Three dimensional numerical analysis of inducer about suppression of cavitation instabilities by asymmetric slits on blades

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Abstract. Cavitation is the phenomenon in which liquid evaporates and vapor bubbles occur in the low pressure region such as a pressure of liquid is roughly less than saturated vapor pressure. The cavitation causes a bad influence such as vibration, noise, and a decline in performance on the turbomachineries. Moreover, the unsteady cavitation brings the oscillations in the turbomachinery which is called cavitation instabilities. In our laboratory, the suppression technique of the cavitation instabilities by using asymmetric slits on each blade has been investigated as a simple method. From the numerical results, it was confirmed that the cavitation instabilities are completely suppressed by a certain arrangement of asymmetric slits. In this study, the three-dimensional numerical analysis of the inducer was conducted. Two inducers which have asymmetric slits were used for this calculation. Moreover, to consider the asymmetric slit for effectiveness of cavitation instabilities, transient analysis are conducted. Although arranging the asymmetric slit cannot completely suppress the phenomenon, the cavity volume becomes smaller than without slit in all blades. This indicates that arranging asymmetric slits has the possibility to weaken the amplitude of cavitation instabilities.

1. Introduction
Cavitation is the phenomenon in which liquid evaporates and vapor bubbles occur in the low pressure region such as a pressure of liquid is roughly less than saturated vapor pressure. Usually, this phenomenon is observed in the high-speed turbomachinery, for example, pumps and hydroturbine. The cavitation causes a bad influence such as vibration, noise, a decline in performance on these turbomachineries. The cavitation instabilities are generally classified into two types. One is cavitation surge [1] and the other is rotating cavitation [2]. The cavitation surge is the phenomenon that cavity volume changes at same period in same phase in all blades, and the system instability which yields flow rate and pressure fluctuations in the working fluid. The rotating cavitation is the phenomenon that cavity volume changes periodically with phase difference and seems to propagation from blade to blade, and the local instability which causes asynchronous axial vibration in turbomachinery. As the example of accident caused by the phenomenon, launch failure in the Japanese liquid propellant rocket happened due to the rotating cavitation in 1999. Therefore, it is important to find the suppression and control technique of these instabilities for designing of the highly performance and reliable turbomachinery. For the above reasons, the techniques which aim to suppress the cavitation instabilities have been developed by some researchers such as POGO
suppressor [3], Casing treatment [4], J-Groove treatment [5], and obstacle plate [6]. However, the existing suppression techniques is not simple because additional parts or complicated processing of casing inside is needed. In our laboratory, the suppression technique of the cavitation instabilities by using asymmetric slits on each blade has been investigated as a simple method to suppress cavitation instabilities [7] [8]. In the primary investigation, numerical simulation of cascade was conducted in which the three-blade flat-plate cyclic-cascade with asymmetric and symmetric slits in each blade was analyzed and compared with the cascade without slit. From the result of cavity volume around each hydrofoil and slit mass flow rate, oscillation frequency of cavitation in each foil are influenced to arrange asymmetric slit. Furthermore it was confirmed that the occurrence of cavitation surge and rotating cavitation are suppressed by a certain arrangement of asymmetric slits in which one or two slits are arranged upstream of the throat and the others are arranged around the throat. Also, experiment with a slit on single hydrofoil which have tip clearance was conducted. [9] As a result, it was confirmed that the slit is effective for controlling the three-dimensional oscillation characteristics with leakage vortex cavitation.

In this study, for the purpose of adaptation of asymmetric slit for actual inducer, the three-dimensional numerical analysis of inducer with and without slits are conducted. Specifically, unsteady analysis under the condition where the cavitation instability occurs is conducted in inducer with and without of slits respectively, and behaviors of cavitation is compared. In addition, we validate the pump performance of the inducer without slit, with the experimental data, and the influence of the slit on the pump performance is investigated. Then, the effectiveness of the suppression technique by an asymmetric slits on the inducer is examined.

2. Numerical Methods
2.1. Numerical Scheme
For numerical analysis, a commercial software, ANSYS CFX 17.2 is used. As the governing equation, three-dimensional incompressibility gas-liquid two phases Navier-Stokes equation is used. As the cavitation model, the simplified model implemented in CFX 17.2 is used. SST $k - \omega$ is used for turbulent model.

2.2. Modeling of a Three-Bladed Inducer
A schematic diagram of the inducer used in this analysis is shown in Figure1. This inducer was made on the basis of an inducer for a typical liquid oxygen turbopump. The design specifications of the pump are shown in Table1.

The shape of the slit of the inducer used in the three-dimensional numerical analysis of this study was determined from the numerical analysis of the three-blade cyclic cascades performed in the previous study [7]. Figure2 shows a schematic diagram of the inducer having an asymmetric slit in this study. Figure2(a) is called Inducer035, Figure2(b) is called Inducer335, respectively. Each number in the name indicates the position of the slit, respectively. The area, which is from the swept leading edge position of the blade tip to the position where the blade tip and the leading edge of the adjacent blade overlap, is divided into five equal parts. The number in the name indicates what division is the slit locating on. Also, 0 in Inducer035 indicates that there is no slit in the blade. The slit width is 5mm and the slit depth is 30mm.
Figure 1. Schematic view of the inducer without slit.

| Table 1. Design characteristics of test inducer. |
|-----------------------------------------------|
| Inlet tip diameter | 152mm | Inlet hub ratio | 0.3 |
| Outlet tip diameter | 152mm | Outlet hub ratio | 0.5 |
| Tip solidity | 2.7 | Leading-edge sweep | sweptback |

Figure 2. Three-dimensional inducer with asymmetric slit.

2.3. Calculating Area and Object

The computational mesh is unstructured mesh, using tetrahedron in all regions. The schematic view of whole computational region is shown in Figure3, and the enlarged view of mesh near the inducer blades is shown in Figure4, respectively. The flow path of this calculation is a straight pipe, and each boundary condition is set to 800mm on the upstream side of the inducer and 1,000mm on the downstream side, respectively. In this calculation, the inducer is fixed and the whole area is calculated in the system of rotating axis around the x axis. At this time, calculations are performed with the inlet boundary condition
being constant at total pressure and the outlet boundary condition being constant flow rate. The number of elements for each inducer is 4.29 million for inducer without slits, 7.13 million for Inducer035, and 6.55 million for Inducer335.

\[ k_2 = \frac{p_{in} - p_v}{\frac{1}{2} \rho u_t^2} \]  

Figure 3. Schematic view of whole computational region.

Figure 4. Schematic view of the inducer.

As the calculation condition, the flow rate \( Q_{[kg/s]} \) is set as the design flow rate \( Q_{d[kg/s]} \), and the rotation speed of the inducer is set to 6,000rpm. Working fluid is a water-vapor mixture, and the reference temperature of the fluid is set at 298.15K.

The cavitation number \( k_2 \), which is a parameter representing the possibility of cavitation, is defined as follows using the rotating speed at the inducer tip \( u_t \) and the time averaged inlet boundary pressure \( p_{in}[Pa] \).

\[ k_2 = \frac{p_{in} - p_v}{\frac{1}{2} \rho u_t^2} \]  

Where, \( \rho \) and \( p_v \) are density of the water and saturated vapor pressure.

In this calculation, the condition for unsteady calculation is the condition of \( k_2 \approx 0.36 \), which is the value obtained when the super synchronous rotating cavitation occurred on the inducer without slit in calculation.
Also, using inlet and outlet total pressure, which is obtained at 656.88mm upstream of inducer and 113.12mm downstream of inducer, the head coefficient $\psi$ is estimated by equation (2.2).

$$\psi = \left( \frac{(p + 1/2\rho u_n^2)_{out} - (p + 1/2\rho u_n^2)_{in}}{\rho g} \right) \left( \frac{u_n^2}{g} \right).$$  (2.2)

Where, $u_n$ is normal velocity of inlet flow.

3. Results

3.1. Influence of slit on pump performance

In this section, we evaluate the relationship between the flow rate and the pump head and relationship between cavitation number and pump head suction performance by steady numerical analysis. We will consider how is the influence on these performance by the slit. The $\psi$ - $Q$ curves of the inducer without slit and Inducer035, 335 obtained from the steady numerical analysis in the noncavitation state is compared with the experimental results of the same inducer without slit at the Kakuda Space Center of JAXA. Figure 5 shows the result of the head coefficient $\psi$ for each flow rate ratio by changing the flow ratio $Q/Q_d$ by 10% from 0.8 to 1.2. First of all, when compared with the experimental result, the head coefficient obtained from the numerical analysis of inducer without slit is overestimated in the low flow rate condition. It is considered to be difficult to reproduce the experiment under the low flow rate condition because the numerical results which is obtained in Yonezawa et al. [10] and calculated with same software shows the same tendency. In addition, we compare how the performance of the inducer differs depending on whether there is a slit or not. However, there is no significant difference in performance depending on whether there is a slit or not in noncavitation condition. The reason for this result is considered to be that slit mass flow rate is low in noncavitation condition. From this result, it can be said that slit does not much affect pump performance in noncavitation condition.

![Figure 5](image_url)

**Figure 5.** Relationship between flow rate and pump head in noncavitation condition.

Next, comparison of suction performance with presence or absence of slit is shown in Figure 6 together with experimental result of inducer without slit. We reduced the upstream pressure under the condition of the flow rate ratio $Q/Q_d = 1.0$ and calculated the breakdown of the head coefficient $\psi$ for each cavitation number $k_2$. As a result of Figure 6, from the comparison of the numerical and experimental result of the inducer without slit, in the region where the head is constant, the value obtained by numerical analysis is excessive compared with the value obtained by the experiment. This can also be seen from the result of
the $\psi - Q$ curve in Figure 5. Also with regard to the head breakdown point, the numerical analysis result of the inducer without slit cannot reproduce the experimental result. The fact that the head does not decrease implies that the cavity volume is underestimated. Therefore it is necessary to examine convergence of mesh or cavity model, and so on.

Also, we compare inducer with and without slit in the result of numerical analysis of suction performance. In the high cavitation number region, decrease of the head coefficient by the slit is not observed. This result is shown also in $\psi - Q$ curve in Figure 5 and the same tendency is shown in the numerical analysis result by Hagiwara[7]. However, as for the breakdown point of head, each inducer shows different results. Although the inducer without slit don’t show a remarkable breakdown of the head in the range of the present numerical analysis, the head breakdown is accelerated for inducer with slit. In addition, the head drop is more accelerated for Inducer335. The gradual decrease in head is observed near the $k_2 = 0.05$ in Inducer335, although the steep decrease is observed near the $k_2 = 0.035$. The reason why the effect of slit appears in cavitation condition although that does not appear in non-cavitation condition is that the differential pressure between the suction side and pressure side becomes large when cavity covers suction side of slit and then the flow rate through the slit becomes large. Therefore, it is shown that the slit affects the head performance some extent only in cavitation condition.

![Figure 6. Pump suction performance ($Q/Q_d = 1.0$).](image)

### 3.2. Unsteady cavitation flow

In this section, we compare cavity volume around inducer with and without slit in order to judge the occurrence of cavitation instabilities. The cavitation which occurs in inducer is mainly the tip leakage vortex cavitation in both inducer with and without slit as shown in Figure 8(a), which is caused by the pressure difference between the upstream and downstream of the inducer. Then in order to quantitatively evaluate the amount of cavitation in each blade, time evolution of cavity area at the tip is compared. The inducer without slit is shown in Figure 7(a) and the Inducer335 is shown in Figure 7(b), regarding the temporal change of the cavitation area occurring at the blade tip of each blade, respectively. As shown in these figures, the blade at which the cavity length take the maximum value is rotating in the same direction as the direction of rotation of the inducer, like Blade3→Blade2→Blade1 in both inducer with and without slit. Accordingly, the super-synchronous rotating cavitation cannot be suppressed under this condition of $k_2$.

On the other hand, the cavity area occurring in Inducer335 decreases compared with that in inducer without slit. Thus it can be said that the asymmetric slit promotes suppression of cavitation. Then, it is predicted that the shaft vibration will be suppressed by the asymmetric slit. Additionally, each maximum and minimum cavity areas are almost same in each blade in Inducer335, although the slit position is
asymmetric. Therefore, it is shown that the position of slits doesn’t affect the cavity volume and the frequency in the present slit position and the size.

![Cavity area at blade tip for the inducer without slit (a) and inducer335 (b) (Q/Qd = 1.0, k2 ≈ 0.036).](image)

**Figure 7.** Cavity area at blade tip for the inducer without slit (a) and inducer335 (b) (Q/Qd = 1.0, k2 ≈ 0.036).

### 3.3. Flow field around the slit

In order to investigate the effect of slit on cavitation, we visualized cavitating flow field around the slit. Figure 8 shows cavity aspect (a) and circumferential relative velocity vector around the slit in Blade1 in Inducer335. At this time, the upper side of the figure indicates upstream and suction side, and the lower side of the figure is the opposite. The right side of the figure is leading edge side. As the visualization of cavitation, the isosurface with the void fraction α = 0.5 is shown.

As shown in Figure 8(b), the liquid flow from the downstream side to the upstream side occurs through the slit, and then it is observed that the slit jet is generated. Because this condition is cavitation condition, the differential pressure at the slit increases and the jet is induced. Then, cavitation appears to be divided by slit jet as shown in Figure 8(a). Together with the analysis results of the two-dimensional cyclic cascade of the previous study, it can be said that there is a possibility that the slit jet affects suppression of oscillation intensity. That is because the slit jet increases the flow angle at trailing edge side of the slit, hence the strong vortex stationary structure occurs. Therefore the divided cavity at trailing edge side of the slit exhibits the appearance of a localized vortex cavity, and then cavity volume is decreased. However, in this numerical analysis, it is presumed that the effect is not enough to suppress the cavitation instability although the cavity volume is suppressed.

By the way, in Hagiwara analysis[7], the timing when cavitation covers the slit changes by applying the asymmetric slit, then cavitation surge period becomes irregular because the period at which slit jet inhibits the growth of cavitation is shifted. Therefore cavitation instability like the rotating cavitation is suppressed. Altogether, it is considered that the unsteadiness and the irregularity of the slit flow rate is a factor for quantitatively determining how much the slit has influence on the flow field around the inducer. Thus we will show time evolution of the slit mass flow rate for each blade in Figure 9. At this time, Blade1,2,3 correspond with the each slit position at Inducer335.

From this figure, although the slit flow rates of each blades has regular periodicity, the shape of waveform is different in each other blade. Especially, the waveforms of the slit flow rate in Blade1 and 2 are different in each other, although the slit positions are same in Blade1 and 2. It means that
the asymmetric arrangement of the slits has possibility to disturb the regularity of the slit flow rate and suppress the cavitation instabilities because that is fundamentally regular oscillation. Consequently, it can be said that there is a possibility to suppress the cavitation instabilities by optimizing the slit position. In the future work, further verification on the shape or arrangement of the slit will be investigated.

![Visualization of inducer with slit under cavitation condition](image1)

**Figure 8.** Visualization of inducer with slit under cavitation condition ($t = t_0 + 50.0\, \text{ms}$, $Q/Q_d = 1.0$, $k_2 \approx 0.036$).

![Slit mass flow rate in each blade in Inducer335](image2)

**Figure 9.** Slit mass flow rate in each blade in Inducer335 ($Q/Q_d = 1.0$, $k_2 \approx 0.036$).

### 4. Concluding Remarks

In this paper, in order to obtain knowledge about suppression effect of an inducer with asymmetric slits on cavitation instability, we conducted numerical analysis around inducer and compared cavity time averaged pump performance and unsteady cavity behavior between inducer with slit and without slit. The result obtained in this analysis is as summarized below.

1. The influence of asymmetric slit on the pump performance such as $\psi - Q$ curve and suction performance is examined in steady analysis. As a result, regarding the $\psi - Q$ curve in non cavitation condition, there is almost no difference in performance depending on whether the inducer has the
slits or not. As for suction performance, although the breakdown point of the head occurs earlier in the inducer with slit compared with that in without slit, the head remains constant at the lower cavitation number condition in Inducer035 compared with that in Inducer335.

2). By unsteady analysis of super-synchronous rotating cavitation, it is shown that cavity volume is decreased by the slit. However, rotating cavitation cannot be suppressed.

3). By visualization of the flow field around the slit near the blade tip in the circumferential direction, it is observed that jet from the slit divided cavity and then cavity volume is considered to be decreased. Additionally, because the time evolution of the slit flow rates are different in each blade in the inducer with the asymmetric slit, the asymmetric arrangement of the slit has possibility to disturb the regularity of the rotating cavitation and then to suppress it.

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