8. Suppression of cavitation instabilities

Avoidance of cavitation instabilities is an essential issue for the design of reliable inducers. Unfortunately no reliable design rules for the avoidance is available at this moment and it is treated on empirical bases. Three possible methods are examined in this section, i.e., leading edge sweep, casing enlargement at the inlet and the alternate leading edge cut back.

8.1 Leading edge sweep

It has been shown in Section 7, that various types of cavitation instabilities occur if the steady cavity length becomes larger than about 65% of the blade spacing. Since the cavity length is a function of $\sigma/2\alpha$ and the cavity length increases as we decrease the value of $\sigma/2\alpha$, using smallest possible incidence angle $\alpha$ is desirable to avoid cavitation instabilities. However, if we use too small $\alpha$ the allowance for higher flow rate will decrease and the head will decrease rapidly at higher flow due to the development of cavity on the pressure surface.

It has been empirically known that the leading edge sweep has favorable effects on cavitation. Here we discuss how the leading edge sweep affects the development of cavitation (Acosta et al., 2001).

8.1.1 Geometrical relations

We consider a cascade shown in Fig.8.1; several views are shown which are needed for clarity. The upper or plan view of the cascade shows straight uncambered blades $s$ apart along the cascade axis (the plane normal to the inducer axis in Fig.8.1(b). The blades are inclined at the blade angle $\beta$ with respect to this axis. The leading edges of these blades are shown in the meridional view inclined at angle $\delta$ from what would be a radial line in Fig.8.1(b). Let us select two points on one blade, $O$, and $A$. Corresponding points in the meridional plane lie along $l-l$ spanning a vertical height $\eta_s$ (in radial direction). These points and at the next blade $O',A'$ are observed in the true view of the blade leading edge defined by cut $B-B$. The bold line $OA$ is the true view of the leading edge. This line makes an angle $\lambda$ to the plane of the inducer axis, namely, the projection $O-O'$. The adjacent blade in this true view is $O'-A'$. The plane normal to $OA,O'A'$ and to the plane of the paper is the cross flow plane. Note that the line $O'A'$ is hidden from view by the first blade. Now in the true view plane, $BB$, project a normal to $OA$ from $O'$ ending at $P$, a point on the leading edge of blade $B_1$. 

1
Point $P$ also appears in the plan view on the leading edge of blade $B_1$. Imagine now we progress from $P$ normal to the leading edge along blade $B_1$ in the cross flow plane, $CC$, until we are underneath the normal to the next blade, $B_2$, at point $Q$. From $Q$ we move to point $O'$ on blade $B_2$ seen in the plan view. The cross flow plane in the plan view may be identified by the points $P, Q, O'$ (a portion of it is shown, cross-hatched for clarity).

We will be concerned with the flow velocities and the effective cascade geometry in this cross flow plane. Before completing the definitions of the cross-flow cascade geometry, let us consider the velocity components: The velocity approaching the inducer seen in Fig. 8.1(b) is presumed to be purely axial; relative to the rotating inducer the flow speed is $V_1$ and is inclined to the blades with incidence angle $\alpha$ shown in the plan view of Fig. 8.2. This velocity vector lies in the plane of the inducer in Fig. 8.2. There is a component of $V_1$ that is normal to the cascade blade, $V_n$, and a component tangential to the blade surface $V_c$ also shown in Fig. 8.2. The tangential component is resolved into component $V_c$ normal to the true view of the leading edge and $V_p$ parallel to it. We see in the cross flow plane (Fig. 8.2, section $CC$) component $V_c$ approaching a cascade but one characterized by a new spacing, $s_c$, and a new blade angle, $\beta_c$. The normal distance between the blades $B_1, B_2$ shown in the cross-flow and plan view is of course the same, i.e.,

$$ssin\beta = s_c sin\beta_c, \quad \beta_c = sin^{-1}(s / s_c) sin \beta)$$  \hfill (8.1)

Then sweep angle $\lambda$ is constructed in the true view plane from

$$tan \lambda = \frac{\eta}{(\eta tan \delta / sin \beta)}, \quad \lambda = tan^{-1}\left(\frac{sin \beta}{tan \delta}\right)$$  \hfill (8.2)

The effective spacing is determined from its projection $P - O'$ in the true view plane and the normal distance above to get

$$s_c = \sqrt{(s cos \beta sin \lambda)^2 + (s sin \beta)^2}$$  \hfill (8.3)

Note that $s_c \leq s$. The true thickness of the blades is $t$; the ratio $t/s$ is an important geometric parameter governing cavitation. Clearly then the effective thickness-spacing ratio $(t/s)_{eff}$ is

$$\left(\frac{t}{s}\right)_{eff} = \left(\frac{t}{s}\right) \left(\frac{s}{s_c}\right) \geq \left(\frac{t}{s}\right)$$  \hfill (8.4)

Thus the cross-flow geometry is blunter than the normal flow. For a leading edge in the shape of a wedge of included angle $\theta$, it follows that
\[ \theta = \tan^{-1}\left(\frac{\tan \theta}{\sin \lambda}\right) \]  

(8.5)

If as is the case with many small commercial inducers with leading edge machined on a lathe, \( \theta = \beta \). Finally, there is the flow incidence angle in the cross flow plane for which

\[ \alpha_c = \tan^{-1}(V_n / V_c) \quad \alpha_c = \tan^{-1}(\tan \alpha / \sin \lambda) \]  

(8.6)

8.1.2 Cavitation scaling

Let the pressure in the cavity be \( p_v \) and the velocity there be \( V_k \). Then in the usual way from Bernoulli equation, i.e.,

\[ \frac{p_1}{\rho} + \frac{1}{2} V_1^2 = \frac{p_v}{\rho} + \frac{1}{2} V_k^2 \]  

(8.7)

we define the cavitation number

\[ k = \frac{p_1 - p_v}{\rho V_i^2 / 2} \]  

(8.8)

and so we can say

\[ V_k = V_i \sqrt{1 + k} \]  

(8.9)

in the physical plane. The total velocity approaching the cascade in the cross flow plane is

\[ V_{\text{total}} = \sqrt{V_c^2 + V_n^2} \]  

(8.10)

and based on this velocity we can define a cross-flow cavitation number as

\[ k_c = \frac{(p_1 - p_v)}{(\rho V_{\text{total}}^2 / 2)} \]  

(8.11)

And on the cavity we have

\[ V_{kc} = V_{\text{total}} \sqrt{1 + k_c} \]  

(8.12)

These definitions must take the true velocity on the cavity precisely the same requiring that

\[ V_k^2 = V_{kc}^2 + V_p^2 \quad \text{or} \quad V_k^2(1 + k) = (V_c^2 + V_n^2)(1 + k_c) + V_p^2 \]  

(8.13)

After substituting these definitions we have the simple result

\[ k_c = k / (\cos^2 \alpha \sin^2 \lambda + \sin^2 \alpha) \]  

(8.14)

Note that if \( \lambda \to \pi/2 \) (no sweep), \( k \to k_c \). For typically small incidence angles \( \alpha \ll 1 \),

\[ k_c = (k / \sin^2 \lambda)(1 - O(\alpha^2)) \approx k / \sin^2 \lambda \]  

(8.15)

which is the relation we will use. The equivalent formula for a swept isolated wing quoted by Ihara et al is (in our notation)
The slight difference arises because our cross flow velocity is parallel to the chord.

The effect of sweep appears through two mechanisms. One is through the change of cascade geometry in cross flow as shown by Eqs.(8.3)-(8.6) obtained in the preceding section. The other is through the cavitation scaling as shown by Eq.(8.16). It has been shown by two-dimensional linear analysis such as Acosta(1955) that the cavity length and hence the cavity development is a function of \( k/2\alpha \). If we combine Eq.(8.6) and Eq.(8.16), we obtain

\[
k_{c}/2\alpha_{c} = \frac{k/2\alpha}{\sin \lambda}
\]

(8.17)

If we increase the leading edge sweep, \( \lambda \) is decreased. Then \( k_c/2\alpha_c \) is increased and hence the cavity length \( l/s = (l_c/s_c)(\cos \beta/\cos \beta_c) \) is decreased. This can be the major reason why the cavitation performance is increased by simply sweeping the leading edge.

### 8.1.3 Comparison of steady cavity length with experiments and discussions

In order to study the effects of leading edge sweep, systematic experiments were carried out at Osaka University under the support of SNECMA, division SEP. Three inducers quoted here have helical blades with the same camber line with straight part near the leading edge. Forward and backward swept inducers were produced by cutting back the straight part of an unswept inducer so that the inlet blade angle is not changed. Thus, all of the inducers have the same inlet and outlet blade angles. Dimensions of the inducers are shown in the Table 8.1. The basic design is the same as for the LE-7 LOX turbopump inducer except that 3 blades are employed for LE-7. Inducer 0 is without sweep and has a straight radial leading edge. Inducer B50 is produced by cutting back the leading edge by about 47.3 deg. as shown in Fig.8.2. Inducer F30 is produced by offsetting the leading edge by 35 deg at the root and then giving forward sweep by 25 deg. The tip/leading edge corner is rounded with radius 4 mm. The leading edge curve is obtained by shifting the circumferential location of an involute curve with base radius 26 mm (this produces sweep with 85.3 deg) proportionally to the amount of sweep. The blade thickness is 2 mm and the suction surface near the leading edge is filed to a wedge angle 2.75 deg with the leading edge radius of 0.2mm.

Figure 8.3 shows the non-cavitating characteristics of the inducers. Nominal incidence angle at the tip (\( \alpha = \beta - \tan^{-1} \phi \)) is also shown. As expected, three inducers
have nearly the same non-cavitating performance for \( \phi > 0.06 \) \( (\alpha < 4 \text{ deg}) \).

Figure 8.4 shows the plot of cavity length \( l/s \) at the tip against the cavitation number \( k \) for the three inducers. For all inducers and all incidence angles shown, alternate blade cavitation (in which cavity length differs alternately) starts to develop when the cavity length exceeds about 65% of the spacing. The cavitation becomes unsteady for the condition with \( k \) smaller than that with the data point. In most cases unsteady cavitation starts to occur when the length of the shorter cavity exceeds 65% of the spacing. As expected, the cavity develops faster for the cases with larger incidence angle \( \alpha \). These results clearly show the favorable effects of sweep. These observation agree fairly well with the theoretical findings mentioned in Section 7.

Figure 5 shows the plot of cavity length against \( k/2\alpha \), where \( \alpha \) is the nominal incidence angle at the tip. As expected from linearized analysis, the development of cavity is nearly the same for all the incidence angles. The comparisons among three inducers clearly show that the development of steady cavity is significantly delayed by giving both forward and backward sweep.

Neglecting all the difference of the cascade geometry in the cross flow plane, the cavity length \( l/s \) is replotted against \( k_c/2\alpha_c \) in Fig.8.6. Nominal values at the tip have been used for replotting. We find that the alternate blade cavitation starts to develop at \( k_c/2\alpha_c \approx 0.9 \) and it shifts to unsteady cavitation at \( k_c/2\alpha_c \approx 0.4 \).

The present results show that the delay of cavity development can be explained by the cross flow effect. The secondary flow caused by the centrifuging of blade boundary layers and the leakage from the pressure side near the tip should be quite different for forward and backward sweep. However, the delay of cavity development is quite the same for forward and backward sweep as shown in Fig.8.5 and it can be explained by the cross flow effects as shown in Fig.8.6. This fact shows that the cross flow effect is more important than the secondary flow effects. It has been shown in section 7, that the various kinds of unsteady cavitation depends only on the steady cavity length \( l/s \) or equivalently on \( k_c/2\alpha_c \). In this respect the present correlation with \( k_c/2\alpha_c \) explains not only the steady cavity development but also the onset of unsteady cavitation for \( k_c/2\alpha_c < 0.4 \).

Table 8.2 shows the cascade parameters in the cross flow plane. Comparisons in Fig.8.6 have been made by neglecting the difference of cascade geometry in cross flow plane. To examine the effect of geometrical difference, calculations were made by
using a singularity method mentioned in Section 7. Figure 8.7 shows the cavity length in cross flow plane. It is shown that the geometrical effects also delay the development of cavity when the cavity is shorter than the spacing. Figure 8.8 compares the exact cavity length in physical plane estimated from exact cascade geometry in cross flow plane with the approximate cavity length estimated from the original cascade geometry in physical plane. Although the difference in the cascade geometry cannot be ignored, the major effect of sweep comes from the $k_c/2\alpha_c$ effect. Unfortunately the agreement with experiment in Fig.8.5 is not good perhaps caused by non-linear and 3-D effects.

The results of Fig.8.7 show that the sweep does not affect the cavity development largely for the cavities longer than the spacing. This is caused by the cancellation of the favorable effects of $k_c/2\alpha_c$ by the deteriorating effects of the cross flow cascade geometry as shown in Fig.8.8 for $l_c/s_c > 1$. Analyses based on the correlation $k_{choke} = \alpha(\beta - \alpha)$ for the choke cavitation number of thin blade cascade show that the sweep does not affect the cavitation number and is caused by the cavitation number as mentioned. To examine the effect on the choke cavitation number for the cascades with wedged leading edge cascade, calculations are made based on a linear theory by Acosta as shown in Fig.8.9. The cavity is assumed to start from the end of the leading edge wedge as shown in the figure. Fig.8.10 shows the choke cavitation number obtained. The results are not shown for larger angle of attack for which the cavities will start from the leading edge tip. The choke cavitation number is clearly decreased by the sweep and the effect is more significant for the cases with smaller angle of attack. This shows that the leading edge geometry significantly affects the cavity development. Unfortunately, the breakdown cavitation number could not be determined in the series of experiments caused by the limitation of experimental apparatus. Careful experiments are needed to determine the effect of sweep on the choke cavitation number paying attention to the leading edge geometry and the location of the cavity detachment point.

8.1.4 Effects of sweep on cavitation instabilities

In the last section it was shown that the development of steady cavitation is significantly delayed by the cross flow effects. In this section the effect of sweep on cavitation instabilities and also the limitation of the $k_c/2\alpha_c$ correlation are discussed (Tsujimoto et al., 2001, Yoshida et al., 2001). Experiments were carried out for five inducers as shown in Table 8.3 and Fig.8.11, with the rotational speed of 4,000 rpm (66.7Hz). The blade angles are the same for all the inducers but the solidity at the tip
differs as shown in Table 8.3. Figure 8.12 shows non-cavitating performance of the inducers. For forward swept inducers F30 and F50, the head is smaller than that for Inducer 0 at smaller flow coefficient $\phi < 0.06$ but the head is not largely affected by the sweep in a wide range $0.06 < \phi < 0.1$ around the design point $\phi_d = 0.078$. Figure 8.13 shows the velocity fluctuations at 5 mm upstream of the leading edge, at 7 radial locations, for Inducer 0, B90 and F50, measured by LDV. The circumferential locations are shown by $\theta$ measured from the leading edge. Figure 8.14 shows the circumferentially averaged distributions of axial and tangential velocities at $\phi = \phi_d = 0.078$ and at $\phi = 0.070$. At the design point $\phi = \phi_d = 0.078$ we observe backflow for Inducer 0 and B90, but not with Inducer F50 near the tip. At the reduced flow rate $\phi = 0.070$ we observe backflow for all inducers but the backflow region with $V_z/U_1 < 0$ is smaller for F50. The region with swirl $V_\theta/U_1 > 0$, becomes larger in the order of F50, 0, B90. This shows that the backward sweep enhances the backflow but the forward sweep has the effect to suppress the backflow.

Figure 8.15 shows the sketches of cavitation for the five inducers with equal length and alternate blade cavitation. We consider first for equal length cavitation. For non-swept inducer 0, we observe a blade surface cavitation whose length is larger at the tip. For the backward swept inducers B50 and B90, we observe cavitation only near the tip. For forward swept inducers F30 and F50, we observe blade surface cavitation and the cavity length becomes maximum at midspan. With alternate blade cavitation, the cavities near the tip merges into two separate cavities. The blade surface cavity for F30 and F50 appears alternately, typical for alternate blade cavitation. Thus the cavity development differs from inducer to inducer and also differs at different radial location but we will take the cavity length at the tip for characterizing the cavity development.

Figure 8.16 shows the spectrum of inlet pressure fluctuation at $\phi = 0.080$. We observe rotating cavitation (and cavitation surge for B50 and F30) at a cavitation number smaller than that with alternate blade cavitation, except for the Inducer B90. They are herein called “unsteady cavitation”. Note that no unsteady cavitation was found for Inducer B90. The region of cavitation numbers for various types of cavitation is summarized in Fig.8.17 in terms of the sweep angle $\lambda$ at the tip (see Fig. 8.11), for $\phi = 0.080$. The boundary cavitation numbers decrease as we decrease $\lambda$ (increase sweep), to $sin \lambda = 0.5$, but further decrease in $\lambda$ does not the cause further decrease in $\sigma$. This
shows that the cross flow effects represented by $k_c/2\alpha_c$ appear only for the cases of small sweep, with $\lambda$ larger than 35 deg. The cavity length at the tip $l/h$ is also shown in Fig.8.17. We find that the alternate blade cavitation starts to occur with $l/h \approx 0.65 - 0.70$. The unsteady cavitation occurs when the length of shorter cavity $l_s/h$ of alternate blade cavitation becomes 55-70% of the blade spacing.

**Figure 8.18** shows the spectrum of inlet pressure fluctuation at a reduced flow coefficient $\phi = 0.070$. For Inducer B90, the spectrum is noisy and no distinct cavitation instabilities could be identified except for the cavitation surge at very small cavitation number. This is because the boundary of the backflow region is near the location of the pressure sensor and it detects irregular passage of backflow vortex cavitation. On the other hand, we can identify various components for F50. First, we should note that we can identify forward rotating cavitation at the cavitation number larger than the alternate cavitation onset. In addition to this, we observe a backward rotating cavitation. **Figure 8.19** shows the plot of the phase difference of pressure fluctuations at various circumferential locations. For forward rotating cavitation, the phase delays as we proceed in the direction of impeller rotation but it advances for backward rotating cavitation. This clearly shows the direction of the rotation of the cell. For alternate blade cavitation, the phase delays by $4\pi$ as we proceed $2\pi$ circumferentially. **Figure 8.20** shows the cross spectrum at two circumferential locations separated by 90 deg, averaged over 0.4 second. This result includes both forward and backward components. Detailed examination with a wavelet transform suggested that the direction of propagation is changing between forward to backward, about every 10 turns of the impeller. The propagation velocity of the forward mode is about 1.65, which is significantly higher than normal rotating cavitation.

**Figure 8.21** shows the suction performance and the region of various cavitation instabilities for the five inducers. Note that the breakdown cavitation number is decreased from $\sigma = 0.03$ for Inducer 0 to $\sigma = 0.02$ for Inducer B50 and B90. Further improvement was observed for forward swept inducers, especially for F50: no breakdown was observed at the minimum cavitation number $\sigma = 0.015$.

We find that the region of $\sigma$ for alternate blade cavitation and also unsteady cavitations is shifted to significantly smaller $\sigma$ for B50 and F30. However, further improvement was not found if we increase the sweep further (B90 and F50). With smaller flow rate, rotating cavitation was found at larger cavitation number than for
alternate blade cavitation for forward swept inducers. In this respect, forward sweep is not recommended although the breakdown cavitation number is significantly decreased by the sweep.

8.2 Housing enlargement at the inlet.

8.2.1 Results with LE-7 LOX turbopump

The method of housing enlargement at the inlet was first applied by Kamijyo et al. (1993), to suppress rotating cavitation in LE-7 LOX turbopump inducer. The major design parameters are shown in Table 8.4. A comparatively large sweepback was necessary in order to decrease the stress at the hub near the leading edge. Five kinds of inducer housing with dimensions shown in Fig.8.22 and Table 8.5 were tested in order to find a method to suppress the rotating cavitation observed with Housing A.

Suction performance and rotating cavitation

Figure 8.23 shows the inducer suction performance. With Housing A and C, no significant head degradation occurs for $\sigma \geq 0.014$. However, the head decreases slightly in the region $\sigma = 0.02 - 0.05$ with Housing A. Figure 8.24 shows the spectrum of impeller displacement for the case with Housing A. A super synchronous shaft vibration is observed in the same range of cavitation number $\sigma = 0.02 - 0.05$ as the degradation of head occurred. In particular, the amplitude of the shaft vibration is larger at $\sigma = 0.027$, where the dip in the head shown in Fig.8.23 is larger. Figure 8.25 represents shaft vibration at larger cavitation number $\sigma = 0.045 - 0.055$. Figure 8.26 shows the ratio of supersynchronous vibration frequency $f_{SN}$ to the inducer rotational frequency $f_{N}$. This ratio decreases as we decrease the cavitation number. From the frequency ratio observed, it was concluded that the supersynchronous vibration is caused by rotating cavitation.

Suppression

It was conjectured that rotating cavitation might be closely related to the tip leakage and backflow vortex cavitation, judging from the visual observations. Some efforts were made to influence the tip vortex cavitation. Firstly, the influence of tip clearance on the supersynchronous shaft vibration was investigated by using inducer housings D and E in Table 8.5. The tip clearances for housings D and E are 0.5 and 1.0mm, respectively. Increasing the tip clearance was fairly effective in decreasing the amplitude of the supersynchronous shaft vibration as shown in Fig.8.27, but it could not completely extinguish the vibration. Acosta (1958) reported that increasing the tip leakage and
backflow vortex cavitation helped prevent oscillating cavitation to some extent. Secondly, the suction ring shown in Fig.8.28, which is usually used to control the backflow at the inlet (Sloteman et al., 1984), was also very effective in suppressing the supersynchronous vibration. There were some instances in which the vibration was completely extinguished. In spite of the remarkable effect, it was not applied to the flight model because it required a large number of tests to confirm its durability. Lastly, the influence of the inducer upstream housing diameter was investigated. Figure 8.29 presents the spectrum of impeller displacement tested using the housing C. Note that the housing diameter $D_1$ is increased by only twice the tip clearance $2C_2 = D_2 - D_1$ from $D_2$. This device was applied to the flight model since there is no durability problem. It was confirmed that the device was very effective in suppressing the supersynchronous shaft vibration in the LE-7 engine test as shown in Fig.8.30.

In order to identify the possible cause of suppression, the values of mass flow gain factor was measured with housings Case 1 (similar to Housing A) and Case 2 (similar to Housing C) (Shimura, 1993). The result is shown in Fig.8.31. It was found that the mass flow gain factor is decreased and the cavitation compliance is increased by modifying the casing to Case 2 (similar to Housing C) both have the effect to suppress rotating cavitation. However, it is not explained why such changes occurred by a small modification of the housing.

8.2.2 Results with an inducer for LE7A LH2 turbopump

In order to examine the effects of housing enlargement at the inlet on another geometry of inducer, a series of tests were conducted on the original design of LE7A LH2 turbopump. It suffered also from rotating choke and it was eventually replaced with other design. The dimensions of the inducer are shown in Table 8.6. It has smaller blade angle at the inlet and hence smaller flow coefficient as compared with the LE7 LOX inducer mentioned in the preceding section. The geometry of the impeller is shown in Fig.8.32 and the test section in Fig.8.33. Eight housing geometries as shown in Fig.8.34 are tested. The “tightness” of the casing is decreased in the order Casing 0-Casing 7. The effects of tip clearance can be examined by comparing the results for Casing 0 and 3. Figure 8.35 shows typical spectrum of inlet pressure fluctuation, at the design flow coefficient $\phi = \phi_d = 0.067$ at 3000 rpm, for Casing 0, 3 and 6. Except for Casing 6, rotating cavitation denoted by R.C. first appears followed by attached asymmetric cavitation denoted by A.C.. For Casing 6, no rotating cavitation occurred. Figure 8.36
show the regions of rotating cavitation, attached asymmetric cavitation and cavitation surge with various casing geometries at three typical flow rates smaller than design ( $\phi = 0.060$ ), at design ( $\phi = \phi_d = 0.067$ ), and larger than design ( $\phi = 0.072$ ) flow coefficients. These results show that,

1. Enlarging the tip clearance is effective in reducing the rotating cavitation onset cavitation number for all flow rates (from comparison of Casing 0 and 3).

2. The casing enlargement at the inlet has favorable effects at higher flow coefficient but adverse effects at smaller flow coefficient (from comparisons of Casing 3, 4, and 5).

3. The overlapping of the enlarged part has favorable effects at higher flow rates. It appears suddenly at a certain flow coefficient as we increase the flow rate (from Casing 5 and 6).

4. At larger flow coefficient $\phi = 0.072$, the rotating cavitation onset cavitation number decreases as we decrease the “tightness” of the casing (in the order Casing 0, 1, …).

5. At larger flow coefficient $\phi = 0.072$, the transition cavitation number between rotating cavitation and attached asymmetric cavitation is increased as we move the enlargement point closer to the impeller (Casing 0, 1, and 2), or decreasing the amount of enlargement (Casing 5, 4, and 3).

6. At larger flow coefficient $\phi = 0.072$, there can be seen the tendency that the transition point between cavitation surge and attached asymmetric cavitation is increased as we reduce the “tightness” of the casing (Casing 0, 1, 2, …, 7).

Figure 8.37 shows the inlet backflow vortices for three casings, Casing 0, 3, and 6. It can be seen that the backflow vortex cavitation becomes longer as we reduce the “tightness” of the casing. Figure 8.38 shows the maximum length of the backflow vortex cavitation. At larger cavitation number $\sigma > 0.04$, the vortex length is not affected by the cavitation number, including the cases with rotating cavitation, and we have shorter vortices for tighter casings. When attached asymmetric cavitation appears, the backflow vortex cavitation suddenly becomes shorter. This suggests the abrupt change radial flow pattern.

The above results suggest favorable effects of backflow cavitation. At smaller flow coefficient, we do have more extensive backflow cavitation but rotating cavitation occurs at larger cavitation number. So, we cannot explain the mechanisms of the favorable effects of casing enlargements only from backflow cavitation.

Figure 8.39 and 8.40 shows radial distributions of averaged axial and tangential
velocity at design flow coefficient. This figure suggests the backflow regions in \( z/D \leq 0.402 \) for Casing 0 and \( z/D \leq 0.92 \) for Casing 6. The comparison with Fig. 8.36 shows that the backflow vortex cavitation actually extends beyond the region of backflow.

Figure 8.41 shows the pictures of tip leakage cavitation. For the case with smaller tip clearance (Casing 0), the density of shear cavitation is not very large but it increases as we increase the tip clearance (Casing 3). For the case with the overlap of the casing enlargement (Casing 6), the shear cavitation is limited to the region with enlarged part. For all cases, tip vortex cavitation extends downstream from the region of shear cavitation.

From the comparison of the results shown in this and the preceding sections, the effectiveness of casing enlargement differs significantly depending on the design of the inducer. So, we need to accumulate more data and make more efforts to find out the mechanism of the favorable effects.

8.3 Alternate leading edge cutback

As shown in Section 7.1, alternate blade cavitation occurs for inducers with even number of blades. Theoretically, alternate blade cavitation and rotating cavitation start to occur at similar cavitation number. However, in reality, alternate cavitation occurs at a cavitation number larger than the onset cavitation number of rotating cavitation, as shown in Fig. 8.42 (Goirand et al., 1992) and Section 8.1. Viewed from a frame rotating with the impeller, alternate blade cavitation is steady and brings about no unsteady force on the impeller. In addition, the blade forces are balanced and no radial force will be exerted on the shaft, for inducers with even number of blades equal or larger than 4. So, it will be beneficial if we can reduce the region of rotating cavitation by promoting alternate blade cavitation. With this motivation, a series of theoretical analyses and tests were conducted by cutting back the leading edge of a four bladed inducer alternately (Horiguti, et a., 2000, Yoshida, et al., 2001).

Figure 8.43 shows the inducers tested. They are named Inducer 0-0, Inducer 0-15, Inducer 0-30, and Inducer 0-50 after the amount of cutback. The blade is straight near the leading edge and the blade angle is not changed by the cutback. The specifications are shown in Table 8.7, and are completely the same as the inducers treated in Section 8.1, and the same as the three-bladed inducer mentioned in Section 3, except for the number of
blades. Figure 8.44 shows the non-cavitating performance of the four inducers. The performance is almost unchanged by the cutback.

Figure 8.45 shows typical spectra of inlet pressure fluctuation with Inducer 0-0 at $\phi = 0.08$ and $\phi = 0.085$. We observe the components of equal blade cavitation, alternate blade cavitation, rotating cavitation and cavitation surge. Figure 8.46 shows the length fluctuation on each blade measured at the tip, for the cases with Inducer 0-0, (1) $\phi = 0.08$ (a) equal length cavitation, (b),(c) alternate blade cavitation, (d) rotating cavitation and (2) $\phi = 0.085$, (e) alternate blade cavitation and (f) cavitation surge. Figure 8.47 shows the steady cavity length on each blade at the tip, as compared with the theoretical results treated in Section 7.1. It is shown that the cavity length can be correlated with $\sigma/2\alpha$ and that the alternate blade cavitation starts to develop when the cavity length reaches about 65% of the spacing, $h$, or $L0$. This is well simulated by the analysis but the value of $\sigma/2\alpha$ is quite different, possibly caused by the blade thickness and three dimensional effects. Figure 8.48 compares the propagation velocity ratio of 4-bladed inducer, Inducer 0-0, and 3-bladed inducer with the same specifications mentioned in Section 3, as well as the results of stability analysis mentioned in Section 7. We find that the 4-bladed inducer has a larger propagation velocity ratio than the 3-bladed inducer and that the propagation velocity ratio decreases as we decrease $\sigma/2\alpha$. These characteristics are well reproduced by the stability analyses except for the absolute value of $\sigma/2\alpha$.

Now we proceed to the effects of leading edge cutback. Figure 8.49 shows the inlet pressure spectra for the four inducers at $\phi = 0.074$ ($\phi_s = 0.078$). The ranges of various cavitation types are summarized in Fig.8.50. The range of rotating cavitation is decreased as we increase the amount of cutback, as expected. Cavitation surge are often observed at the boundaries of the cavitation types.

Interesting phenomena occurred with the leading edge cutback. Figure 8.51 shows the cavity length with smaller amount of cutback (Inducer 0-15) at smaller flow rate $\phi = 0.06$. At larger cavitation number the cavities are longer on longer (uncut) blades. However, at smaller cavitation number, we have longer cavity on shorter blade, and then longer cavities on longer blades again at extremely small cavitation number. We observe significant hysteresis between the cases when we decrease or increase the cavitation number. This behavior was predicted by the two dimensional steady flow calculations and stability analyses mentioned in Section 7, as shown in Fig.8.51 (c). From the
correlation with the theoretical results, we find that this strange behavior is closely related with alternate blade cavitation in equal blade inducers. Figure 8.52 shows the picture of these two types of cavitation at the same condition $\phi = 0.055$, $\sigma = 0.060$, with (a) increasing (b) decreasing cavitation number. Longer cavity is observed on (a) longer (b) shorter blades. We observe a surge mode oscillation (denoted by S.M.O.) at the boundary of these modes. The cavity length fluctuation under the surge mode oscillation is shown in Fig.8.53.

With larger amount of cutback (Inducer 0-30 and 0-50), the alternate blade cavitation switched directly to asymmetric attached cavitation without the range of rotating cavitation, as shown in Figs. 8.49 and 8.50. The development of the cavity length for Inducer 0-30 is shown in Fig. 8.54. Asymmetric cavitation occurs when the cavity on shorter blade becomes zero, after passing through a small region of cavitation surge. Figure 8.55 shows the development of cavity for Inducer 0-50, at smaller flow coefficient $\phi = 0.060$. As for the case of Inducer 0-30, no switching of cavity length as shown in Fig. 8.51 for Inducer 0-15 can be seen. The development of cavitation is well predicted by a two-dimensional calculation.

Figure 8.56 shows the suction performance and the regions of various cavitation instabilities. The regions of unsteady cavitation is significantly reduced as we increase the amount of cutback. However, with smaller amount cutback, we observe a region of surge mode oscillation associated with alternate blade cavitation, at smaller flow rate. In addition, the head start to decreases gradually at larger cavitation number for the inducers with larger amount of cutback. This is perhaps caused by increased loading near the leading edge of longer blades and we need to take this into consideration. From this point of view, inducers with alternately different amount of sweep might be recommended.

References in Section 8.


