SUPPRESSION OF CAVITATION SURGE OF A HELICAL INDUCER OCCURRING IN PARTIAL FLOW CONDITIONS

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ABSTRACT
Various cavitation instabilities such as rotating cavitation, cavitation surge and etc., have been serious problems in developing high-speed turbopump inducer. These instabilities should be avoided or settled for applying inducers widely in industrial fields. In the present study, the attempts to suppress the cavitation surge, which has been observed under partial flow conditions in our helical inducers, are made by installing the obstacle plates just upstream of inducer. Two kinds of obstacle plates were used; One of which is a ring-shaped axi-symmetric plate with blockage of 39% passage at the maximum near tip region to suppress the growth of inlet back flow under partial flow conditions. The other is to block the flow axi-asymmetrically up to 69% of flow passage and make the inlet distortion, being used to examine the suppressive effects of asymmetric inflow on the cavitation surge. In this paper, the effects of the proposed obstacle plates on the head-rise and suction performances of inducer are firstly reported. Then, the onset regions of cavitation surge with/without the obstacle plates are presented with spectrum analyses of measured wall pressures upstream and downstream of the inducer. Finally, the suppression mechanisms of those plates are discussed utilizing the high-speed video observations as well as casing pressure measurements.

INTRODUCTION
The installation of inducer just upstream of main impeller is known to be an efficient way to achieve the high suction performance for turbopumps, since an inducer is able to keep the high head-rise performance even in severe cavitating conditions. However, various cavitation instabilities such as rotating cavitation, cavitation surge and etc., have been serious problems by causing, for example, a harmful vibration in developing high-speed turbopump inducer for rocket launching engines. These instabilities should be avoided or settled for applying inducers more widely in the industrial fields.

The cavitation surge, being focused in the present study, is a viciously unstable phenomenon \([1]\), in which all blade cavities in the inducer become periodically elongated and shortened with the same phase and the flow rate is changed. When the frequency of the cavitation induced oscillation would coincide with the resonance of pump system, the operation of the pump system would become dangerous and the apparatus might be broken. Therefore, development of means to avoid and control cavitation surge phenomenon is required in realization of safety operation in wide flow rate range of small sized and high-speed turbopump. In previous report \([2]\) of authors the onset region of cavitation surge oscillation has been clarified for helical inducers with various blade angles types and an advance detection method of cavitation surge has been proposed.

On the other hand, there have been some trials to control cavitation instability phenomena passively. One of the well-known examples is Kamijo’s method \([3]\) to avoid the rotating cavitation by the suction pipe with weak contraction at the inducer inlet, being adopted for a turbopump inducer of H2 and H2A rocket engine. Kurokawa et al. \([4]\) has proposed an adoption of J-groove, meaning that lots of grooves are attached on the inner surface of suction pipe, to control a rotating back flow cavitation. Against these two control methods on improving a back flow in blade tip region of inducer inlet, Yoshida et al. \([5]\) has reported effectiveness of inducer with inequality of the pitch to make onset region of rotating cavitation narrower. This report demonstrates that an axi-asymmetry flow might be effective to control of cavitation induced oscillation. And Fujii et al. \([6]\) has shown experimentally that the onset region of rotating cavitation becomes narrower by making flow distortion of inducer inlet. These results encourage the following study of authors.
In the present study, effects of installation of obstacle plates at the inducer inlet on suppression of cavitation surge oscillation are investigated. Two types of plates, that is, ring-shaped axisymmetry type (RP) and axi-asymmetry type (BP) were tested. Changes of the onset region of cavitation surge are clarified in this paper and the mechanism of cavitation surge suppression is discussed with wall pressure measurements and observation of cavitation behaviors.

EXPERIMENTAL APPARATUS

Experiment has been done with a closed loop cavitation tunnel [2]. Figures 1 and 2 show schematic views of test section and inducer. The test inducer [1] is a flat plate helical type with blade number of 2, tip solidity of 2.0, blade tip angle of $\beta_{t}=14^\circ$, blade tip diameter of $D=64\text{mm}$ and hub-tip ratio of 0.47. The tip clearance between blade tip and suction casing surface is 0.5mm. Figure 3 shows the onset region of cavitation surge oscillation in the test inducer. The vertical and horizontal axes are dimensionless NPSH of $\tau=gH_{sv}/UT^2$ and flow coefficient of $\phi=Q/UA_T$, respectively, where $g$: gravitational acceleration, $H_{sv}$: NPSH, $Q$: flow rate, $A$: cross-sectional area of flow passage and $U_T$: inducer tip speed. In authors’ experiment [1], cavitation surge oscillation with low frequency of about 10Hz occurs at low flow rate range with inlet back flow at the inducer tip.

Obstacle plates, used for the control of cavitation surge, are installed at the upstream section of $0.555D$ from the inducer leading edge. Figure 4(a) shows ring-shaped axisymmetry obstacle plates (RP) with height of $h$ which is changed as the percentage of the blockage area to the flow passage being 13.7, 26.6 and 39.4%, respectively and named as RP014, RP027 and RP039. In the design of plates (RP), the blockage area of RP039 was, at first, chosen to be equivalent to a measured back flow region at $\phi=0.017$ under the non-cavitation condition based on the experimental result [1] that cavitation surge oscillation is deeply related with large-scale back flow of inducer inlet tip. Figure 4(b) shows another type of obstacle plate (BP), which is designed to make axi-asymmetric distorted flow at the inducer inlet. This idea was reduced from measured results [1] that the tail end of blade cavity on all blade surfaces simultaneously enters the inlet throat section and the three-dimensional inlet flow with back flow becomes unstable. BP027 and BP069 respectively block 26.5% and 69.4% of flow passage.

Figure 5 shows head-rise performances of inducer under non-cavitating condition with/without the obstacle plates, in which inducer head of $H$ was evaluated from static head difference between upstream section of the inlet contraction and downstream one of the outlet guide vanes and normalized as $\psi=gH/UT^2$. As can be seen in this figure, in the cases of all obstacles except BP069, head loss due to the installation of the obstacle plates is small over the wide range of flow rate and negligible especially at low flow rate range. Though there is a minor head difference in comparison between RP027 and BP027 with the same blockage, the negligible head loss is favorable as the target of controlling the cavitation surge oscillation is generally at low flow rate range. On the other hand, inducer head-rise of BP069 is apparently deteriorated all over the flow rate range. It is considered as the causes not only that the head loss due to the obstacle is increased but also that the theoretical head of inducer is deteriorated due to the large blockage area of the obstacle.

In the present study, the cavitation experiments were carried out with decreasing NPSH under the condition of constant rotating speed of 5000rpm and constant flow rate of $\phi$. The discussions are made using the measured static pressure variations at the casing wall in upstream and downstream of the inducer as well as the cavity behavior observations with the aid of a high-speed video camera.
RESULTS AND DISCUSSIONS

The effects of axi-symmetry obstacle plates

Figure 6 shows the suction performance of inducer with/without the axi-symmetric obstacle plates, RP014 to 039 at flow coefficients of $\phi=0.017$ and 0.008, where the cavitation surge oscillation was apparently observed in the case of no obstacle plates. The cavitation surge occurring points are depicted as solid symbols in this figure. Figure 6(a) shows the result at $\phi=0.017$. In the case of no obstacles, the inducer head begins to decrease at around $\tau=0.04$. With further decrease of $\tau$, the head continues to decrease gradually and the breakdown finally occurs at $\tau<0.01$. The occurring point of the head decrease at around $\tau=0.04$ coincides with the appearance of cavitation surge oscillation since this oscillation begins just after the blade cavity enters the inlet throat section of inducer. This tendency is seen also at $\phi=0.008$ as shown in Fig. 6(b).

On the other hand, results in the case of the axi-symmetry obstacles are different from each other, notwithstanding that the inducer head takes almost the same value as that without obstacles until around $\tau=0.04$. In the case of RP014, cavitation surge oscillation and head breakdown occur with higher value of $\tau$ than that in the case of no obstacles. In the cases of RP027 and 039, the cavitation surge never occurs at this flow rate in Fig. 6(a). For these cases, the head gradually decreases with decrease of $\tau$ and reaches the breakdown. In the case of RP039, the head breakdown NPSH becomes lower than that in the case of no obstacles.

Figure 6(b) shows results at $\phi=0.008$. In the weakly cavitating condition with $\tau>0.05$, the inducer head takes larger value in the case of obstacle plates than in the case of no obstacles and takes the maximum value with RP027, despite that it takes almost the same value with and without obstacles in non-cavitating condition. When NPSH is, then, further decreased, the character of head deterioration appears to differ among the RP plates. In the case of RP014 the cavitation surge oscillation occurs in higher range of $\tau$. The head breakdown occurs, however, at the same value of $\tau$ as in the case of no obstacles. In the case of RP027, the cavitation surge occurs in the very narrow range of $\tau$. The inducer head begins to decrease gradually from $\tau=0.05$, then the head breakdown finally occurs with the same value of $\tau$ as in the case of no obstacles. In the case of RP039, the cavitation surge oscillation never occurs and the head breakdown occurs at the lower value of $\tau$ than in the case of no obstacles.

Figure 7 summarizes the onset region of the cavitation surge with/without the axi-symmetric obstacle plates. Apparently, the installation of the axi-symmetric obstacle plates
has a potential to suppress the cavitation surge; the larger the blockage is, the narrower the onset region of cavitation surge becomes and the cavitation surge was never observed with RP039.

As shown in Fig. 8(a) the blade cavity in helical inducer with no obstacles appears in the blade tip region of inducer leading edge and grows downstream along the blade surface. Then, when the tail end of cavity enters the inlet throat section the cavitation surge oscillation occurs[2]. However, in the cases with the axi-symmetry obstacle plates as shown in Fig. 8(b), the blade cavity mainly grows near the middle and hub regions instead of tip even in the low NPSH conditions. The cavity near the tip side remains small and suddenly becomes large with head breakdown. This tendency can be seen with all the axi-symmetric obstacle plates and it is found that the larger the blockage ratio is the shorter the blade cavity near the tip region becomes. Figure 9 depicts time averaged static heads at the casing wall of inducer inlet between with and without the axi-symmetric obstacle plates. It is recognized from this figure that, in the cases with RP027 and RP039, the inlet wall head is higher than that without obstacle under the same NPSH condition and that the amount of head increase becomes larger as the blockade ratio becomes larger. Therefore, it would be considered that the increase of static head at the tip region, which might be caused as the stagnation of the back flow from the inducer to the axi-symmetry obstacle plates, would suppress the growth of the blade cavity near the blade tip of the inducer. This behavior would avoid to choke the inlet throat section and delay the head
breakdown in the case of RP039. The suppression mechanism of the cavitation surge oscillation with this type of obstacle plates will be investigated from flow measurement in the future work.

Figures 10(a) and (b) show the spectrum of the static head fluctuation at the inlet and outlet of the inducer without the obstacle and with RP027, respectively, at $\phi = 0.017$. In the case of no obstacles, a large head fluctuation (denoted as A in Fig. 10(a)) at the inducer inlet and outlet can be seen with very low frequency in low NPSH region, indicating the occurrence of the cavitation surge oscillation. On the other hand, in the case of RP027, no head fluctuations with low frequencies are observed; that is, the cavitation surge is apparently suppressed. However, seeing the spectrum of the inlet head fluctuations, a fluctuation component with small amplitude (denoted by B) is found for both cases with/without RP027 just before the occurrence of the cavitation surge in the case of no obstacles and its frequency decreases with decrease of NPSH. By measuring head fluctuations at two different circumferential locations, it was recognized that this pressure fluctuation component rotates in the circumferential direction and also from visual observations with a high-speed video camera that the blade cavities on the two blades fluctuated in turn with the same cycle. The head fluctuations, therefore, might be caused by the unsteady cavity behaviors. However no reasons to explain why the head fluctuation propagates circumferentially in the test helical inducers with two blades are found at the present stage.

**The effects of axi-asymmetric obstacle plates**

Figure 11 shows the suction performance curve at $\phi = 0.017$ with/without the axi-asymmetric obstacle plates, BP027 and BP069. The cavitation surge occurring points are depicted as solid symbols in this figure as the same manner in Fig. 6. In the case of BP027, almost the same inducer head in the range of around $\tau > 0.1$ is provided as the case of no obstacles and the head breakdown point is also the same. As NPSH is decreased from $\tau = 0.1$, however the inducer head is increased. The NPSH range of cavitation surge occurring becomes narrower while cavitation surge oscillation occurs in wide range of NPSH in the case of no obstacles.

In case of BP069, the inducer head under non-cavitating condition is low due to head loss of obstacle as mentioned in Fig.5. The head is slightly increased with decrease of NPSH from around $\tau = 0.14$ as the same tendency as the case of BP027. In this case there is no range of cavitation surge oscillation occurring. Head breakdown occurs at the same $\tau$ as others, notwithstanding the existence of head loss due to upstream...
Changes of static heads at the inducer inlet and blade cavity length with NPSH at the same flow rate of \( \phi = 0.017 \) as results of Fig. 11 are shown in Figs. 12 and 13, respectively. In the case of axi-asymmetric obstacle plates, the static head at the wall of inducer inlet is different peripherally due to influence of upstream obstacle. Therefore the static heads were measured at two different positions of no-obstacle (NBP) and obstacle (BP) sides. Though measured data of static head are not on a smooth curve and scattered with some errors as shown in Fig. 12, it is found from Fig. 12 that there is a tendency of higher head in BP side than that in NBP side. Therefore, seeing Fig. 13, in the case of no obstacles, each blade cavity in two bladed inducer is elongated by almost the same length with the decrease of NPSH. When the tail-ends of both blade cavities enter simultaneously the inlet throat section, inlet flow becomes choked and unstable and the back flow cavitation also appears at the inducer inlet at this flow condition. Then, cavitation surge oscillation occurs [1]. Widely changed solid line means this oscillation in the top of Fig. 13. On the other hand in the case of BP027, blade cavity length is varied at rotating position in one revolution of shaft. The minimum length of blade cavity appears when the blade leading edge passes in BP side while the maximum length appears in NBP side as shown in the bottom of Fig. 13. This behavior corresponds to the static head level in Fig. 12. Figure 14 demonstrates the difference of observed blade cavity in the case of BP027. It is considered from this result that, as the tail ends of blade cavity do not enter the inlet throat section simultaneously in the case of BP plates and one of throat section is never choked, the inlet flow might not become unstable and cavitation surge oscillation could be suppressed. However in the case of BP027 the oscillation appears in the range of \( \tau = 0.02 \) to 0.01. At the present stage no reasons on the oscillating mechanism are found and research work is still remained.

Figure 15 summarizes the onset region of the cavitation surge with/without the axi-asymmetric obstacle plates. The installation of axi-asymmetric obstacle plates has a potential to suppress the cavitation surge; the larger the blockage is, the narrower the onset region of cavitation surge becomes, and the cavitation surge was never observed with BP069. It is considered that there might be a sufficient amount of inlet flow distortion to suppress the oscillation.

However when this method would be adopted, inlet flow distortion might cause to increase the amplitude of the rotating and blade passing frequency components of head fluctuation and shaft vibration, which would depend on the operating flow rate, in addition to increasing head loss due to upstream obstacle. As one solution of this problem, there is adoption of gate valve installed upstream of inducer instead of obstacle plate. And when advance detection method [2] of cavitation surge is combined with it, it is able to use effectively only in the flow rate range in which cavitation surge occurs.

Figure 16 shows the spectrum of the static head fluctuation at the inlet and outlet of the inducer at \( \phi = 0.017 \) with BP027 and BP069. In the case of BP027, NPSH range of cavitation
surge occurring becomes narrower and the amplitude of fluctuation smaller. In the case of BP069, it is recognized from this figure that cavitation surge oscillation does not occur. In addition, the propagating fluctuation component appearing in the case of axi-symmetry obstacle plates (RP) is not observed in this case. There is a tendency of the amplitude of blade passing frequency (BPF) component at the inducer outlet becoming larger with installing axi-asymmetry obstacle plates.

CONCLUSION

Effects of installing two kinds of obstacle plates, which are axi-symmetry type and axi-asymmetry type, upstream of inducer on suction performance of the inducer and the cavitation surge phenomenon. The results are summarized as follows.

1) By installing axi-symmetry obstacle plate of ring type, NPSH and flow rate ranges of onset region of cavitation surge

![Fig.14 Observed blade cavity behaviors](image)

(a) NBP side

(b) BP side

Fig.14 Observed blade cavity behaviors In case of BP027 at $\phi=0.017$ and $\tau=0.02$

![Fig.15 Onset conditions of cavitation surge with axi-asymmetric plates BP027](image)

![Fig.16 Spectrum analyses of measured head fluctuation at BP side of inducer inlet and outlet with axi-asymmetric obstacle plates](image)

(a)With BP027

(b)With BP069

![Graph: Non-dimensional NPSH vs Flow coefficient](image)
oscillation occurring can be narrowed. However in this case undesired fluctuation component of static head with rotating cell may appear at the inducer inlet.

2) By installing axi-asymmetry obstacle plates, NPSH and flow rate ranges of cavitation surge oscillation occurring can be narrowed as well as axi-symmetry type. However as this type has some problems on blade loading fluctuation and shaft vibration, some caution should be required in its adoption.

3) When the obstacle plates with blockage factor of around 30% are adopted to suppress cavitation surge oscillation, the deteriorations of inducer head and suction performance are negligible by the installation though suppression effects become larger with increase of blockage factor.

Many obscure points such as the mechanism of control, the most suitable passage blockage factor and shape, the installation position and so on are still remained to investigate. Future works with flow measurement and numerical analysis will make clear them.

REFERENCES