A Study of Swirling Backflow and Vortex Structure at the Inlet of an Inducer*

Kazuhiko YOKOTA**, Kazuhiro KURAHARA***,
Dai KATAOKA***, Yoshinobu TSUJIMOTO**
and Allan J. ACOSTA****

This paper describes a vortex structure at the inlet of an inducer which appears on the boundary of backflow region. The vortex structure was visualized by the cavitation voids found by operating at cavitation number of $\sigma=0.050$ and recorded by a high speed video. It was measured quantitatively by two laser displacement sensors. The passing frequency and the shape of vortex filaments were determined from the outputs of the laser displacement sensors which respond to the passage of the vortex cavitation. The results show that the number of vortex filaments, their propagation angular velocity and radial location depend on the steady velocity profile at the inlet.

Key Words: Inducer, Vortex, Cavitation, Swirling Flow, Shear Flow, Backflow

1. Introduction

It is well-known that backflow just upstream of an impeller occurs at low flow rates. This backflow region can extend upstream of an impeller even ten times further than the inlet diameter. It is reported that this inlet backflow is caused by the steep axial pressure gradient and the axial momentum defect near the casing wall⁽¹⁾ and is affected by the tip clearance flow⁽²⁾. It has the effect to suppress the blade stall and hence the positive slope of the characteristic line because the blockage effect of the backflow region increases the axial velocity of the main flow⁽³⁾. On the other hand, it is known that a vortex structure appears associated with the backflow. Brennen⁽⁴⁾ discussed the vortices in the inlet backflow region and termed this backflow vortex. Yamamoto⁽⁵⁾ investigated the backflow vortex cavitation with its relation to cavitation surge at lower flow rate. Okamura⁽⁶⁾ ad-

ressed the strong erosion due to the backflow vortex cavitation. Although many researchers describe the existence of the inlet backflow vortices, their structures and characteristics have not yet been investigated in detail. In the present study, we try to clarify the structure and the characteristics of these inlet backflow vortices by means of experiments under cavitating and the non-cavitating conditions.

2. Nomenclature

D : diameter of inducer [m]

n : rotational speed of inducer [rpm]

N : number of vortices

p_1, p_2 : inlet and outlet static pressure [Pa]

p_v : vapor pressure [Pa]

r : radial coordinate [m]

U_t : tip speed ($=\pi Dn/60$) [m/s]

V : flow velocity [m/s]

z : axial coordinate [m]

ρ : water density [kg/m³]

ϕ : flow coefficient = mean axial velocity at inducer inlet/ U_t

ψ : static pressure coefficient $=(p_2-p_1)/(\rho U_t^2/2)$

σ : cavitation number $=(p_1-p_v)/(\rho U_t^2/2)$

Superscripts and Subscripts

r : radial direction

z : axial direction

θ : circumferential direction

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** Graduate School of Engineering Science, Osaka University, 1-3 Machikaneyama, Toyonaka 560-8531, Japan. E-mail: yokota@me.es.osaka-u.ac.jp

*** Kawasaki Heavy Industries, LTD., 2-1-18 Wadayama-dori, Hyogo-ku, Kobe 652-0884, Japan

**** California Institute of Technology, Pasadena, California 91125, USA

Fig. 1 Rig section

Fig. 2 ϕ - ψ curve (Uncertainty in $\phi = \pm 0.005$ and in $\psi = \pm 0.02$)

3. Experimental Apparatus

A closed loop facility with a loop pressure control tank is used. The loop pressure can be adjusted by using a vacuum pump connected to the tank. The inlet pipe between an inducer and the tank has an inner diameter of 150 mm and a length of 2 000 mm. The details of the facility are reported in Ref. (7).

The test impeller, shown in Fig. 1, is an inducer for the liquid oxygen turbopump of the LE-7 main engine of H-II rocket. It has three blades with leading edge sweep, outer diameter of 149.8 mm, tip clearance of 0.5 mm, and the inlet and the outlet blade angles of 7.5 degs. and 9.0 degs., respectively. The solidity is 1.90 at the tip and the blade angle β at the inner radius r is designed following $r \cdot \tan \beta = \text{const.}$ The shockless flow coefficient is 0.132. The casing is made of transparent acrylic resin so that the visual observations and the measurements with laser sensors can be made. The inducer is followed by a volute. No significant effect of the volute on the inlet flow could be seen throughout the present study. Axial locations of laser measurements are indicated by TL, those of steady velocity traverse and pressure measurements by TT and TP.

Figure 2 shows the non-cavitating performance

Fig. 3 Suction Performance and a map showing the occurrence region of various oscillating cavitation types (Uncertainty in $\phi = \pm 0.005$, in $\psi = \pm 0.02$, $\sigma = \pm 0.002$)

of the inducer. The design flow coefficient is $\phi = 0.077$. The suction performance is shown in Fig. 3, with the regions of various oscillating cavitation⁽⁷⁾. The figure includes the region of cavitation in backflow vortices determined from inlet pressure fluctuation. Visual observations in the present study showed that backflow vortices occur in much wider region, including the region of rotating cavitation onset and the non-cavitating region.

4. Results and Discussions

4.1 Outline of the phenomenon

Figure 4 shows a photograph of the backflow vortex filaments at the inlet of the inducer taken by a high-speed video (Kodak HS-4540, 4500 frames/sec-ond). The main flow is from left to right in the figure. The inlet backflow vortices (or vortex filaments) can be seen from the cavitation present. It can be seen that at least seven inlet backflow cavitating vortex filaments extend from the impeller upstream, i.e., in the left direction. All these vortex filaments rotate in the same direction as the impeller approximately keeping their relative positions. The rotational speed is 0.1-0.2 times of the impeller rotational speed. The upstream ends of these vortex cavities appear to attach to the casing and the other ends to the blade. The vortex filaments are found to be twisted in the circumferential direction.

Figure 5 shows a schematic sketch of the backflow and the vortex structures based on such photographs and additional quantitative measurements described in the following sections.

Fig. 4 Photograph of backflow vortex filaments at inducer inlet ($\phi=0.078$, $\sigma=0.050$, $n=3\,000$ rpm)

Fig. 5 Schematic sketch of backflow vortex filaments

4.2 Geometry of the vortex filament

Since the backflow vortex cavitation can be detected from the inlet pressure fluctuation only when the cavities are extremely large (region i in Fig. 3) or when the vortex sweeps the pressure transducer, it was decided to use a laser displacement sensor (Keyence LB-6) which detects the distance between the sensor and the light reflecting target, the vortex cavitation for the present case, for the quantitative measurements.

Figure 6 shows an example of temporal output from the laser sensor. The voltage is proportional to the distance from the sensor to the target. The dips in the signal indicate the passage of the cavitating vortex filaments across the laser sensor beam. The radial

Fig. 6 Example of laser sensor temporal outputs ($\phi=0.075$, $\sigma=0.050$, $z/D=0.18$)

Fig. 7 Histograms of radial location and reciprocal of dip interval from laser sensor outputs ($\phi=0.075$, $\sigma=0.050$, $n=3\,000$ rpm, $z/D=0.18$. Uncertainty in $1/\Delta T = \pm 0.1$ Hz)

location of the vortex filament is calculated by multiplying the depth of the dip by a proportionality constant readily obtained. The vortex passing frequency is determined from the number of the dips found in six seconds.

Figure 7 shows histograms of the radial location determined from the depth of the dips and the reciprocal of the time interval ΔT of the dips. Both the radial location and the frequency distribute over wide ranges, showing that the phenomenon is rather irregular. This way explains why we could not determine the frequency from a simple FFT analyses of wall pressure fluctuation or the laser sensor output. Therefore, the radial location and the vortex passing frequency are estimated directly from the raw temporal outputs as shown in Fig. 6.

Figure 8 shows the graph of the radial locations of the vortex filaments versus the axial locations measured from inducer blade leading edge at the hub. That is, the figure shows the profiles of the vortex filaments projected to the meridional plane. The symbols $\bullet$ and $\times$ indicate the center of each vortex and their arithmetic average, respectively. As

Fig. 8 Profile of vortex filaments projected to meridional plane ($\sigma=0.050$. Uncertainty in $r/D=\pm 0.01$)

mentioned for Fig. 7, the scatter of the individual data points is not caused by measurement errors but indicates the unsteady nature of the phenomena. No dips were found in the laser sensor output at the measuring locations where there is no data points. Therefore, the attaching point of the vortex filament on the casing is somewhere between the most upstream measuring point with data and the next one. Comparing the four figures, it is found that the vortex filaments extend upstream and the radial locations of the vortex filaments near the impeller shift inward with a decrease of flow coefficient.

Figure 9 shows a graph of the axial lengths of the vortex filaments (measured from inducer blade leading edge at the hub) versus flow coefficient estimated from various experimental methods at $\sigma=0.050$. For "Laser sensor", simply the most upstream measuring point with data in Fig. 7 is plotted. This is because the video observation shows that the vortex cavities appear to attach to the casing wall nearly perpendicularly to it. The figure also includes the plots of the axial extent of the backflow regions estimated from tuft movement and velocity traverses under non-cavitating condition. The figure indicates no

Fig. 9 Axial length of vortex filament compared with axial extent of backflow region (Uncertainty in $z/D=\pm 0.05$ for high speed video, ± 0.2 for laser sensor, ± 0.1 for pressure transducer, ± 0.05 for tuft movement)

significant difference between the results for the several methods of observation. We should also note that the axial length of the vortex filament approximately corresponds to the axial extent of the backflow region.

To confirm that cavitation does not affect the structure and the characteristics of the vortex filaments, we compared the results under cavitating and the non-cavitating conditions. Under non-cavitating condition, the vortices were made visible by air bubbles. It was found that the vortex structure depends only on flow coefficient and is not affected significantly by the existence of cavitation. The subsequent experiments were performed under cavitating condition to facilitate visualization.

Figure 10 shows a graph of the radial location of the vortex filaments at $z/D=0.18$ versus flow coefficient. To compare with these data, the steady velocity measurements were made by using a Pitot tube (cylindrical, three hole type with probe diameter of 6 mm, hole diameter of 0.5 mm) and the results are shown in Fig. 11. The radii where the steady circumferential velocity becomes half of the maximum one are indicated by $\square$ in Fig. 10 to show the approximate radial location of the shear layer. Figure 11 shows that the values of r/D with $V_z=0$ are larger than the values of r/D where V_θ becomes half of the maximum value. We may at least judge that the vortex filaments are located in the vicinity of the shear layer

Fig. 10 Radial location of vortex filaments from laser sensor, compared with shear layer location estimated from steady velocity distributions ($z/D=0.18$. Uncertainty in $r/D=\pm 0.01$)

(a) Axial flow velocity

(b) Circumferential flow velocity

Fig. 11 Steady velocity distribution ($\bar{V}_z$ =mean axial velocity. $\sigma=0.855$, $n=2000$ rpm, $z/D=0.18$. Uncertainty in normalized velocity= ± 0.1)

of the steady flow.

The circumferentially propagation angular velocity of the vortex filament is determined as follows. Two laser sensors are placed at circumferentially different locations. Figure 12 shows an example of the

Fig. 12 Output signals from laser sensor ($\phi=0.075$, $\sigma=0.050$, $z/D=0.18$, $\Delta\theta=30$ degs.)

Fig. 13 Comparison between normalized propagation velocity and maximum circumferential velocity ($n=3000$ rpm, $z/D=0.18$. Uncertainty in normalized velocity= ± 0.02)

temporal outputs from the two laser sensors. The upper signal is from the sensor located at $\Delta\theta$ from another sensor in the direction of the impeller rotation. The passage of the vortex filaments is shown by the dips in the signal. The time difference ΔT between corresponding dips in the two laser sensor outputs is determined as shown in Fig. 12. It was not difficult to identify the corresponding dips from the waveforms of the output signal. The propagation angular velocity is obtained by $\Delta\theta/\Delta T$.

Figure 13 shows the comparison between the propagation angular velocity normalized by the impeller angular speed and the maximum steady circumferential flow velocity at $z/D=0.18$, which occurs near the pipe wall, normalized by the tip speed. The propagation angular velocity which varies from

Fig. 14 Profile of vortex filaments projected to axial-circumferential surface compared with vorticity vectors from steady velocity distributions ($\phi = 0.060$, $\sigma = 0.050$, $n = 3\,000$ rpm. Uncertainty in $z/D = 0.02$ and in circumferential location $= \pm 5$ deg.)

0.1 to 0.15 with decreasing flow is found to be about half of the maximum circumferential velocity ranging from 0.2 to 0.3. Therefore, the increase of the propagation angular velocity at lower flow coefficient can be explained by the increase of the steady circumferential velocity in the backflow region.

Figure 14 shows a profile of the vortex filament projected to the cylindrical, i.e. z - θ , surface. The profile is obtained as follows. Two laser sensors are placed at the axially different locations. One reference sensor is located at $z/D = 1$. The time difference ΔT between corresponding two dips in the two laser sensor outputs is determined in the same manner as mentioned with Fig. 12. The propagation angular velocity is assumed to be the mean values of the data in Fig. 13. The circumferential location of the vortex filament is estimated as the product of the time difference ΔT and the propagation angular velocity. Figure 14 shows that the vortex filaments are twisted in the circumferential direction such that they proceed near the impeller. Two arrows in Fig. 14 show the direction of the vorticity vectors of the steady flow estimated at the average radial location of the vortex filaments. The arrows are almost aligned with the direction of the vortex filament profile.

The above observations suggest that the vortex filaments occur as a result of the roll-up of the shear layer between the axial main flow and the swirling backflow.

4.3 Number of the vortex filaments

Figure 15 shows the number of the vortex filaments estimated by dividing the vortex passing frequency shown in Fig. 22 with the propagation angular velocity shown in Fig. 13. The results of visual observation using a high speed video are also plotted. Note that the number of the vortex filaments can

Fig. 15 Number of vortex filaments estimated from vortex passing frequency/propagation rotational frequency ($\sigma = 0.050$, $n = 3\,000$ rpm, $u/D = 0.18$. Uncertainty in number $= \pm 2$)

increase as many as 12, which is much larger than the inducer blade number of 3. The figure indicates that the number of the vortex filaments decreases with a decrease of the flow coefficient. It is reported in Ref. (8) introduced by a reviewer that the number of vortex filaments is the same as the number of blades.

To examine the factor determining the number of the vortex filaments, a two-dimensional stability analysis similar to that for Kármán vortex street⁽⁹⁾ was performed. The vortex filaments in a circular pipe are modeled as the two dimensional vortices in a circular wall neglecting the circumferential twisting of the vortex filaments as shown in Fig. 14. Figure 16 shows the model for the stability analysis. The location of the k -th vortex is given by

$$P_k = p_k + \delta p_k \quad (|\delta p_k| \ll |p_k| < 1). \quad (1)$$

The first and the second terms indicate the mean vortex location and the disturbance on it, respectively. We assume that the vortices move with the local velocity induced by the vortex system, i.e.

$$\frac{d\bar{P}_k}{dt} = u - iv. \quad (2)$$

Here, the over bar indicates a conjugate complex number. Using Milne-Thomson's circle theorem, we can obtain the equation of vortex motion to satisfy the boundary condition on the circular wall. By ignoring the higher order terms of δp , we can obtain the equation of motion of the l -th vortex disturbance component,

$$\frac{d\bar{\delta p}_l}{dt} = \frac{1}{i} \left[- \sum_{\substack{k=0 \\ k \neq l}}^{N-1} \frac{\delta p_k - \delta p_k}{(p_l - p_k)^2} + \sum_{k=0}^{N-1} \frac{\bar{\delta p}_k + \bar{P}_k^2 \delta p_l}{(p_l \bar{P}_k - 1)^2} \right]. \quad (3)$$

Here N means the number of vortices. We assume the

Fig. 16 2D vortex model for stability analysis

expressions of the mean vortex locations and the disturbances as

$$p_k = r \cdot \exp \left[i \frac{2\pi k}{N} \right],$$

$$\delta p_k = \delta p_0 \cdot \exp \left[i \frac{2\pi M k}{N} \right] \quad (0 \leq M < N). \quad (4)$$

Here M means the circumferential wave number of the disturbances. Substituting Eq. (4) into Eq. (3), we obtain the disturbance equation,

$$\frac{d \delta r}{dt} = \frac{1}{i} [(A+B) \delta r + C \delta \bar{r}]$$

$$\left(\delta r = \delta p_0 \cdot \exp \left[i \frac{2\pi(M-1)}{N} l \right] \right). \quad (5)$$

Here the A , B and C is real functions of r , N and M . From Eq. (5), we obtain

$$\frac{d^2 \delta r}{dt^2} = [(A+B)^2 - C^2] \delta r. \quad (6)$$

Now, we can judge the vortex stability from Eq. (6). That is, the system becomes unstable for $(A+B)^2 - C^2 \geq 0$, and neutrally stable for $(A+B)^2 - C^2 < 0$. Therefore, $(A+B)^2 - C^2$ is named a stability parameter in the present study.

Figure 17 shows the stability parameter obtained for $N=4$. In this case, the circumferential wave number M of the disturbance is changed from 0 to 3. When the stability parameter is positive, the magnitudes of the displacements of the vortices grow larger exponentially. On the contrary, when the stability parameter is negative, the vortices keep the oscillation around the mean location with constant amplitude. Therefore the vortex structure is neutrally stable in the region with negative stability parameter. In Fig. 17, the parameter becomes negative for all

Fig. 17 Stability parameter for $N=4$

Fig. 18 Stability map for 2D vortices in a circular wall

wave numbers for the mean radius larger than 0.345. This radius is named "stability limit radius" for the case with $N=4$.

Figure 18 shows the stability limit radii versus N . The figure indicates that there exists a maximum number of the vortices for each given radial location of the vortices, for the vortex structure to be neutrally stable. The maximum number of the vortices decreases with a decrease of the radius of the location of the vortices. Here it should be noted that the present analysis gives only a necessary condition, and only the maximum number of neutrally stable vortices is obtained for each radial location of the vortices. This is different from the case of Kármán vortex street, in which the arrangement of the vortices is uniquely determined from the stability analysis. The figure also shows the range of the number and the

Fig. 19 Temporal outputs from pressure transducer on casing ($\phi=0.075$, $n=3\,000$ rpm, $z/D=0.18$. Uncertainty in time = ± 0.4 msec and in pressure = ± 1 kPa)

radial locations of the vortex filaments observed in the experiment. We find that the experimentally observed numbers of the vortex filaments are close to the maximum neutrally stable vortex number although they are all in "unstable region". The tendency of the decrease of the vortex number with a decrease of the radius of the vortex location is well simulated by the model. However, it is not known why the maximum number is realized in the experiment. The decrease of the vortex number with a decrease of flow coefficient as shown in Fig. 15 can be partly explained by the inward shift of the shear layer (i.e. the vortex radial location) due to the inward extension of the backflow region and the results of the stability analysis.

4.4 Pressure fluctuation due to the backflow vortex filaments

Figure 19 shows the waveforms of the outputs of the pressure transducer (Kyowa PGM-5KC, strain gauge type, flush mounted, phase delay of amplifier 30 degs./200 Hz) on the inlet pipe wall at $z/D=0.18$ and $\phi=0.075$. The upstream end of the vortex filament sweeps the transducer at this flow coefficient. The large pressure dips in the waveforms indicated by $\downarrow$ in Fig. 19 for large cavitation number can be found only under the situation when the vortex filament may sweep the pressure transducer and is considered to indicate the passage of the vortex core. Here the inception cavitation number is $\sigma=0.100$. When the minimum temporal pressure becomes close to the vapor pressure at smaller cavitation number, steep pressure rises appear in the temporal pressure fluctuation as indicated by $\uparrow$ in Fig. 19.

It was found that there are four types of pressure waveforms which appear as the passage of the cavitating vortex filaments as shown in Fig. 20. The

Fig. 20 Four typical waveforms of pressure fluctuation on casing ($\phi=0.075$, $\sigma=0.050$, $n=3\,000$ rpm, $z/D=0.18$)

Fig. 21 Pressure pulse frequency ($z/D=0.18$. Uncertainty in frequency = ± 2 Hz)

dips below the vapor pressure may be caused by the overshoot of the pressure transducer. Under cavitating condition of $\phi=0.075$, $\sigma=0.050$ and $z/D=0.18$, the percentages of the types in Figs. 20(a) and (b) sum into 3.5%. Those in Figs. 20(c) and (d) are 11% and 85.5%, respectively. Since three types with a steep rise as indicated in Figs. 20(a), (b) and (d) appear only under cavitating condition, the steep pressure rise is considered to be produced by the collapse of cavitation. But the mechanism of the collapse producing these pressure rises is not clarified in detail at the present time.

Figure 21 shows the total frequency of such pressure fluctuations under cavitating and non-cavitating conditions. The frequency under cavitating condition ($\sigma=0.050$) involves all the types in Fig. 20, and agrees with the frequency of dips under non-cavitating condition ($\sigma=0.200, 0.380$). Hence, all the waveforms in Fig. 20 are considered to be caused by the passage of the vortex filaments. This result also suggests that the backflow vortex is not significantly affected by the cavitation.

Fig. 22 Comparison between vortex passing frequency and pressure pulse frequency ($\sigma=0.050$, $z/D=0.18$. Uncertainty in frequency = ± 2 Hz)

Figure 22 shows the comparison between the vortex passing frequency obtained by using the laser sensor at $z/D=0.18$ and the pressure pulse frequency obtained by using the pressure transducer at $z/D=0.18$. This frequency data from the laser sensor have been used to determine the number of vortex filaments shown in Fig. 15. The pressure pulse frequency is only about 30% of the vortex passing frequency for $\phi \geq 0.075$. This difference may be attributed to the fact that all of the upstream ends of the vortex filaments does not necessarily sweep the pressure transducer on the casing.

5. Concluding Remarks

By observing the backflow vortex filaments at an inducer inlet under cavitating and non-cavitating conditions, the following conclusions are obtained.

(1) The schematic sketch of the backflow vortex filaments is obtained from the observation using a high speed video and the quantitative measurements using laser displacement sensors. The experimental data suggests that the vortex structure occurs as a results of roll-up of the shear layer between the axial main forward flow and the swirling backflow.

(2) The backflow vortex filaments exist in the vicinity of the shear layer between the main flow and the backflow.

(3) The backflow vortex filaments are twisted: they are almost in the same direction as the vorticity vector in the shear layer.

(4) The propagation angular velocity of the backflow vortex filaments is approximately half of the maximum steady flow angular velocity of backflow. It increases with a decrease of flow coefficient.

(5) As the flow coefficient is decreased, the radial

location of the vortex filaments moves inward corresponding to the extension of the backflow region. In the same time, the number of the vortex filaments decreases.

(6) A 2-D stability analysis of the vortices in a circular wall has been made. It was found that there exists a maximum number of neutrally stable vortices for each radial location of the vortices. This maximum number decreases with a decrease of the radius at which the vortices exist. This result explains the decrease of the number of vortices with a decrease of flow coefficient.

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