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Cause of Cavitation Instabilities in Three-Dimensional Inducer

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ABSTRACT

Alternate blade cavitation, rotating cavitation and cavitation surge in rocket turbopump inducers were simulated by a commercial CFD code. In order to clarify the cause of instabilities, the velocity disturbance caused by cavitation was obtained by subtracting the velocity vector under non-cavitating condition from that under cavitating condition. It was found that there exists a disturbance flow towards the trailing edge of the tip cavity. This flow has an axial flow component towards downstream which reduces the incidence angle to the next blade. It was found that all of the cavitation instabilities start to occur when this flow starts to interact with the leading edge of the next blade. The existence of the disturbance flow was validated by experiments.

INTRODUCTION

In modern turbopumps for rocket engines, it is generally recognized that cavitation instabilities are major concerns. They occur in the range where the head is not yet decreased, and cause the high dynamic loads on the shaft and the blades.

By a two dimensional stability analysis for blade surface cavity in cascades [1], it was found that the steady cavity length is the dominating factor of cavitation instabilities and that various modes of cavitation instability start to occur when the cavity length becomes about 65% of blade circumferential spacing. This result agrees reasonably with experiments for three dimensional inducers if we consider the cavity length at the tip. By the two dimensional stability analysis for alternate blade cavitation [2], it was shown that alternate blade cavitation also starts to occur when the cavity length becomes about 65% of the blade circumferential spacing. By a closer observation of the flow field around alternate blade cavitation, it was found that there exists a region near the cavity trailing edge where the velocity vector is tilted towards the suction surface. When this

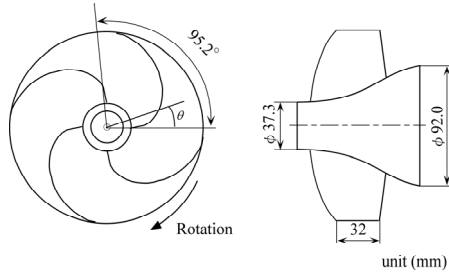
region gets closer to the leading edge of the next blade, the incidence angle to the next blade gets smaller and the cavity length on the next blade becomes smaller, hence it results in alternate blade cavitation.

Hosangadi. A., et al.[3] successfully simulated rotating cavitation in a cavitating inducer by an unsteady three dimensional simulation and discussed the cause of cavitation instabilities. They observed rotational cavitation modes and explained that the interaction of the cavity with the next blade leads to the cavitation instabilities. The cavity forming on the pressure side of the blade leads to the reversal in the blade loading, altering the incidence angle to the next blade, and hence it results in the rotational cavitation modes.

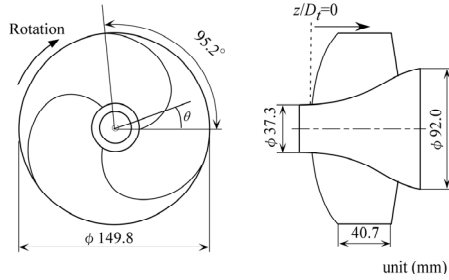
The present paper focuses on the clarification of the mechanism of cavitation instabilities in real three dimensional flow based on detailed analyses of the velocity field under cavitation instabilities obtained by using a commercial three dimensional CFD code.

SPECIFICATION OF INDUCER

Figure 1 and Table 1 show the main dimensions of 4 and 3-bladed inducers with the backward leading edge sweep and the diameter of 149.8mm. The inlet and outlet blade angles are 7.5 deg and 9.0deg at the tip, respectively. The design flow coefficient ϕ_d is 0.078. The flow coefficient ϕ is defined as v_1/U_t , where v_1 is the mean axial velocity in the plane at $z/D_t=0$, and U_t is the tip speed of the impeller. The axial coordinate z is set in the downstream direction from the origin at the leading edge of blades at root as shown in Fig.1(b).



(a) 4-bladed inducer



(b) 3-bladed inducer

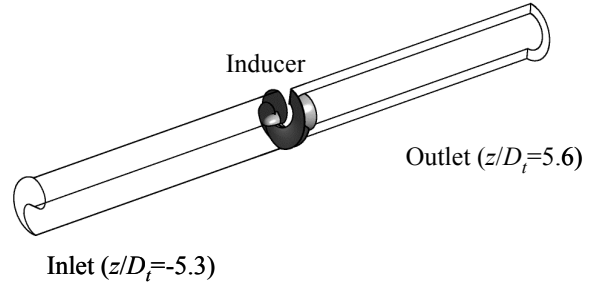
Figure 1: Leading edge geometry for the 3 and 4-bladed inducers

Table 1: Geometrical properties for the 3 and 4-bladed inducers

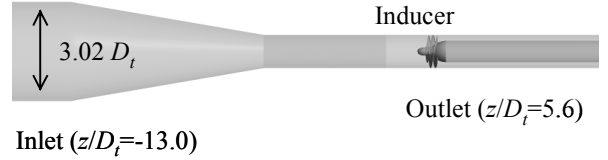
Number of blades	3-bladed inducer	4-bladed inducer
Tip diameter	149.8 mm	←
Inlet tip blade angle	7.5 deg	←
Outlet tip blade angle	9.0 deg	←
Hub/tip ratio at the inlet	0.25	←
Hub/tip ratio at the outlet	0.51	0.53
Solidity at tip	1.91	←
Design flow coefficient	0.078	←
Tip clearance	0.5 mm	←
Blade thickness at tip	2 mm	←

COMPUTATION METHOD

A commercial software, ANSYS-CFX11.0, was used for the simulation of cavitating flows in inducers. The simplified Reyleigh-Plesset model was applied as the cavitation model. The $k-\omega$ turbulence model was used. Zero circumferential velocity and the total pressure were specified at the inlet and constant mass flow rate was specified at the outlet. The working fluids were water and its vapor. The rotational speed was fixed at 3000rpm which is the same as experiments.



(a) 4-bladed inducer



(b) 3-bladed inducer

Figure 2: Computational domain

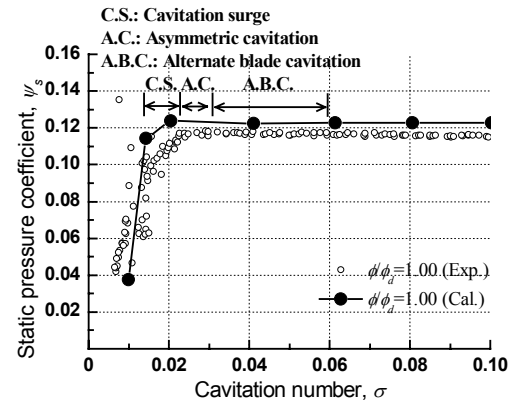


Figure 3: Suction performance curve with the occurrence regions of the cavitation instabilities for the 4-bladed inducer

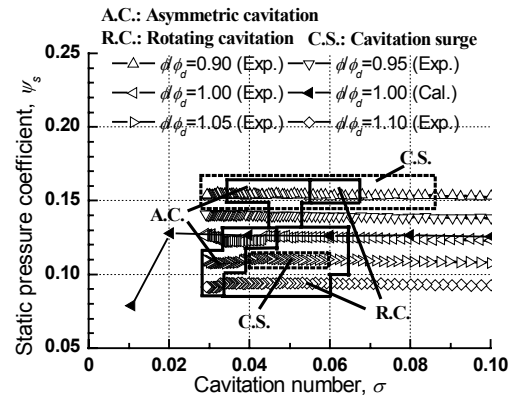


Figure 4: Suction performance curve with the occurrence regions of the cavitation instabilities for the 3-bladed inducer

Table 2 Cavitation instabilities and their frequencies for various cavitation numbers, by computations at $\phi/\phi_d=1.0$

Cavitation number	Instability name	Frequency
$\sigma=0.10$	Steady cavitation	-
$\sigma=0.050$	Cavitation surge	$0.33N$
$\sigma=0.045$	Cavitation surge	$0.31N$
$\sigma=0.040$	Rotating cavitation	$1.20N$
$\sigma=0.035$	Rotating cavitation → Cavitation surge	$1.2N \rightarrow$ $0.22N$
$\sigma=0.030$	Asymmetric cavitation → Cavitation surge → Divergence	-

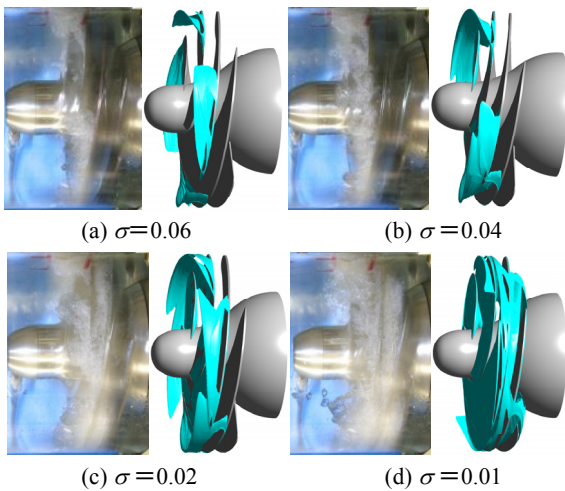


Figure 5: Cavity shape for the 4-bladed inducer at $\phi/\phi_d=0.078$, 3000rpm

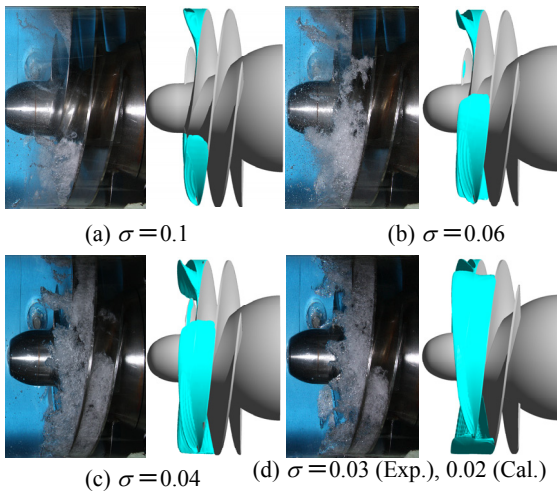


Figure 6: Cavity shape for the 3-bladed inducer at $\phi/\phi_d=0.078$, 3000rpm

For the simulation of alternate blade cavitation, steady flow calculations in two blade channels of the 4-bladed inducer were made by assuming the periodicity over 2 blades, as shown in Fig.2(a). The number of computational cells was about 2,200,000. For the simulation of rotating cavitation and cavitating surge, unsteady flow calculations were made for all blades of the 3-bladed inducer. To obtain stable solution, the inlet pipe was enlarged as shown in Fig.2(b). The number of computational cells was 3,300,000.

COMPARISONS WITH EXPERIMENTS

Figure 3 shows the regions of various cavitation instabilities observed in experiments with suction performance curve at $\phi/\phi_d=1.0$, for the 4-bladed inducer. The horizontal axis shows the cavitation number σ defined as $(p_1-p_v)/(\rho U_t^2/2)$ where p_1 is the inlet pressure measured 302mm upstream of the blade leading edge at the tip and p_v is the vapor pressure. The vertical axis shows the static pressure coefficient ψ_s defined as $(p_2-p_1)/(\rho U_t^2)$, where the p_2 is the outlet pressure measured 66mm downstream of the blade leading edge at the tip. In experiments, the cavitation instability was identified by the inlet pressure fluctuations measured by pressure transducers flush mounted 44mm upstream of the blade leading edge at the tip, and the suction performance curve at $\phi/\phi_d=1.0$ evaluated by steady CFD is also shown. Alternate blade cavitation occurred in $0.03 < \sigma < 0.06$ in experiments, and at $\sigma=0.04$ and 0.02 in steady CFD computations.

Figure 4 shows the regions of various cavitation instabilities observed in experiments with suction performance curves at various flow coefficients, for the 3-bladed inducer. The suction performance curve at $\phi/\phi_d=1.0$ evaluated by steady CFD computations is also shown. In experiments, asymmetric cavitation occurred at all flow rates and rotating cavitation was observed at most flow rates except for $\phi/\phi_d=0.95$. Cavitation surge was found in a wide range of cavitation number at $\phi/\phi_d=0.9$ and in $0.04 < \sigma < 0.06$ at $\phi/\phi_d=1.05$. In unsteady CFD computations at $\phi/\phi_d=1.0$ various cavitation instabilities were observed as shown in Table 2. However, The occurrence regions of cavitation instabilities do not exactly agree with experiments.

Figures 5 and 6 show the cavity shape for the 4 and 3-bladed inducers, respectively, obtained from experiments and steady CFD computations. The cavity was shown by a plane with the void fraction $\alpha=0.01$. When the cavity length becomes about 65% of the blade circumferential spacing, alternate blade cavitation occurs as shown in Fig.5(b), in agreement with the two dimensional stability analysis. In experiments for the 3-bladed inducer, rotating cavitation occurred in $0.046 < \sigma < 0.064$ when the cavity length becomes about 65% of the blade circumferential spacing as shown in Fig.6(b) (Average cavity is shown). The steady CFD code can simulate the tip cavity shape reasonably except for the unsteady cavitation and backflow vortex cavitation.

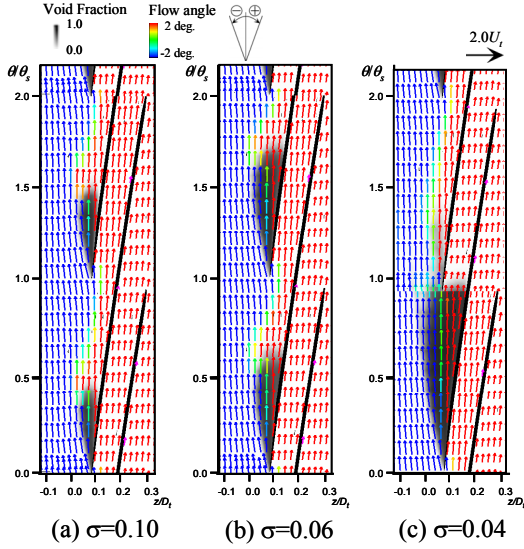


Figure 7: Relative velocity vector and void fraction and flow angle distributions in z - θ plane at $r/R_t=0.98$, $\phi=0.078$, 3000rpm

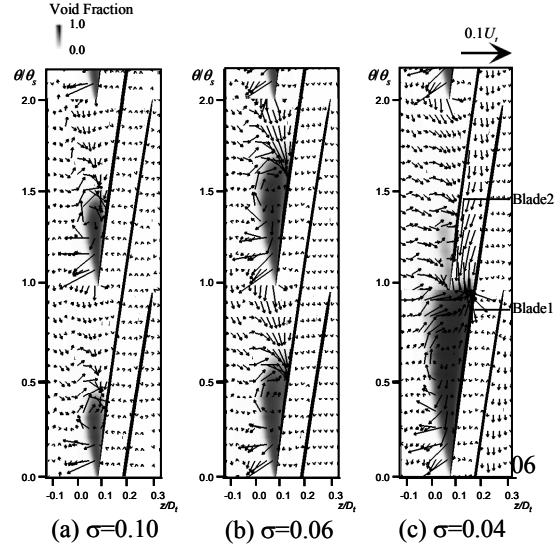


Figure 8: Disturbance velocity vector and void fraction distribution in z - θ plane at $r/R_t=0.98$, $\phi=0.078$, 3000rpm

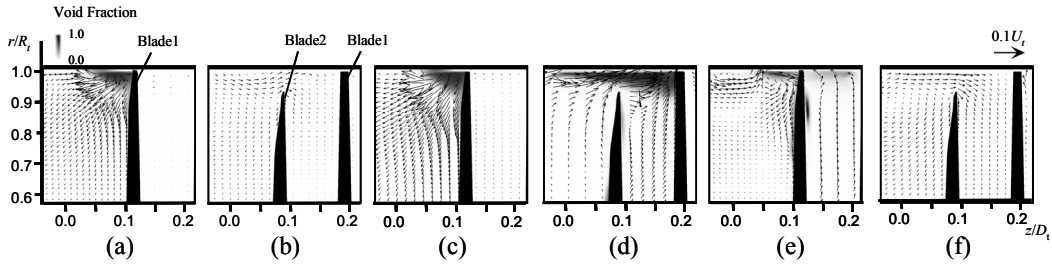


Figure 9: Disturbance velocity vector and void fraction distribution in meridional plane at $\phi=0.078$, 3000rpm
 $\sigma=0.06$: (a) $\theta/\theta_s=0.2$, (b) $\theta/\theta_s=0.9$
 $\sigma=0.04$: (c) $\theta/\theta_s=0.2$, (d) $\theta/\theta_s=0.9$, (e) $\theta/\theta_s=1.2$, (f) $\theta/\theta_s=1.9$

ALTERNATE BLADE CAVITATION

Since the cavities on each blade are steady for alternate blade cavitation, the steady CFD can simulate alternate blade cavitation in the 4-bladed inducer.

Figure 7 shows the relative velocity vector, void fraction and flow angle distributions in the axial-circumferential plane at $r/R_t=0.98$. Unlike blade surface cavitation, the velocity vector obtained by the bubbly flow model is not parallel with the cavity surface. The flow angle is negative in the upstream due to the backflow. We can observe a region with positive flow angle downstream of the cavity trailing edge. To clarify the effect of cavitation, the disturbance velocity vector was evaluated by subtracting the velocity of non-cavitating flow from that of cavitating flow, and shown in Fig.8. We can observe a source-like flow around the cavity leading edge and a flow towards the cavity trailing edge. These flows are caused by the growth and collapse of cavitation bubbles. The velocity vector towards the cavity trailing edge has a component in

positive z direction. When the local flow near the cavity trailing edge starts to interact with the leading edge of the next blade, as shown in Fig.8(b), the incidence angle to the next blade is decreased and the cavity size on the next blade is decreased. This results in alternate blade cavitation shown in Fig.8(c).

Figure 9 shows the disturbance velocity vector and the void fraction distribution in meridional planes at $\theta/\theta_s=0.2$ and 0.9 . The source-like flow near the cavity leading edge are shown in Figs.9(a) and (c). The flow towards the trailing edge of the longer cavity of alternate blade cavitation is shown in Fig.9(d). This figure clearly shows how the incidence angle to the next blade at $z/D_t=0.09$ is decreased. The radial component of the velocity disturbance is much smaller than the axial component. This is why the interaction of local flow near the cavity trailing edge with the leading edge of the next blade is important for tip cavities.

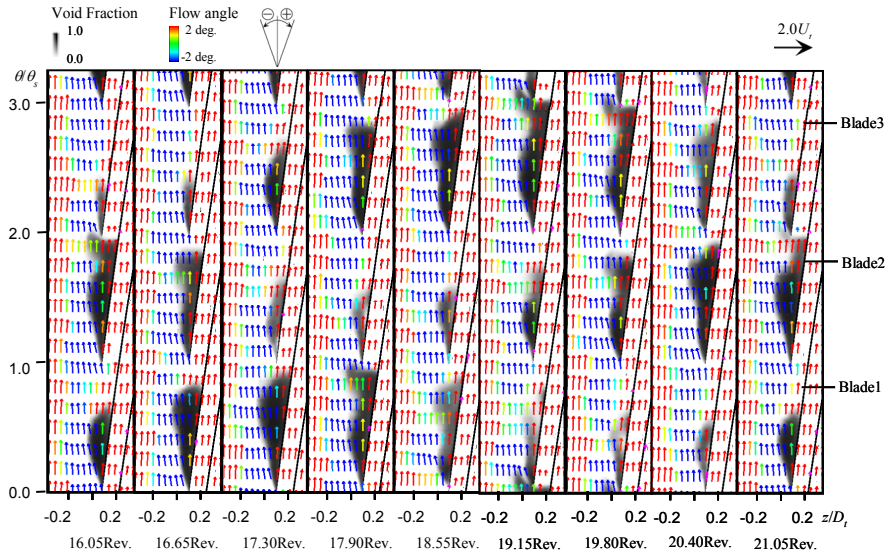


Figure 10: Relative velocity vector, void fraction and flow angle distributions in z - θ plane at $r/R_t=0.98$, $\phi=0.078$, $\sigma=0.04$, 3000rpm

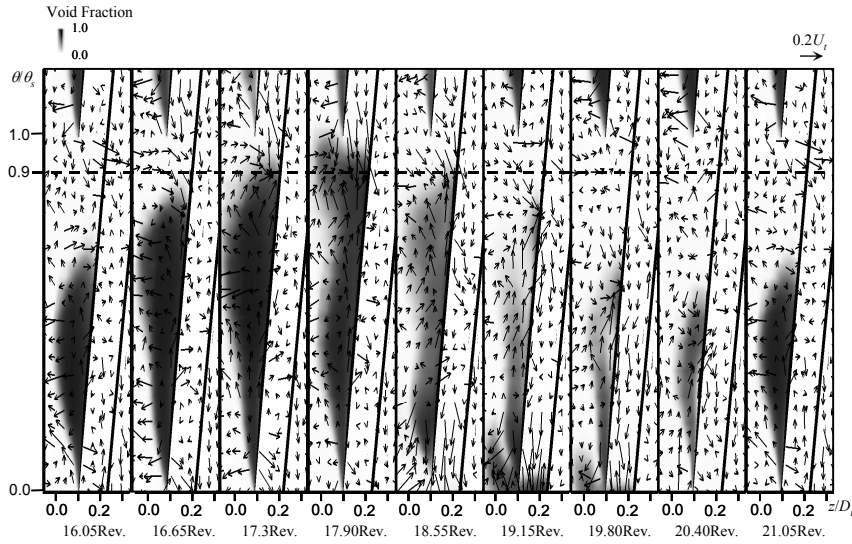


Figure 11: Disturbance velocity vector and void fraction distribution in z - θ plane at $r/R_t=0.98$, $\phi=0.078$, $\sigma=0.04$, 3000rpm

ROTATING CAVITATION

In order to simulate rotating cavitation, we carried out unsteady cavitating flow calculation of 3-bladed inducer at $\phi/\phi_d=1.0$, $\sigma=0.04$.

Figure 10 shows the relative velocity vector, void fraction and flow angle distributions in the axial-circumferential plane at $r/R_t=0.98$. The propagation speed of rotating cavitation is about 1.2 times rotating speed of impeller. This propagation speed is reasonable as compared with experiments. We can explain the propagation of the cavity as follows. We focus on the growth of the cavity on each blade during 16.05Rev.~17.9Rev. shown in Fig.10. If the cavity on blade 1 gets larger, the incidence angle to blade 2 is decreased and the cavity length on the blade is decreased. Due to the decrease of the cavity length on blade 2, the incidence angle to blade 3 is increased and the cavity on blade 3 grows.

Figure 11 shows the disturbance velocity vector in axial-circumferential plane at $r/R_t=0.98$. Due to the oscillation of the cavity itself, the disturbance velocity field is not as clear as for alternate blade cavitation shown in Fig.8. However, we can observe a source-like flow near the cavity leading edge and the flow towards the cavity trailing edge.

Figure 12 shows the disturbance velocity vector and the void fraction distribution in meridional plane at $\theta/\theta_s=0.9$. We can observe that the flow near the leading edge of blade 2 is subjected to higher axial disturbance velocity at the cavity trailing edge on blade 1. Thus, the propagation of rotating cavitation can be explained by the interaction of the flow towards the cavity trailing edge with the next blade. However, rotating cavitation was observed in experiment, in $0.046 < \sigma < 0.064$ at $\phi/\phi_d=1.0$.

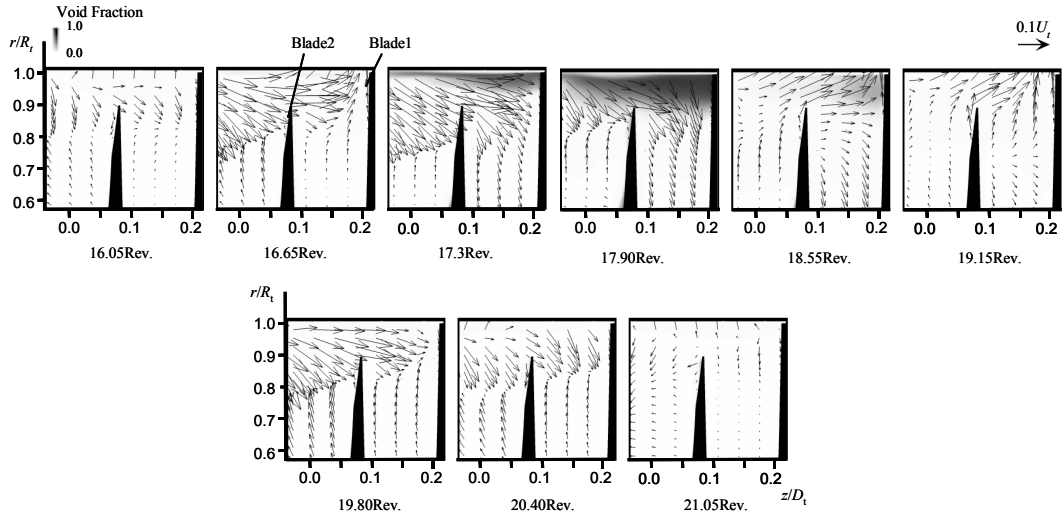


Figure 12: Disturbance velocity vector and void fraction distribution in meridional plane at $\theta/\theta_s=0.9$, $\phi=0.078$, $\sigma=0.04$, 3000rpm

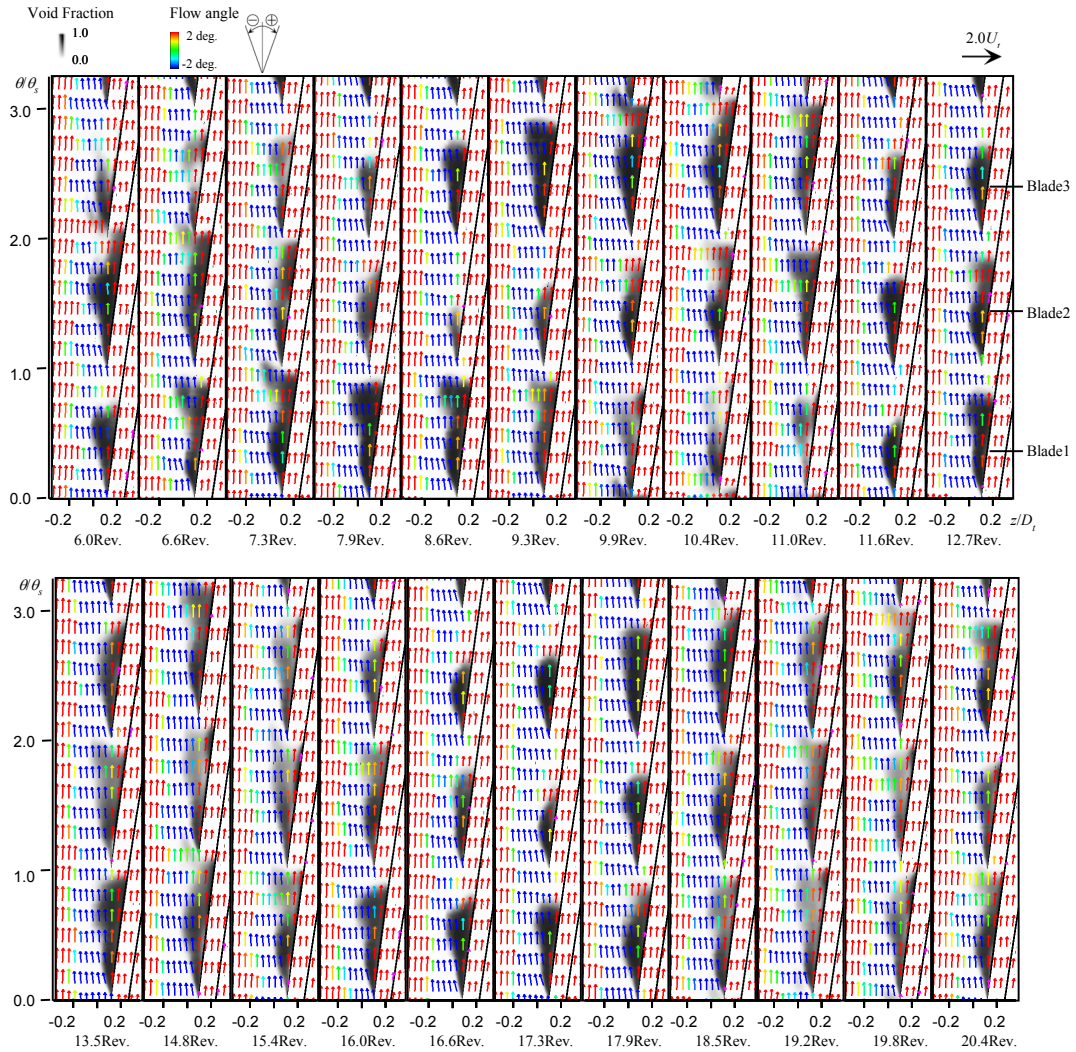


Figure 13: Relative velocity vector, void fraction and flow angle distributions in z - θ plane at $r/R_t=0.98$, $\phi=0.078$, $\sigma=0.035$, 3000rpm

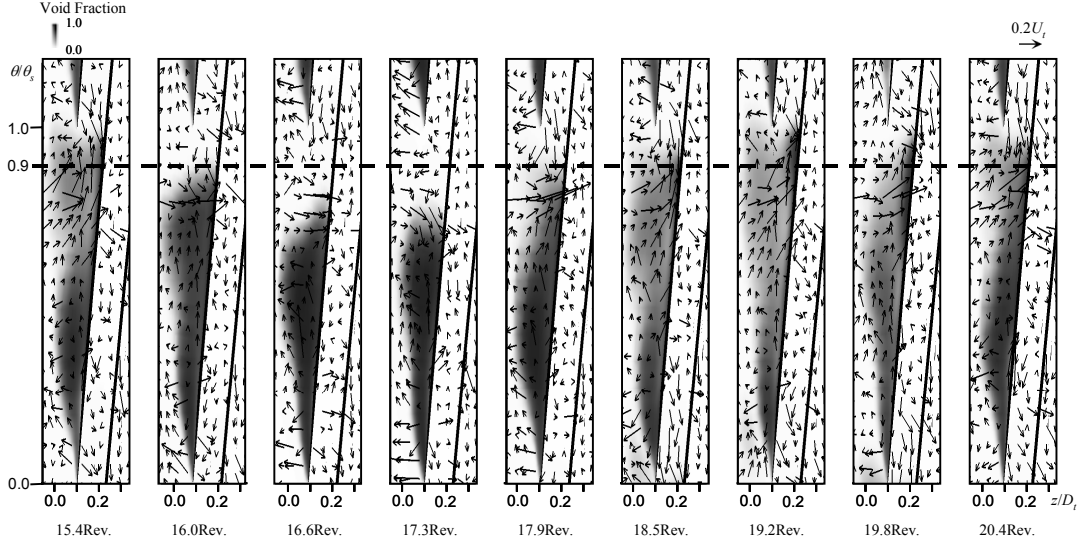


Figure 14: Disturbance velocity vector and void fraction distribution in $z-\theta$ plane at $r/R_i=0.98$, $\phi=0.078$, $\sigma=0.035$, 3000rpm

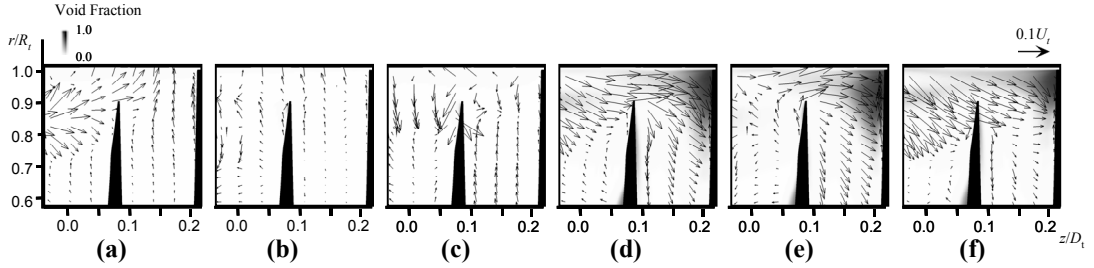


Figure 15: Disturbance velocity vector and void fraction distribution in meridional plane at $\sigma=0.035$, $\phi=0.078$, 3000rpm
 17.3Rev.: (a) $\theta/\theta_s=0.9$, (b) $\theta/\theta_s=1.9$, (c) $\theta/\theta_s=2.9$
 19.2Rev.: (d) $\theta/\theta_s=0.9$, (e) $\theta/\theta_s=1.9$, (f) $\theta/\theta_s=2.9$

CAVITATION SURGE

Cavitation surge was found at $\phi/\phi_d=1.0$, $\sigma=0.035$. The flow data at $\phi/\phi_d=1.0$ and $\sigma=0.04$ under rotating cavitation was used as the initial value for the calculation of cavitating surge.

Figure 13 shows the relative velocity vector, void fraction and flow angle distributions in the axial-circumferential plane at $r/R_i=0.98$. We observe a rotating cavitation in 6.0~11.0Rev., but it switches to cavitation surge at 11.6Rev. The frequency of cavitation surge is about $0.2N$, where N is the frequency 50Hz of the impeller rotation. This frequency is reasonable as compared with experiments. However, cavitation surge was observed in experiment, in $0.04 < \sigma < 0.06$ at $\phi/\phi_d=1.05$.

Figure 14 shows the disturbance velocity vector around blade 1. When the cavity is shed from the trailing edge, the flow toward the shed cavity is more evident.

Figure 15 shows the disturbance velocity vector in meridional planes at $\theta/\theta_s=0.9$, 1.9 and 2.9. The disturbance velocity is small for all blades when the cavity is small (17.3Rev.) and we observe a strong axial velocity disturbance for all blades when the cavity is large (19.2Rev.). Thus, cavitation surge also can be explained from the interaction of

the disturbance flow near the cavity trailing edge with the next blade.

DISTURBANCE VELOCITY MEASUREMENTS

Since it has been shown that the disturbance velocity due to tip cavity plays an important role in cavitation instabilities, velocity measurements were made with the 4-bladed inducer. The absolute velocity was measured by using LDV (Kanomax, probe:FLVP-K(Model 1884), laser unit: FLV8851, signal processing board 8008). About 10~40 data were averaged at each measurement point. The cavity shape was evaluated from the pictures. The velocity measurement were made at $\sigma=0.375$ and $\sigma=0.10$ and the relative velocity near the leading edge is shown in Fig16.(a) and (b). Since the cavity is small at $\sigma=0.375$, the velocity disturbance due to cavity is evaluated by subtracting the velocity at $\sigma=0.375$ from that at $\sigma=0.10$ and shown in Fig16.(c). Although the scatter is large, we can observe a source-like flow near the cavity leading edge and the flow towards the cavity trailing edge. This result is similar to the disturbance vectors shown in Fig.8(a) and validates the results of numerical simulation. The flow towards the cavity will cause cavitation instabilities when it interfere with the leading edge of the next blade.

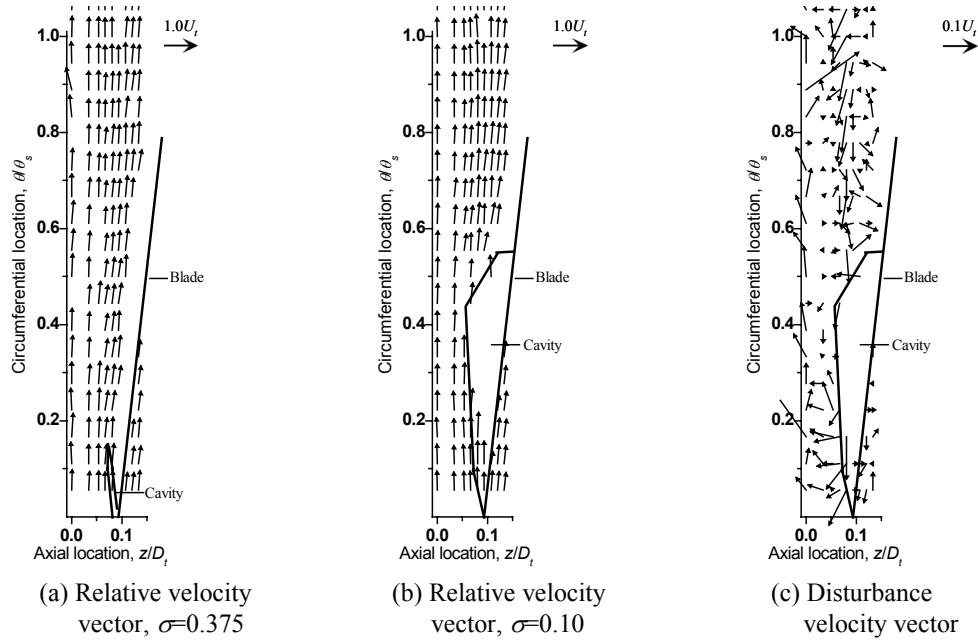


Figure 16: Velocity vectors obtained from experiments at $r/R_t=0.98$, $\phi=0.078$, 3000rpm

CONCLUSIONS

It was found that there exists a disturbance flow toward the trailing edge of tip cavity. The existence of this disturbance flow was confirmed by experiments. This flow has an axial flow component towards downstream which reduces the incidence angle to the next blade. It was found that all of the cavitation instabilities start to occur when this flow starts to interact with the leading edge of the next blade. This explains why various cavitation instabilities occur, when the tip cavity length becomes about 65% of the blade circumferential spacing. This also suggests that cavitation instabilities can be avoided by avoiding the interaction of the tip cavity with the next blade. Actually several stable inducers could be designed based on this design guideline [4].

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