A Study of Vortex Structure in the Shear Layer between Main Flow and Swirling Backflow

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The present paper describes the vortex structure and the flow field of model experiments simulating the inlet flow of turbomachines at low flow coefficients. A new experimental apparatus was devised to freely set the axial velocity of the main flow and the axial and tangential components of the swirling backflow. The vortex structure was visualized by small air bubbles. It occurs in the shear layer between the main flow and the backflow. The number and the radial location of vortices are determined mainly by the axial and tangential velocities of the backflow normalized by the axial velocity of the main flow. These characteristics agree with those of the backflow vortex structure of real turbomachines. This shows that the vortex structures are caused by the roll-up of the shear layer between the axial main flow and swirling backflow, not associated with the flow interaction with individual blade of the impeller. It was shown that a two-dimensional linear stability analysis can reasonably predict the relation between the number of vortices and their radial location.

Key Words: Backflow, Vortex, Swirling Flow, Turbomachine, Inlet

1. Introduction

It is well-known that a swirling backflow occurs at the inlet of turbomachines when the flow rate is decreased. A backflow vortex structure appears in the shear layer between the main flow and the swirling backflow. A backflow vortex cavitation occurs in the low pressure region of the vortices when the inlet pressure becomes small(1). Yamamoto(2) investigated the relation between the backflow cavitation and cavitation surge. Okamura et al.(3) studied on the erosion due to the backflow cavitation. In turbopump inducers, the backflow cavitation occurs even at the design point since they are designed with a certain angle of attack to avoid premature cavitation breakdown. It is reported that the large backflow cavitation can be one of the causes of the fatigue failure of the inducer blade encountered in the 8th H-II Rocket.

Yokota et al.(4) investigated the characteristics of backflow vortices and the relation between vortex structure and the backflow region. They reported that the backflow vortex has a spiral shape and the several vortices exist in the circumferential direction. Moreover, they carried out a two-dimensional linear stability analysis with respect to the number and the radial location of vortices, and the results agree with the experimental ones. The investigation suggested that the vortex structure is caused by the roll-up of the shear layer between the main flow and the backflow, which is not directly associated with the effects of individual blade of the impeller. The purpose of the present study is to prove this postulation by means of the model experiments. In the tests with real inducers, the axial velocity of the main flow, and the axial and tangential velocities of the backflow cannot be adjusted arbitrarily.

In the present study, a new experimental apparatus is devised, in which the axial velocity of the main flow, and the axial and tangential velocities of the backflow can be arbitrarily adjusted. The characteristics of the backflow vortex are investigated in wider ranges of the three flow...
velocities. Moreover, the number and the radial location of vortices are compared with the results of the 2D linear stability analysis by Yokota et al.\(^4\)

2. Nomenclature

\[N: \text{number of vortices [mm]}\]
\[r: \text{radial location [mm]}\]
\[r_i: \text{outer radius of inner circular pipe [mm]}\]
\[r_o: \text{inner radius of outer circular pipe [mm]}\]
\[r_v: \text{radial location of vortex filament center in section at } z=0 \text{ [mm]}\]
\[r_{vd}: \text{radial location where gradient of tangential velocity becomes maximum [mm]}\]
\[v_{me}: \text{axial velocity of main flow [m/s]}\]
\[v_{bc}: \text{axial velocity of backflow [m/s]}\]
\[v_{b\theta}: \text{tangential velocity of backflow [m/s]}\]
\[z: \text{axial location [mm], positive in main flow direction, zero at upper end of inner pipe}\]
\[\theta: \text{tangential angular [deg.]}\]

3. Experiment

3.1 Flow field

Figure 1 shows the schematics of the flow field at an inducer inlet and the backflow vortices by Yokota et al.\(^4\) The gray region indicates the swirling backflow. The backflow vortex filaments exist along the boundary between the axial main flow and the swirling backflow in the meridian section in Fig. 1 (a). The vortex filaments are twisted in the circumferential direction. Several vortices exist and rotate in the swirling direction of the backflow in Fig. 1 (b).

3.2 Experimental apparatus

Figure 2 (a) shows the newly-devised experimental
apparatus to simulate the flow at an inducer inlet in Fig. 1. The apparatus is composed of closed loop circuits of the main flow and the swirling backflow, using water as the working fluid. The main flow is introduced into the test section from the upper tank through the main circular pipe. On the other hand, the backflow is introduced into the swirl generator through flow paths 2 and 3 in Fig. 2 (a). The axial velocity of the main flow can be adjusted by controlling the flow rate in flow path 1. On the other hand, the backflow is introduced into the swirl generator through flow paths 2 and 3 in Fig. 2 (a).

Figure 2 (b) shows the swirl generator. The flows through flow paths 2 and 3 are introduced in the tangential and axial directions, respectively. Therefore, flow path 2 gives the tangential velocity to the backflow. The axial and tangential velocities of the back flow can be adjusted independently by controlling the flow rates in flow paths 2 and 3.

Figure 2 (c) shows the test section. The test section consists of concentric circular pipes. The main flow comes into the test section from the upper part in the meridian view in Fig. 2 (c). On the other hand, the swirling backflow comes into the test section from the lower part passing through the clearance between the inner and outer pipes. The main flow and the swirling backflow meet at the upper end of the inner pipe. These are simulating the flow at the impeller inlets of turbomachines. Moreover, the inner pipe was changed to vary the radial width of the swirling backflow. In the present study, three inner pipes with the outer radii of 30, 35 and 38 mm are used.

The coordinate system is as follows. The main flow direction of the inner and outer pipe axes is $z$ axis, and its origin is the upper end of the inner pipe as shown in Fig. 2 (c). The swirling direction of the backflow is defined as $\theta$, and its origin is shown in Fig. 2 (b).

### 3.3 Experimental flow conditions

We have three experimental parameters: the axial velocity of the main flow $v_{mz}$, the axial velocity of the backflow $v_{bz}$, and the tangential velocity of backflow $v_{thz}$. The axial velocity of the main flow is defined as the averaged axial flow velocity of the main flow, which is obtained by dividing the flow rate in flow path 1 in Fig. 2 (a) by the inner cross section area of the outer circular pipe. The axial velocity of the backflow is defined as the averaged axial flow velocity in the clearance between the inner and outer pipes shown in Fig. 2 (c), which is obtained by dividing the sum of the flow rates of flow paths 2 and 3 by the section area of the clearance. The tangential velocity of the backflow is defined as the tangential velocity measured at the center of the clearance between the inner and outer pipes, which is obtained by averaging the flow velocities measured at three circumferential locations by a Laser Doppler Velocimeter (LDV). The measuring points are located at $z = 5$, $r = \frac{1}{2}(r_i + r_o)$ and $\theta = 0, 90, –90^\circ$. Here, the measurement at $\theta = 180^\circ$ was not possible in the present experimental apparatus.

### 4. Results and Discussions

#### 4.1 Visualization

To investigate the flow field, the visualization was made by using air bubbles which are small enough not to affect the flow field. A high-speed video camera (NAC, HSV-500) was used to observe how the backflow vortices appear, rotate and disappear. The number, the radial location and the duration of vortices were visually measured from the records.

Figure 3 shows a snapshot of the typical flow field. The regions with many air bubbles are considered to be the centers of the vortex filaments because air bubbles gather in the low-pressure regions. Figure 3 indicates that two vortex filaments extend upward from inside of the inner pipe, and the upper ends of two vortex filaments touch the inner surface of the outer pipe. The video observations show that the vortex filaments form a pattern and rotate in the swirling direction while changing their relative locations and numbers. These results agree with the ones by Yokota et al.(4) observed with a real inducer. Therefore, the present model experiment can simulate the flow field with the swirling backflow at the inlet of turbomachines.

It should be noted that the number of vortices varies temporally in some flow conditions. One of the causes is considered the fluid dynamical instability concerning to the number of vortices. It is also possible that some vortices cannot be occasionally visualized by air bubbles and consequently the number of vortices varies. Then, the number of vortices $N$ is defined as the maximum number of vortices observed for 30 seconds in the present study.

#### 4.2 Map of number of vortices

Figure 4 shows the map of the number of vortices $N$ for the cases with $r_i = 30$ mm and $r_o = 40$ mm. The abscissa

![Fig. 3 Snapshot of backflow vortices](image-url)
and the ordinate in Fig. 4 represent the non-dimensional axial and tangential velocities of the backflow, respectively. They are defined as $v_{zc}/v_{mc}$ and $v_{bθ}/v_{mc}$. The numbers in closed and open circles represent $N$ for the cases with $v_{mc}$ of 0.166 m/s and 0.232 m/s, respectively.

Figure 4 clearly indicates that almost the same numbers of vortices are observed for the same values of the non-dimensional axial and tangential velocities of the backflow. That is, $N$ is not affected by the dimensional velocity $v_{mc}$ of 0.166 m/s and 0.232 m/s. The maximum number of $N$ is 4 which occurs with the non-dimensional axial and tangential velocities 1.0 – 2.0 and 2.0 – 2.5, respectively. Figure 4 also indicates that $N$ decreases as the non-dimensional axial and tangential velocities become far from the maximum conditions mentioned here.

4.3 Backflow region and number of vortices

In real turbomachines, it is well-known that the backflow region extends inward as the flow coefficient decreases. To simulate this behavior of the backflow region, three different circular pipes with outer radii $r_i$ of 30, 35 and 38 mm were used in the present experiments.

Figure 5 shows the map of the number of vortices for $r_i$ of 38 mm and $v_{mc}$ of 0.232 m/s. The abscissa and the ordinate in Fig. 5 are same as in Fig. 4. The numbers in open circles in Fig. 5 can be compared with those in Fig. 4 to see the effects of the radial width of the backflow region. When the non-dimensional tangential velocity of the backflow becomes larger than 2, some of them are larger in Fig. 5 for the outer radius of the inner pipe of 38 mm than in Fig. 4 for the one of 30 mm. This means that the number of vortices increases as the radial width of the backflow region decreases. This tendency agrees with the experimental results of Yokota et al.[$^4$] by using a real inducer. This also suggests that the present model experiment can simulate the flow field with the swirling backflow at the inlet of turbomachines.

The number of vortices becomes the maximum of 7 for the non-dimensional axial and tangential velocities of the backflow of about 2 and 2.5, respectively. These values of axial and tangential velocities of the backflow to make $N$ maximum are almost same in Figs. 4 and 5.

Figure 5 indicates that no vortex is observed when the non-dimensional tangential velocity of the backflow is less than 2. We consider that there do exist many vortices but they are not visualized by air bubbles since the circulation of each vortex is too small to attract air bubbles.

4.4 Location of center of vortices

The radial location of vortices $r_v$ is defined as the ensemble average of the radial locations of air bubbles at $z = 0$ and is visually determined from the high-speed video recording. For visualization, a rectangular acrylic tank filled with water surrounding the test section was used to avoid the refraction of the circular surface.

Figure 6 shows the map of the radial locations of vortices with respect to the non-dimensional axial and tangential velocities of the backflow for the case with $r_i = 35$ mm. The abscissa and the ordinate in Fig. 6 are same in Fig. 4. The radial locations of vortices are shown by the symbols as defined in Fig. 6. The data are scattered somewhat due
to the unsteadiness of the backflow vortex structure. When the non-dimensional tangential velocity of the backflow becomes less than 2, the data are not plotted because the radial locations of vortices cannot be identified.

Figure 6 indicates that the radial locations of vortices becomes the maximum of 31–28 mm for the non-dimensional axial and tangential velocities of the backflow of 1.0–2.0 and 2.0–3.0, respectively. These conditions of the non-dimensional axial and tangential velocities are almost the same as those with maximum number of vortices $N$ shown in Figs. 4 and 5. The way of decrease of $r_v$ from the maximum is similar to that of $N$ shown in Figs. 4 and 5, as the flow conditions depart from those for maximum values. These results indicate that there exists the obvious correlation that $N$ decreases as $r_v$ decreases.

4.5 Comparison of experiment and analysis

Figure 7 shows the comparison between the experimental and analytical results with respect to the number and the radial location of vortices. The analytical results are obtained from a 2D linear stability analysis of a circumferential vortex row by Yokota et al. The abscissa and the ordinate represent the number $N$ and the non-dimensional radial locations of vortices, respectively. The non-dimensional radial location of vortices is defined as $r_v$, normalized by $r_o$, the inner radius of the outer circular pipe. The solid line represents the boundary between the neutrally stable and the unstable regions. That is, the disturbance is neutrally stable and unstable in the upper and the lower regions of the boundary, respectively.

Figure 7 indicates that the experimental data are located in the vicinity of the boundary although they are scattering. It is considered that the obvious correlation that $N$ decreases as $r_v$ decreases is corresponding to the positive gradient of the boundary in Fig. 7, indicating that $N$ increases as $r_v$ increases.

4.6 Shape of vortex filaments in meridian section

Here, it should be noted that some data are plotted in the unstable region in Fig. 7. This tendency is also seen in the experimental results of Yokota et al. This tendency is considered to be caused by the 3D shape of the vortex filaments that the vortex filaments are gradually curved outward in the radial direction in the upstream direction in the meridian section, as clearly shown in Fig. 3. To show this quantitatively, the radial locations of the vortex filaments in the axial direction are measured.

Figure 8 shows the time-averaged radial and axial locations of the vortex filaments for the case with $r_i = 35$ mm. The abscissa and the ordinate represent the radial and axial locations of the vortex filaments, respectively. Each symbol shows the time-averaged shape of the vortex filaments projected to the meridian section, for each condition indicated in the figure.

Figure 8 clearly indicates that the vortex filaments are gradually curved outward in the radial direction in the upstream direction and therefore the radial locations of the vortex filaments become minimum at the section of $z = 0$. If the radial locations averaged in the axial direction in Fig. 8 are used as the radial location of vortex filaments in Fig. 7, the plotted data shift upward, and consequently it is considered that almost all the data are located in the stable region. It should be noted that $r_v$, which is defined as the radial location of vortex filament at the section of $z = 0$, can be used as the representative radial location of the vortex filaments because the experimental data reasonably agree with the analytical ones in Fig. 7.

Figure 8 also indicates the followings. The squares and circles represent the same non-dimensional axial and the different non-dimensional tangential velocities of the backflow. The circles, representing the data for the larger non-dimensional tangential velocity, are located more inward and upstream than the squares, representing the data for the smaller non-dimensional tangential velocity. On the other hand, the squares and triangles represent the different non-dimensional axial and the almost same non-dimensional tangential velocities of the back-
flow. The triangles, representing the data for the larger non-dimensional axial velocity, are located more inward and upstream than the squares, representing the data for the smaller non-dimensional axial velocity. These results mean that the vortex filaments shift more inward and upstream with an increase of the non-dimensional axial and tangential velocities of the backflow.

The relation between the flow velocity conditions and the number of vortices $N$ is considered as follows. The non-dimensional axial and tangential velocities of the backflow vary the vortex filament shape in the meridian section as shown in Fig. 8. The variation of the shape causes the variation of the radial location $r_v$. On the other hand, larger number of vortices is allowed to exist stably at outer radial location as shown in Fig. 7. According to this relation, the radial location $r_v$ determines the number of vortices $N$.

4.7 Time-averaged velocity distributions

To clarify the relation between the vortex structure and the flow field, the time-averaged velocity distributions were measured by a Laser Doppler Velocimeter (LDV) for $r_i$ of 35 mm. The measurements were carried out at a section with $\theta = 0$ because it was confirmed that the flow field is uniform in the circumferential direction.

Figure 9 shows the axial velocity distributions in the radial direction. The abscissa and the ordinate in Fig. 9 represent the radial location and the axial velocity, respectively. Figure 9 (a) and (b) show the results for the sections of $z = -5$ and $z = -15$, respectively, 5 mm and 15 mm upstream from the upper end of the inner pipe, respectively. The symbols showing the experimental conditions in Fig. 9 are same as those in Fig. 8.

Figure 9 (a) indicates the followings. The squares and circles represent the results with the same non-dimensional axial and the different non-dimensional tangential velocities of the backflow. The location where the axial velocity becomes zero shifts inward in the radial direction for the circles, representing the data for the larger non-dimensional tangential velocity. On the other hand, the squares and triangles represent the results with different non-dimensional axial and almost the same non-dimensional tangential velocities. The location where the axial velocity becomes zero shifts inward in the radial direction for the triangles, showing the case with the larger non-dimensional axial velocity. The effects of the axial velocity of the backflow are larger than those of the tangential velocity.

Figure 9 (b) indicates that the axial velocity in the upstream is affected more largely if the axial and tangential velocities of the backflow are larger.

Figure 10 shows the tangential velocity distributions in the radial direction. The abscissa and the ordinate in Fig. 10 represent the radial location and the tangential velocity, respectively. Figure 10 (a) and (b) show the results for the sections of $z = 0$ and $z = -15$, respectively. The symbols showing the experimental conditions in Fig. 10 are the same as in Figs. 8 and 9.

Figure 10 (a) indicates the followings. If we increase the axial and tangential velocities of the backflow, the maximum tangential velocity increases and the region with the tangential velocity extends inward, at the section of $z = 0$. These tendencies in Fig. 10 (a) are similar to those in Fig. 9 (a).

Figure 10 (b) indicates that region with tangential velocity extends more upstream if we increase the non-dimensional axial and tangential velocities of the backflow.

As mentioned above, the increase of the axial and tangential velocities of the backflow causes both the axial and radial enlargements of the region with the tangential velocity. This tendency of the averaged velocity distribution shown in Figs. 9 and 10 corresponds to the change in vortex filament shape shown in Fig. 8.

4.8 Correlation between radial location and maximum gradient of tangential velocity

To clarify the correlation between the shapes of the
vortex filaments and the averaged velocity distribution, the radial location \( r_{v\theta} \), where the gradient of the tangential velocity becomes maximum, are correlated with the radial location of vortices \( r_v \).

Figure 11 shows the correlation for the cases with \( r_i = 30, 35 \) and 38 mm. The abscissa and the ordinate are \( r_{v\theta} \) and \( r_v \), respectively. The solid line represents the relation of \( r_v = r_{v\theta} \). Figure 11 indicates that all data are plotted near the relation of \( r_v = r_{v\theta} \). That is, the center of vortex filament exists at the location where the gradient of the averaged tangential velocity becomes maximum.

### 4.9 Vortex structure and flow field

The relation between the vortex structure and the flow field is summarized as follows. When the axial velocity of the main flow decreases, or the axial and tangential velocities of the backflow increase, the non-dimensional axial and tangential velocities of the backflow increase. Due to these increases, the region with the backflow and the swirl extends inward as shown in Figs. 8, 9 and 10. With the extension, the radial location, where the gradient of the tangential velocity becomes maximum, moves inward, i.e. \( r_{v\theta} \) decreases. According to this shift, \( r_v \) decreases because \( r_v \) and \( r_{v\theta} \) have the relation of \( r_v = r_{v\theta} \) as shown in Fig. 11. Due to this decrease, the number of vortices \( N \) decreases because smaller number of vortices can exist stably as shown in Fig. 7. On the other hand, when the non-dimensional axial and tangential velocities of the backflow decrease, the number of vortices increases based on the opposite considerations. However, the circulation of one vortex decreases with an increase of \( N \). Accordingly, the number of vortices visualized with bubbles has a maximum with respect to the non-dimensional axial and tangential velocities of the backflow as shown in Figs. 4 and 5.

### 5. Concluding Remarks

By observing the backflow vortex in the model experiment, the following conclusions are obtained.

1. The characteristics of the backflow vortex observed in the present model experiments agree well with those of a real inducer. Therefore, it can be concluded that the backflow vortex occurs as a result of the roll-up of the shear layer between the main axial flow and the swirling backflow, which is not directly affected by the impeller blades.

2. There exist a condition of the non-dimensional axial and tangential velocities of the backflow at which the observed number of vortices becomes maximum.

3. The number of vortices increases when the radial location of vortices gets closer to the pipe wall.

4. A 2D stability analysis can reasonably explain the experimental relation between the number and the radial location of vortices.

5. When the non-dimensional axial and tangential velocities of the backflow increase, the location of vortex filaments shift inward in the radial direction and upstream in the axial direction.

6. When the non-dimensional axial and tangential velocities of the backflow increase, the region with the
backflow and the swirl extends inward in the radial direction and upstream in the axial direction.

(7) The radial location of vortices agrees with the radial location of the maximum gradient of the averaged tangential velocity.

References


