Numerical Simulation of Jets Emitted into a Two-Dimensional Channel with Self-Induced Oscillation* (Active Control by Neural Network Observer)

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Active control of jets emitted into a two-dimensional channel with insulated suction near the wall during monitoring with a neural network is described. The aim of this work is to simulate the possibility of controlling the flow pattern with a flip-flop phenomenon by suitable suction. In this case, the output of a neural network is estimated satisfactorily based on 3 flow patterns of teaching data. The periodic flow pattern at the Reynolds number $Re=1.0 \times 10^3$ is reduced by a suction rate of less than 10% for primary jets. Then flow becomes stable as a result of feedback gain of the neural network. Since the control with suction need not be continuous, the power cost is reduced. The nonperiodic case at $Re=1.0 \times 10^4$ is difficult to control, but we achieved good control by with the use of a suitable suction rate with the neural network.

Key Words: Flip-Flop Jet, Separation, Active Control, Suction, Chaos, Neural Network

1. Introduction

In the first report⁽¹⁾, we identified the existence of a recirculated region similar to that for the representative separation bubble, in a jet emitted into a two-dimensional channel. We showed that the process of separation strongly depends on the rate of channel expansion or the Reynolds number. In the second report⁽²⁾, we described the possibility of numerical estimation of the flow state after the neural network (NN) learns flow information concerning the unsteady separated recirculating region. For velocity fluctuation input, we demonstrated that not only the periodic result but also the nonperiodic result could be estimated if the conditions are appropriate.

The purpose of this work is the active control of the separation which exists near the inlet of a jet emitted

into a two-dimensional channel and to repress the flip-flop phenomenon. NN as the observer of control is improved to enable it to choose the teaching data alternatively. In addition, the feedback gain from NN directs the control of suction. The position of suction is set parallel to the mean flow and near the lower portion of the wall. By means of this control with suction, the flip-flop phenomenon in which the jet swayed in the whole channel space was predicted by the NN. If need be, the flow direction can be controlled to keep moving to onewall in the two-dimensional channel. In general, this method is known to control the occurrence of the separation bubble which is considered to be a factor in the loss of the flow and to reduce the resistance for fluid transportation. Although many reports exist on experimental and numerical analyses similar to those in this study, there are few reports on the active control of the instability of flow regions. The research on micro-electro mechanical systems (MEMS) using NN mainly concerns the reduction of conflict resistance at the turbulent boundary layer, so no tests on the control of separation, as in our studies, have been conducted⁽³⁾. One of the achievements of NN architecture is small amount of teaching data required for control.

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Regarding the quality of flow, the Reynolds number (Re) of 10^3 , the case of periodic fluctuation, and of 10^4 , the case of chaotic fluctuation, satisfy the result for control. This result agrees with Masumoto's finding⁽⁴⁾ that it is not necessary to increase the amount of teaching data in order to improve the accuracy of prediction.

2. Conditions of Calculation

We numerically simulate a jet emitted into a two-dimensional channel with incompressible viscous fluid. As shown in Fig. 1, we selected a jet which has a parabolic velocity profile of emission into a two-dimensional channel designed with the aspect ratio ($L:H$) of 6:1 and the flowing width of D ($D \leq H$) from the center to the left. The position of suction is set at a low portion of the left wall with the width d and $D/d=2$. The ratio of H to D is always 5:1 which is the limit of the control force of the flow ratio required to maintain the deviated flow. The boundary condition is nonslip at the wall, and $\frac{\partial V}{\partial x}=0$ at the exit with $x/H=6$ and at the part of the suction.

The numerical scheme includes the finite difference vorticity equation; the unsteady term is solved by the Runge-Kutta-Gill method, the convection term (nonlinear term) by the upwind difference to the first degree of accuracy, and the viscous term by the central difference to the second degree of accuracy. The Poisson equation of the stream function is discriminated using the central difference in the second degree of accuracy. The number of divisions for the calculation region is 60 in the x direction and 50 in the y direction, so we used the Gaussian lattices in divided equally. The representative parameter of the flow region is the Reynolds number $Re = \frac{HU_0}{\nu}$, where U_0 denotes the center velocity of the jet. The time step for calculation is $dt=0.05$, time t is non-dimensionalized by the representative length H and representative velocity U_0 . At the calculation time step 0, a velocity profile to be necessary for a calculation is given, so in the case of $Re=10^3$, we find the transitional state that does not develop to the periodic fluctuation until time step 50 (nondimensional time 3.0).

3. Method of Recognition of Deviated Flow and Suction

The teaching signals are defined as follows.

The state of deviated flow to the upper wall:
mode 1

The state of deviated flow to the lower wall:
mode 0

Fig. 1 Flow configuration and boundary conditions

In order to estimate in which direction the stream flows and how much the stream deviates due to the influence of the separation bubble, we utilize the results in our second report⁽²⁾. We selected referencing of the matching between the typical deviated flow mode in the channel and each visualized datum that is divided equivalently in space on voluntary time. The typical mode is applicable for quantitative evaluation of the transition process, so we need not select the complicated state.

In this study, we extracted 3 patterns, as shown in Figs. 2(a), (b) and (c), from the visualized information of the flow which moved from the upper wall to the lower wall. We show the vorticity and streamline contours and the velocity vector together. At the top on the right in the figure, the value of the mode for the teaching signal is given. We define these states before suction as the first-step teaching data.

For the case of heat convective transition, authors⁽⁵⁾ have extracted many states (47 patterns) of the transitional process and used them as teaching data. Compared to this method, the flip-flop phenomenon of Re in this study is known to have a simple property for the recognition of the state. The small amount of teaching data (3 patterns) reduces the frequency of collecting information for NN and improves the efficiency of learning.

Here, as in Fig. 3, the network is directory type and is composed of 16 input layers, 10 middle layers, and 1 output layer.

When the suction for control starts, NN output might not be judged correctly even if the control effect clearly appears. Because the flow near a suction is a phenomenon with no of a learning experience until now to NN. Based on this result, there is the possibility that the control is adequate. In fact, although the deviated flow to the lower wall is maintained by the suction, NN output is evaluated to be approximately 0.4 in the middle mode. In order to prevent a large difference with above-mentioned result and NN judgement, the teaching data are exchanged at appropriate times and we consider the method in which the observation criterion changes before and after control (Fig.

Fig. 2 Teaching data set

4). We hope to use the state (Fig. 5) determined from the result of calculation in which the suction was continuous. Then the flip-flop phenomenon peculiar to the jet holds down to the lower wall, and we recognize that there is a stable deviated flow to the lower wall. In this case, the suction rate is 0.7. (We describe the details of the definition of suction rate in the next section.) Then the flow is found to move to the lower wall, and mode 0.1 (Fig. 5) is used, in spite of using mode 0.1 in the first-step teaching data (Fig. 2(c)). Thus we define the state as second-step teaching data. As the architecture of the NN, we calculate and prepare the respective weight coefficients for the first- and second-step teaching data. Although control is begun based on the first-step teaching data, NN output suggests that the state has deviated to the lower wall but continues to be controlled by the observation criterion. Using the above-mentioned method, the flow state could be effectively recognized.

Fig. 3 Neural network structure

Fig. 4 Teaching data exchange

Fig. 5 Exchanged data element

4. Rule of Control

The evaluation for the rule of control is described using by the flow ratio of the jet q/Q and the time of control t_c . The equation of the definition of flow is as follows.

$$\begin{aligned} \text{intaking flow by jet } Q &= D \cdot \bar{U} \\ \text{outlet flow by suction } q &= d \cdot \bar{U}_s \end{aligned}$$

$\bar{U}$ denotes the mean velocity for the intaking jet, and $\bar{U}_s$ denotes the mean outlet velocity for suction.

As in Fig. 1, for continuous suction of the fluid, the flip-flop phenomenon is controlled and the state of mode 0 can be maintained as stable deviated flow to

the lower wall. However, this is not promising for improving energy efficiency. Therefore we carried out the following referring to the algorithm of ON-OFF control developed by us ⁽⁵⁾.

(1) When the NN output is beyond the upper limit of the threshold level, suction is begun.

(2) When, due to the suction, flow deviates to the wall and NN output is below the lower limit of the threshold level, the control is stopped.

The evaluation differs according to the threshold level and width of the band of the threshold level. NN output equals 0.1 (at $Re=10^3$) and 0.2 (at $Re=10^4$) and constant threshold level. By delicate ON-OFF control, we evaluated a relation with a few control amount of flow and short control time with a thought of the most suitable control.

5. Result of Control for Periodic Motion

We describe the result of control for the periodic solution ($Re=10^3$). Figure 6 shows the state of flow under which the control of the direction was achieved at the flow ratio of 0.2. Even with this weak suction, the separation bubble is eliminated and pseudosteady flow proceeds.

In Figs. 7(a), (b) and (c), the history of control with change of the control force to 0.7, 0.35 and 0.2 is shown, respectively. The left vertical axis denotes NN output and the right one denotes flow ratio. The horizontal axis denotes nondimensional time. NN output is shown by the solid line and the flow ratio by the broken line. As soon as the flow is judged (NN output is less than 0.1) to deviated flow to the lower wall by the flip-flop phenomenon, the control starts and the teaching data of the NN is exchanged at the same time. This exchange is carried out just at time step one, so we observe a sudden change of NN output near nondimensional time 100. If NN output exceeded 0.1, here, we give a control rule to start with the flow ratio of 0.75 for a suction. The broken line in the figure shows the state of change. After applying this control, when the NN output is over the threshold

Fig. 6 Flow pattern with suction (suction rate 0.2)

level of 0.12, the suction starts at the same flow ratio. When NN output is less than 0.08, the suction stops. By simple repetition of the above, the flip-flop phenomenon that there existed for vertical whole direction of flow region is eliminated and the high frequency reveals with a slight increase near the wall. From above mention in the case of $Re=10^3$, an almost stable deviated flow to the lower wall is maintained by means of suction control.

Fig. 7 Results of control for periodic state (suction rate: (a) 0.7, (b) 0.35, (c) 0.2)

Fig. 8 Difficulty of control

Fig. 9 Neural network output for nosuction

On comparing the difference in the control force in Figs. 7(a), (b) and (c), we find that the time interval of control t_c becomes longer when control force is weakened. The strong flow ratio of 0.7(a) gives rise to a sharp peak in the NN output and an affect of ON-OFF control is obvious. Based on this result, we concluded that it is not always appropriate to stabilize the deviated flow for ON-OFF control by using strong suction.

Figure 8 shows the history of the control at the flow ratio of 0.1. In this case, we confirmed that suction did not have sufficient energy to keep the deviated flow at the lower wall, and we concluded that the threshold control force needed to keep the deviated flow at the lower wall was near 0.1.

Figure 9 shows the NN of output the flip-flop phenomenon when there is no control. Flow movement to the upper wall is inhibited due to the rule of control. Furthermore, with a weak suction, there is no change of the period of the flip-flop, as shown in Fig. 9, but we observed the reduction of the remaining time

Fig. 10 Optimum control relations for periodic state

at the upper wall. In Fig. 10, the relation between the flow ratio and the control time is shown. From this, we can infer the conditions for suitable control. The vertical axis denotes the flow ratio and the horizontal axis denotes control time. Comparing another diagram, the lowest energy cost for reducing the flip-flop phenomenon was at the NN threshold level of 0.1 ± 0.02 (solid circle in the figure). The suitable flow ratio is shown to be near 0.2. When the flow ratio becomes less than 0.2, the purpose of the maintaining the deviated flow can not be maintained or evaluated using this diagram.

6. Result of Control of Chaotic Motion

In this section, we describe the result of control for the case of a chaotic solution ($Re=10^4$). The teaching data for the periodic solution of $Re=10^3$ were used, and the capability of nonperiodic classification was confirmed in our second report⁽²⁾. Here, the control rule is the same as in the periodic case. The output of the chaotic solution at $Re=10^4$ is judged by the NN (Fig. 11). Figures 12(a) and (b) are for the flow ratios of 0.7 and 0.2, respectively. In both cases, deviated flow was maintained at the lower wall with NN output less than 0.4, but control was often required, in contrast to the case of $Re=10^3$. Figure 12(b) shows the case where the control time t_c was constant; we observe the upper limit of NN output near 0.3.

In the case of $Re=10^4$, the output threshold level was changed to 0.2. The associative coefficient for every layer of NN is not changed for the second-step teaching data ($Re=10^3$), so the criterion for the judging the deviated flow to the lower wall is lost. In this way, if the current NN system is adapted for an unknown region, it is necessary for control accomplishment that there is relaxation of the critical value.

Fig. 11 Neural network output for chaos state

Fig. 12 Results of control for chaos state
(suction rate: (a) 0.7, (b) 0.2)

Of course, the teaching data at $Re=10^4$ with suction are always used as the second-step teaching data for NN, so it is needless to say that the deviated flow can

Fig. 13 Result of control under weak suction
(suction rate: (a) 0.1, (b) 0.05)

be judged precisely.

If teaching data are changed case by case for Re , the decision of the control rule requires much time and the characteristic of NN is not utilized effectively. Hence, as shown in this study, controlling unknown behavior through the use of known data enables the full use of the merit of NN.

Figure 13 shows the results for the case of weak suction force with the flow ratios of (a) 0.1 and (b) 0.05. Even if a weak suction exists, the state of the deviated flow can be maintained. Thus the effect of the suction is important. We expect to achieve good control in the case of the chaotic solution.

Figure 14 shows the relations between the flow ratio and the control time. In all cases, the time required for control increases compared to the case of $Re=10^3$. The suitable condition of the control for the flip-flop phenomenon is a flow ratio of 0.2 ± 0.02 (solid circle in figure), which corresponds to the shortest mean control time.

Fig. 14 Optimum control relations for chaos state

7. Conclusion

For the self-induced oscillation phenomenon of an incompressible viscous jet emitted into a two-dimensional channel, suction is controlled by a neural network observer. The separation bubble is depressed and the periodic solution ($Re=10^3$) of the flip-flop phenomenon is controlled. The results for this part are summarized as follows.

1. Since only 3 teaching signal patterns are prepared, these are changed to other teaching signals in the case of the periodic solution with suction and the flip-flop phenomenon is controlled.
2. The rule of control is evaluated using the flow ratio and control time; the strength of suitable suction is 20% of the main flow velocity.
3. Strong suction does not always lead to good

results.

For the chaotic solution ($Re=10^4$), we obtained the same result for control at $Re=10^3$ up to the flow ratio of 15%. The results for this part are summarized as follows.

1. The control for the chaotic solution is achieved in the same manner as in the case of the periodic solution, using the learning result for the periodic solution.
2. In the case of weak suction, such as a flow ratio of less than 10%, control for maintaining stable deviated flow is difficult, but the natural chaotic solution is slightly affected.

Recently, control methods, other than suction, for the chaotic solution have been reported, and using the OGY method, we were able to stabilize the periodic solution using a weak control force of about 5 - 10%. Therefore, the selection of an appropriate control method for the desired purpose will be important in the future.

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