ANALYSIS OF DYNAMIC-CONTROLLED ROUND JET USING POD AND DMD

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Abstract Jets are the most basic flow used in industrial field and are widely used for heating, cooling, mixing. Recently, the improvement of mixing efficiency is required in order to downsize many industrial equipments and upgrade their performance. In the case of jets, their characteristic, such as the diffusion, depends on the inlet condition. Therefore, by controlling jet to give appropriate inlet conditions, the mixing efficiency can be improved. Thus far previous studies have mainly investigated excitation control associated with the instability of jets. However, in our previous study, as a new method we proposed vector control to enhance mixing or diffusion of free jets and have found its characteristics [1]. In this study, we focus on the vector control in which an inflow direction is rotating around the streamwise direction. In order to investigate the performance of the proposed method, the DNS of axisymmetric jet under the vector control are conducted and its structures are visualized; the mixing efficiency based on a mixing measure are quantified; further to make clear the reason for the mixing enhancement, the SPOD(snapshot proper orthogonal decomposition) [2] and the DMD (dynamic mode decomposition) method [3] are applied.

RESULTS

Figure 1 is schematic drawing of the flow field. The inlet velocity distribution is assumed to be top-hat type.In the present calculation, as shown Fig.2, the inflow direction rotates around y direction so that the inflow condition mimics the vector control.

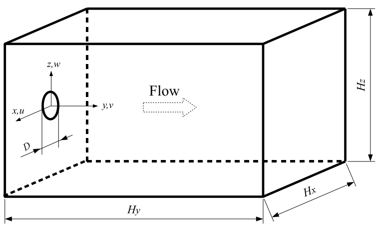


Fig. 1 Coordinate system and computational domain

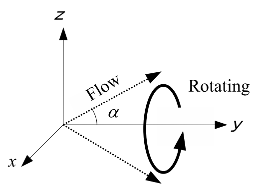


Fig. 2 Detail of inflow condition

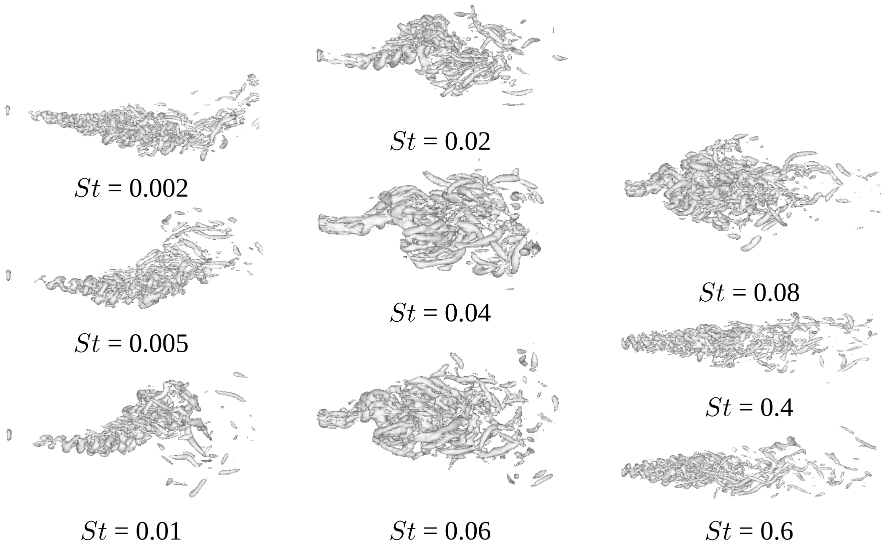


Fig. 3 Instantaneous coherent vortical structures ($Q = 0.05$)

Flow feature of controlled jets In order to examine the instantaneous vertical structures, isosurfaces of the second invariance of velocity gradient tensor Q (=0.05) are visualized in Fig.3. At St=0.002, because of a slow-speed rotation, the effect of the vector control does not appear. Therefore the vortex structure are directed toward the direction of the nozzle axis at any time. At St=0.005-0.02, the vortical structures distribute in a helical manner toward the streamwise direction. The jets readily spread downstream. At St=0.04-0.08, immediately after the injection, the vortices distribute in a helical manner, while the vortex structures downstream are entangled and uniformly distribute to a circumferential direction. At St=0.4, the diffusion of jet is suppressed and its structures are similar to the uncontrolled jet.
Mixing characteristics In order to quantify the mixing state, Everson et al.[4]investigated the statistical entropy based on the passive scalar concentration, and they demonstrated the characteristics of this measure by examining the experimental data. As well as we validate this mixing measure based on the DNS data of active controlled jet[5] In order to investigate the streamwise variation of the statistical entropy,S is summed over the plane perpendicular to the streamwise direction, and $\bar{S}$ is defined as S normalized with the inflow quantity,S_0. From Fig.4, in all cases, the vector control enhances the mixing compared with the uncontrolled free jet. The distribution of St=0.005-0.02 are similar to the St=0.0 until y/D=8. Further downstream the statistical entropy increases with the increase of the Strouhal number, and the mixing around y/D=20 becomes maximum. The reason is considered that the streamwise pitch of a helical structure becomes shorter

with increasing the Strouhal number. The distribution of St=0.04-0.06 are almost similar, namely, the statistical entropy increases rapidly from around y/D=5.0, and the mixing becomes maximum downstream. The reason is that, as mentioned before, the vertical structures at St=0.04-0.06 are entangled downstream irrespective of the rotating frequency.

Coherent structure extracted with SPOD and DMD In order to investigate the reason why the mixing is superior than that of uncontrolled jet, the Snapshot POD (SPOD)[6] method and Dynamic mode decomposition(DMD)[7] method are used. In the SPOD method, as you known, the most energetic mode is extracted. Fig.5 shows the vector plots of an eigenvectors in $y - z$ plane through the rotating axis. The 0th order mode of Fig.5 (a) means the time-averaged value. In the fig, the flow related to an entrainment, is present in the outer edge of the jet. In its downstream, the flow around the rotating axis (y-axis) is slightly slower than near the outer edge. Fig.5 (b) is the vector plots of the 1st mode. Near the center of the figure, the generation of a mode related to a large-scale mixing can be confirmed between the outer edge and the rotation axis. Fig.5 (c) shows the distribution of the 3rd mode. The larger scale motion than the small-scale vortex structures being educed by Q-value, spreads over the downstream region. On the other hand, in the DMD method, the temporally unstable mode is extracted. Fig.6(a) shows the vector plots of the eigenfunction of the dominant dynamic mode. As can been seen from Fig.5, it is similar to the 1st mode of SPOD. Thus it confirms that the DMD method extracts the same spatial mode of SPOD, and that the 1st mode is induced directly by a vector control. Fig. 6(b) shows the eigenvector of the second higher energy mode. The mode is the same as the distribution of the 3rd mode of SPOD(not shown here), and as similar to the above-mentioned result, both the DMD method and the POD method deeply correlate with each other. In addition from the frequency characteristics, we find that, in developing region of the jet, the mode having a fairly slow time scale than both the control frequency and an unstable frequency such as Column instability, may contribute to the mixing.

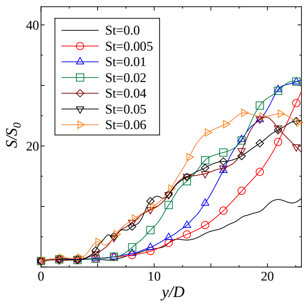
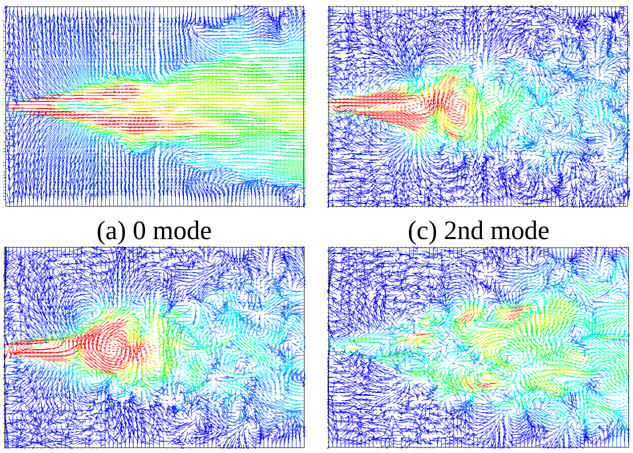


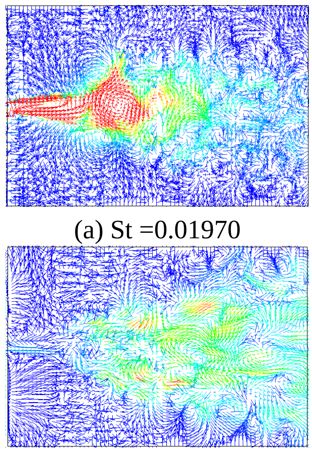
Fig. 4 Mean entropy distribution



(a) 0 mode (c) 2nd mode

(b) 1st mode (d) 3rd mode

Fig. 5 Velocity vectors captured by Snapshot POD



(a) St =0.01970

(b) St =0.0092

Fig. 6 Velocity vectors captured by DMD

Conclusions I1. From the instantaneous vortex structures, it is found that the flow pattern changes due to vector control.
2. From the mixing measures using the statistical entropy, it is found that the mixing efficiency is improved using the rotational mode control compared to the uncontrolled jet.
3. From structure analysis with Snapshot POD method, it is found that the flow involving a surrounding fluid and the structures enhancing the mixing are formed by the vector control.
4. From the results of the DMD method, it is found that the frequency of the dominant dynamic mode quite agree well with the control frequency.

References

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