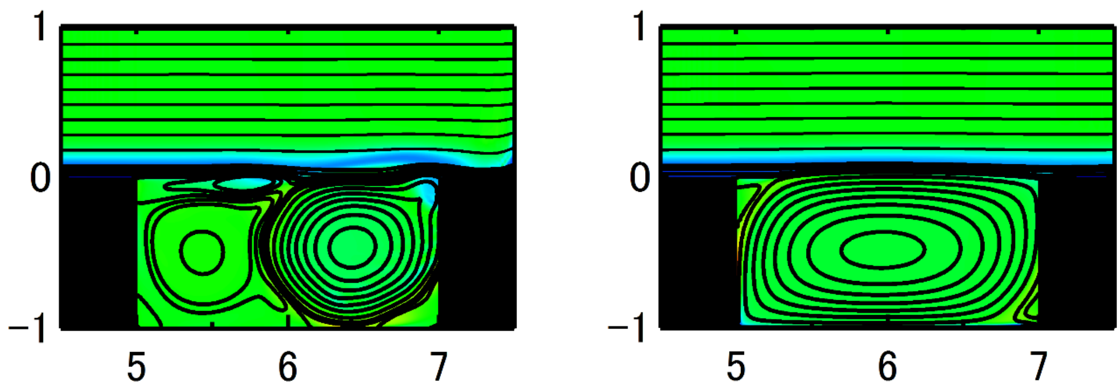
3.1 Mode switching in baseline flow

A series of 2D direct numerical simulations of the baseline flows at the cavity aspect ratio L/D from 1.0 to 4.0 with an interval of 0.1 interval have been conducted in our previous paper [11]. Figure 4 shows the Strouhal number variation with the cavity length L/D. No shear layer oscillation occurs below $L/D = 1.6$. The minimum length for the onset of the self-sustained oscillations is $L/D = 1.7$. The Strouhal number of the oscillations decreases as L/D increases. This variation is interrupted by a sudden jump to a higher value between $L/D = 3.1$ and $L/D = 3.2$. The oscillation regime at $L/D \leq 3.1$ is mode II, while that at $3.2 \leq L/D$ is mode III. The maximum cavity length in mode III is $L/D = 3.6$. The wake



(a) $u_w = 0.0$ (b) $u_w = -0.3$

Figure 5: Time traces of the normal velocity component near the trailing edge for $L/D = 2.0$ cavity; (a) baseline case (b) controlled case.



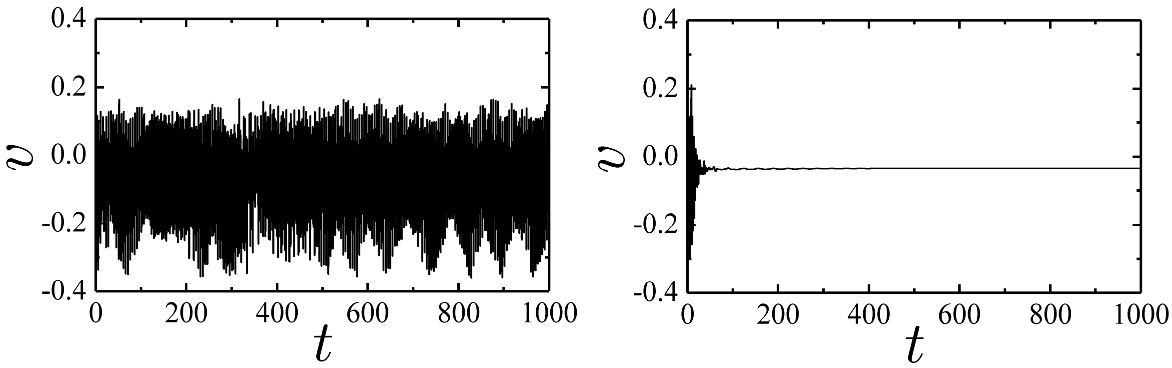
(a) $u_w = 0.0$ (b) $u_w = -0.3$

Figure 6: Instantaneous streamlines and the color contour plots of the vorticity for $L/D = 2.0$ cavity; (a) baseline case (b) controlled case.

mode appears at $3.7 \le L/D \le 4.0$. The present results of shear layer mode closely agree with the experimental data of Knisely and Rockwell [6] (for details, refer to our previous paper [11]).

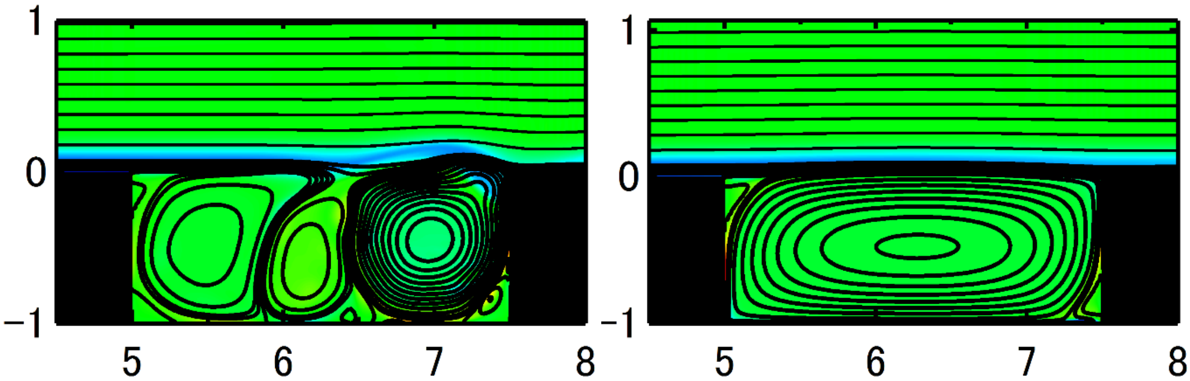
3.2 Control cases in mode II

The active control method using a moving bottom wall is applied for the cases of L/D = 2.0, 2.5 and 3.0 in the mode II. The bottom wall velocity u_w varies between 0.0 and -1.5. The case of $u_w = 0.0$ is the baseline flow without any control. Figure 5 shows the time trace of the normal velocity component v near the downstream edge of the cavity ($x = 6.9$ and $y = 0.0$) for $L/D = 2.0$. The time t is elapsed the time from the start of the wall movement. When the full development of the baseline flow is confirmed, the wall movement is applied and the time t is set to be 0.0. The oscillation of baseline case in Figure 5(a) is periodic. In contrast, the oscillation for $u_w = -0.3$ is reduced and is suppressed completely as shown in



(a) $u_w = 0.0$ (b) $u_w = -0.3$

Figure 7: Time traces of the normal velocity component near the trailing edge for $L/D = 2.5$ cavity; (a) baseline case (b) controlled case.

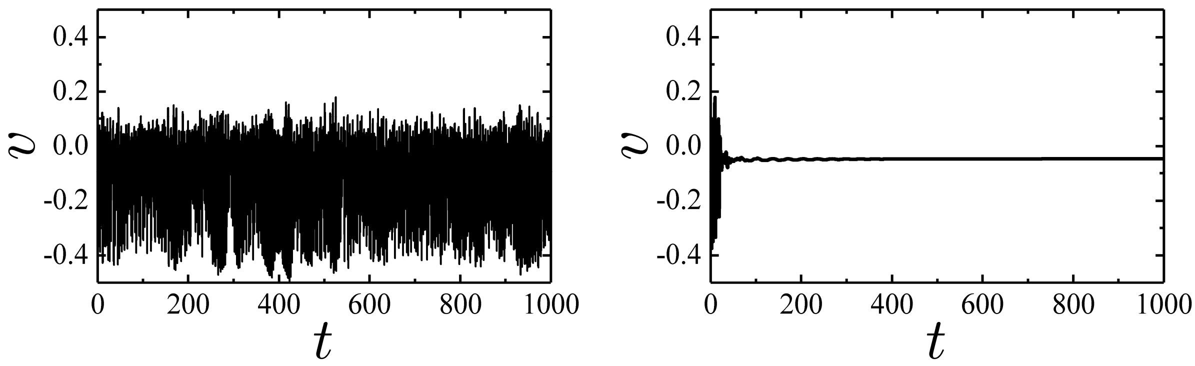


(a) $u_w = 0.0$ (b) $u_w = -0.3$

Figure 8: Instantaneous streamlines and the color contour plots of the vorticity for $L/D = 2.5$ cavity; (a) baseline case (b) controlled case.

Figure 5(b). Instantaneous flow fields at $t = 1{,}000$ for $L/D = 2.0$ are shown in Figure 6, where Figure 6(a) corresponds to the baseline case and Figure 6(b) to the controlled case with $u_w = -0.3$. The black lines show the streamlines and the color contours show the vorticity. In Figure 6(a), the streamlines of the baseline case show two recirculating vortices in the cavity and the vorticity contours of blue color show that the separated shear layer oscillates above the two recirculating vortices. In contrast, Figure 6(b) shows that the clockwise-rotating vortex on the downstream side becomes larger and the counterclockwise-rotating vortex on the upstream side disappears due to the negative wall shear stress and the clockwise-rotating vortex occupies the entire space inside the cavity. The flow on the upper side in the cavity is parallel to the shear layer over the cavity mouth, so that the shear layer becomes stable and the oscillations are suppressed completely. For $L/D = 2.0$, the oscillations are suppressed by the moving bottome wall control in the range of $-1.12 \le u_w \le -0.08$.

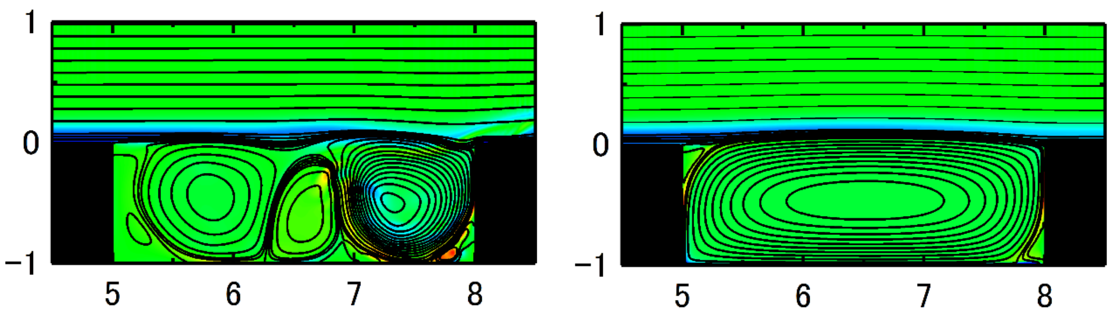
Figure 7 shows the time trace of the normal velocity component near the downstream edge of the cavity ($x = 7.4$ and $y = 0.0$) for $L/D = 2.5$. The oscillation of baseline case in Figure



(a) $u_w = 0.0$

(b) $u_w = -0.4$

Figure 9: Time traces of the normal velocity component near the trailing edge for $L/D = 3.0$ cavity; (a) baseline case (b) controlled case.



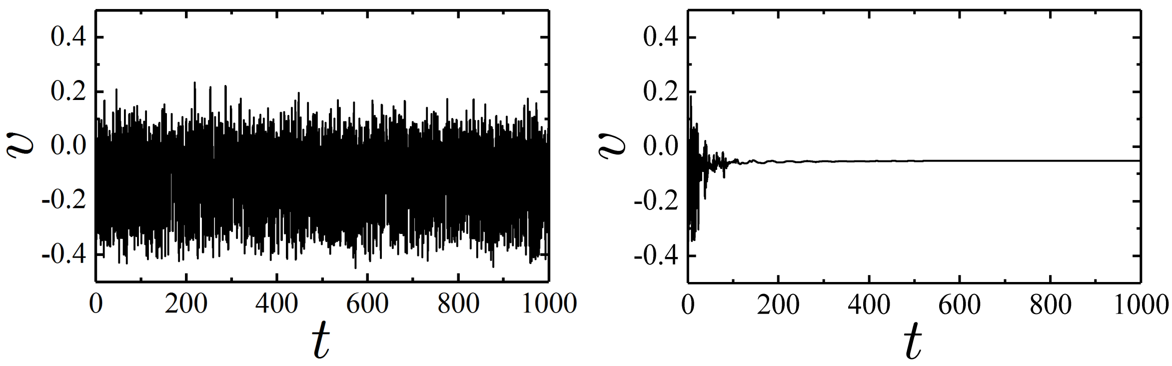
(a) $u_w = 0.0$

(b) $u_w = -0.4$

Figure 10: Instantaneous streamlines and the color contour plots of the vorticity for $L/D = 3.0$ cavity; (a) baseline case (b) controlled case.

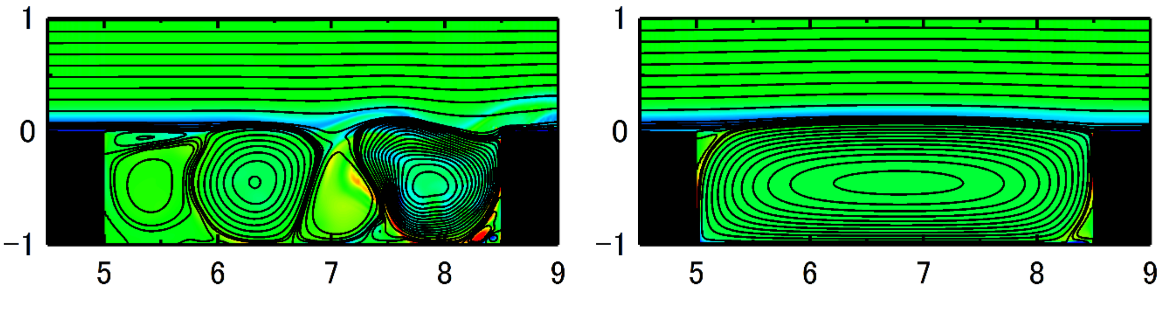
7(a) is periodic. In contrast, the oscillation for $u_w = -0.3$ is reduced and is suppressed completely as shown in Figure 7(b). Instantaneous flow fields at $t = 1{,}000$ for $L/D = 2.5$ are shown in Figure 8. Figure 8(a) shows three recirculating vortices in the cavity and the shear layer oscillation. Figure 8(b) shows one clockwise-rotating large vortex in the cavity and the flat shear layer. For $L/D = 2.5$, the oscillations are suppressed by the moving bottom wall control in the range of $-1.11 \le u_w \le -0.18$.

Figure 9 shows the time trace of the normal velocity component near the downstream edge of the cavity ($x = 7.9$ and $y = 0.0$) for $L/D = 3.0$. The oscillation of baseline case in Figure 9(a) is periodic. In contrast, the oscillation of $u_w = -0.4$ is reduced and is suppressed completely as shown in Figure 9(b). Instantaneous flow fields at $t = 1{,}000$ for $L/D = 3.0$ are shown in Figure 10. Figure 10(a) shows three recirculating vortices in the cavity and the shear layer oscillation. Figure 10(b) shows one clockwise-rotating large vortex in the cavity and the flat shear layer. For $L/D = 3.0$, the oscillations are suppressed by the moving bottom wall control in the range of $-0.8 \le u_w \le -0.21$.



(a) $u_w = 0.0$ (b) $u_w = -0.4$

Figure 11: Time traces of the normal velocity component near the trailing edge for $L/D = 3.5$ cavity; (a) baseline case (b) controlled case.



(a) $u_w = 0.0$ (b) $u_w = -0.4$

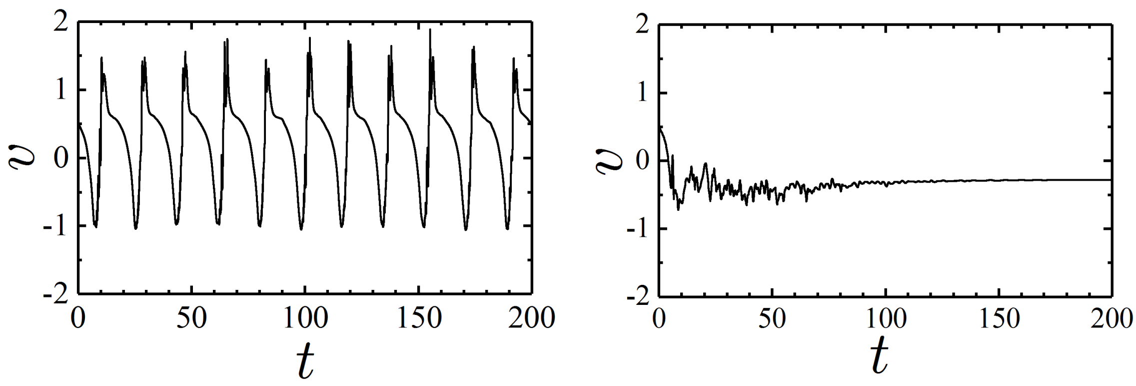
Figure 12: Instantaneous streamlines and the color contour plots of the vorticity for $L/D = 3.5$ cavity; (a) baseline case (b) controlled case.

3.3 Control case in mode III

The active control method using a moving bottom wall is applied for the case $L/D = 3.5$ in the mode III. Figure 11 shows the time trace of the normal velocity component near the downstream edge of the cavity ($x = 8.4$ and $y = 0.0$) for $L/D = 3.5$. The oscillation of the baseline case in Figure 11(a) is periodic. In contrast, the oscillation of $u_w = -0.4$ is reduced and is suppressed completely as shown in Figure 11(b). Instantaneous flow fields at $t = 1{,}000$ for $L/D = 3.5$ are shown in Figure 12. Figure 12(a) shows four recirculating vortices in the cavity and the shear layer oscillation. Figure 12(b) shows one clockwise-rotating large vortex in the cavity and the flat shear layer. For $L/D = 3.5$, the oscillations are suppressed by the moving bottom wall control in the range of $-0.8 \le u_w \le -0.27$.

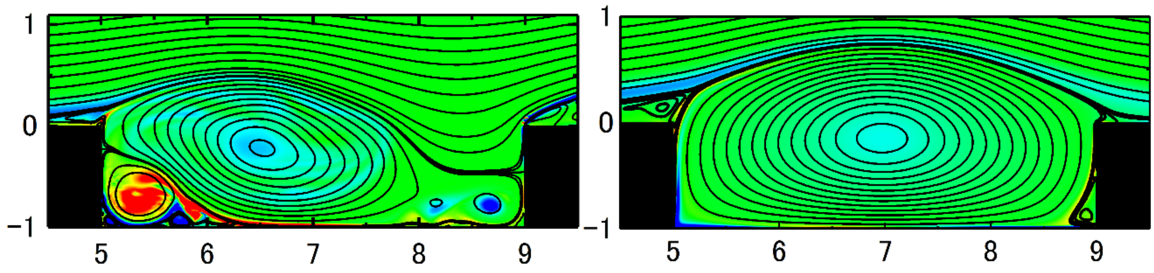
3.4 Control case in wake mode

The active control method using a moving bottom wall is applied for the cases $L/D = 4.0$ in the wake mode. Figure 13 shows the time trace of normal velocity component near the



(a) $u_w = 0.0$ (b) $u_w = -1.0$

Figure 13: Time traces of the normal velocity component near the trailing edge for $L/D = 4.0$ cavity; (a) baseline case (b) controlled case.



(a) $u_w = 0.0$ (b) $u_w = -1.0$

Figure 14: Instantaneous streamlines and the color contour plots of the vorticity for $L/D = 4.0$ cavity; (a) baseline case (b) controlled case.

downstream edge of the cavity ($x = 8.9$ and $y = 0.0$) for $L/D = 4.0$. The oscillation of the baseline case in Figure 13(a) has a large amplitude and a periodicity. In contrast, the oscillation of $u_w = -1.0$ is reduced and is suppressed completely as shown in Figure 13(b). Instantaneous flow fields at $t = 200$ for $L/D = 4.0$ are shown in Figure 14, where Figure 14(a) corresponds to the baseline case and Figure 14(b) to the controlled case with $u_w = -1.0$. Figure 14(a) shows a large scale vortex in the cavity and the vortex shed from the upstream edge of the cavity. Figure 14(b) shows one clockwise-rotating large vortex in the cavity and the smooth curved shear layer. For $L/D = 4.0$, the oscillations are suppressed by the moving bottom wall control in the range of $-1.3 \leq u_w \leq -0.5$.

4 CONCLUSIONS

- This paper studies the mode switching that occurs in flows passing over two-dimensional open cavities by using 2D incompressible direct numerical simulations. The computations have revealed three oscillation regimes: the mode II of the shear layer mode, the mode III of the shear layer mode and the wake mode in the baseline flows.
- This paper is concerned with the active control method using a moving bottom wall for the open cavity oscillations. We have applied our control method to the three oscillation modes of flows over the open cavity. 2D incompressible direct simulations with and without our control method have been conducted for the flows at cavity aspect ratios of $L/D = 2.0,\ 2.5,\ 3.0,\ 3.5$ and 4.0. The results of controlled simulations showed the self-sustained oscillations were completely suppressed by our control method for all L/D and all oscillation modes.

ACKNOWLEDGEMENTS

This work was partly achieved through the use of HCC and OCTOPUS at the Cybermedia Center, Osaka University.

REFERENCES

[1] Rockwell, D. and Naudascher, E., Review—Self-Sustaining oscillations of flow past cavities, *Transactions of the ASME, Journal of Fluids Engineering* (1978) **100**:152-165.

[2] Vinha, N., Mesegure-Garrido, F., de Vicente, J. and Valero, E., A dynamic mode decomposition of the saturation process in the open cavity flow, *Aerospace Science and Technology* (2016) **52**:198-206.

[3] Immer, M., Allegrini, J. and Carmeliet, J., Time-resolved and time-averaged stereo-PIV measurements of a unit-ratio cavity, *Experiments in Fluids* (2016) **57**:101 :1-18.

[4] Kumar, M. and Vaidyanathan, A., Oscillatory mode transition for supersonic open cavity flows, *Physics of Fluids* (2018) **30**, 026101:1-12.

[5] Sarohia, V., Experimental investigation of oscillations in flows over shallow cavities, *AIAA Journal* (1977) **15-**7:984-991.

[6] Knisely, C. and Rockwell, D., Self-sustained low-frequency components in an impinging shear layer, *Journal of Fluid Mechanics* (1982) **116**:157-186.

[7] Gharib, M., Response of the cavity shear layer oscillations to external forcing, *AIAA Journal* (1987) **25**-1:43-47.

[8] Gharib, M. and Roshko, A. The effect of flow oscillations on cavity drag, *Journal of Fluid Mechanics* (1987) **177**:501-530.

[9] Rowley, C. W., Colonius, T. and Basu, A. J., On self-sustained oscillations in two-dimensional compressible flow over rectangular cavities, *Journal of Fluid Mechanics* (2002) **455**:315-346.

[10] Rubio, G., De Roeck, W., Baelmans, M. and Desmet, W., Numerical identification of flow-induced oscillation modes in rectangular cavities using large eddy simulation, *International Journal for Numerical Methods in Fluids* (2007) **53**:851-866.

[11] Yoshida, T. and Watanabe, T., Numerical simulation of flow over an open cavity with self-sustained oscillation mode switching, *Open Journal of Fluid Dynamics* (2016) **6**:361-370.

[12] Rowley, C. W. and Williams D. R., Dynamics and control of high-Reynolds-number flow over open cavities, *Annual Review of Fluid Mechanics* (2006) **38**:251-276.

[13] Cattafesta, L. N., Song, Q., Williams, D. R., Rowley, C. W. and Alvi, F. S., Active control of flow-induced cavity oscillations, *Progress in Aerospace Sciences* (2008) **44**:479-502.

[14] Yoshida, T., Watanabe, T., Ikeda, T. and Iio, S., Numerical analysis of control of flow oscillations in open cavity using moving bottom wall, *JSME International Journal, Series B*, (2006) **49**-4:1098-1104.

[15] Armfield, S. and Street, R., An analysis and comparison of the time accuracy of fractional-step methods for Navier-Stokes equations on staggered grids, *International Journal for Numerical Methods in Fluids* (2002) **38**:255-282.

[16] Kim, J. and Moin, P., Application of a fractional step method to incompressible Navier-Stokes equations, *Journal of Computational Physics* (1985) **59**:308-323.

[17] Morinishi, Y., Vasilyev, O.V. and Ogi, T., Fully conservative finite difference scheme in cylindrical coordinates for incompressible flow simulations, *Journal of Computational Physics* (2004) **197**:686-710.