Effect of suction pipeline resistance on cavitation surge in a turbopump with inducer

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Abstract. Cavitation surge is one of the vital flow instabilities in turbopumps, which should be avoided in actual operation. According to the past stability analyses, it is shown that the suction pipeline resistance has a suppression effect of cavitation surge. In the present study, we experimentally examined this effect by changing the suction pipeline resistance through the opening of butterfly valve installed upstream of inlet pipe. As a result, it was found that the onset range of cavitation surge could be significantly narrowed by the large suction pipeline resistance, which agreed with the above finding by the theoretical analyses.

1. Introduction

In turbopumps, more compact size and high power density are expected, which can be basically realized by increasing the rotational speed. However, with high rotational speed, cavitation often occurs, resulting in various problems such as deteriorations of head and efficiency, machine vibration, erosion, etc. Installing an inducer upstream of main impeller is effective way to improve the suction performance of turbopumps. However, it is known that various kinds of cavitation instabilities such as cavitation surge and rotating cavitation occur under operating conditions of low suction pressure [1], [2]. For long time operation with inducer, instability-free operation is expected as well as improved suction performance in the wide operating range from shut-off to over flow rates.

According to past stability analyses based on lumped parameter model (for example, [3], [4]), the onset criteria of cavitation surge have been derived in the simplest case neglecting discharge flow rate fluctuation as

\[
\frac{M}{K} > 2(\zeta_s + 1)\phi_{in}
\]

(1)

where \(M\) and \(K\) are the normalized mass flow gain factor and cavitation compliance respectively defined as the dynamic characteristics of cavitation volume against the flow incidence angle and suction pressure changes, \(\phi_{in}\) is the suction flow rate and the \(\zeta_s\) is the loss coefficient (flow resistance) of suction pipeline. Since the right hand side of Eq. (1) is generally small, it is understood that the cavitation surge is caused by the positive mass flow gain factor. The similar finding is also derived for rotating cavitation [4]. If we consider the cavity response quasi-statically, the condition of positive mass flow gain factor is easily satisfied as a quite natural consequence, suggesting us that the avoiding the occurrence of cavitation surge is not very easy. Eq. (1) also suggests that the resistance of suction pipeline is influential to the occurrence of cavitation surge; onset condition is relieved by increasing the resistance. Recently, Watanabe and Tsujimoto ([5], [6]) have proposed the modified onset criteria for cavitation surge...
considering the phase delay in cavitation characteristics, but it is still interesting to examine if the suction pipeline resistance affects the occurrence of cavitation surge in actual operation, i.e. in experiment.

In the present study, the effect of the suction pipeline resistance on the cavitation surge of a turbopump with inducer is experimentally investigated. To do so, a butterfly valve has been installed upstream of the suction pipe, and the valve opening is adjusted to add the suction pipeline resistance. The onset range of cavitation surge is investigated by the unsteady pressure measurements as well as by the visual observation using high-speed camera.

2. Experimental method

Figure 1 shows a closed loop cavitation tunnel in this study. Figure 2 shows the test section of the tunnel where a test turbopump is installed. The casing of inducer is made of acrylic resin for the visual access to the cavitating behaviour in the inducer. The tunnel is equipped with the water cooling system of working fluid, water, to enable to conduct the experiment under the constant temperature, although it is not shown in the figure. The pressure inside the tunnel can be adjusted by regulating the pressure inside the pressure tank by using a vacuum pump/ a compressor connected at the top of the tank. The rotational speed of the test pump \( N \) is kept constant by a frequency control inverter. The flow rate \( Q \), the head \( H \), the torque \( T \) are measured respectively by the electromagnetic flow meter (Keyence, FD-UH500H, 0-500 L/min, accuracy \( \pm 0.5\%\text{RO} \) installed downstream of test pump, static pressure transducer (GE Druck UNICK5000, 0-1 MPa differential, \( \pm 0.1\%\text{FS BSL} \)) which is connected to pressure taps \( \circ \) as shown in figure 2, and by the torque meter (MINEBEA TMNR-100NM, Capacity 100 Nm, accuracy \( \pm 0.5\%\text{RO} \)) installed between the driving shaft and the motor. The net positive suction head NPSH is calculated by the static pressure measured static head at the upstream pressure tap of \( \circ \) by static pressure transducer (GE Druck UNICK5000, 0-500 kPa absolute, \( \pm 0.1\%\text{FS BSL} \)) with considering the dynamic head based on the area-averaged axial velocity. NPSH is defined as follows

\[
\text{NPSH} = \frac{p_{\text{in}} - p_v}{\rho g} + \frac{1}{2g A_{in}^2} \frac{Q^2}{\rho g} \tag{2}
\]

where \( A_{in} \) is cross sectional area at measurement point of upstream pressure, \( p_{\text{in}} \) is static pressure at upstream of inducer, \( p_v \) is vapour pressure.

In the present study, a butterfly valve has been installed upstream of the test pump to adjust the suction pipeline resistance. The loss coefficient of suction pipeline \( \zeta_s \) is set to be 591, 59.8 and 4.38 by appropriately adjusting the opening of this valve, while the flow rate is set by the downstream flow control valve. Here, \( \zeta_s \) is defined as follows

\[
\zeta_s = \left( p_{\text{tank}} - p_{\text{in}} \right) \left( \frac{1}{2} \rho A_{in}^2 \right) \left( \frac{1}{2} \rho Q^2 \right) \tag{3}
\]

where \( p_{\text{tank}} \) is the pressure in the pressure tank at the same level of test section.

Table 1 shows the specification of the test pump which consists of a three bladed inducer and a semi-open type centrifugal main impeller. The hydraulic performance of the test pump with fully upstream valve opening condition (\( \zeta_s = 4.38 \)) is shown in figure 3. The flow coefficient \( \phi \), the head coefficient \( \psi \), the shaft power coefficient \( \lambda \) and the efficiency \( \eta \) have been defined as follows

\[
\phi = \frac{Q}{A U_2}, \quad \psi = \frac{H}{U_2^2 / 2g}, \quad \lambda = \frac{T \omega}{\rho A U_2^3}, \quad \eta = \frac{\rho g Q H}{T \omega} = \frac{\phi \psi}{2 \lambda} \tag{4}
\]

where \( A \) is the passage area of the main impeller exit, \( U_2 \) the peripheral velocity of impeller exit, \( \omega \) angular shaft speed, \( g \) gravitational acceleration. Subscript \( d \) denotes the design value, and the all plots in figure 3 are normalized by using the design values. We have confirmed that the upstream valve opening does not affect the hydraulic performance of the test pump. In our previous study [7], we have observed cavitation surge phenomenon at the flow rates mainly lower than \( \phi / \phi_d = 0.57 \).
Figure 1. Cavitation tunnel.

Figure 2. Test section.

Table 1. Specification of test pump.

| Inducer | Main impeller |
|----------------|---------------|
| Number of blades, $Z_i$ | 3 | Number of blades, $Z_m$ | 15 |
| Inlet hub-to tip ratio, $D_{h1}/D_t$ | 0.38 | Inner/outer diameter ratio, $D_{m1}/D_{m2}$ | 0.29 |
| Outlet hub-to tip ratio, $D_{h2}/D_t$ | 0.57 | Outlet blade height ratio, $b_{m2}/D_{m2}$ | 0.074 |
| Tip clearance ratio, $c/D_t$ | 0.003 | Outlet blade angle, $\beta_{mb2}$ [deg.] | 30 |
To evaluate the suction performance of turbopump, measurements are conducted with reducing the tunnel pressure by a vacuum pump connected to a pressure tank, while keeping the flow rate and rotational speed constant. The flow rate is adjusted by hand using the valve installed downstream. Degassed water whose dissolved oxygen content is about 5% of saturated value under the standard atmospheric condition is used. Experiments are conducted with rotational speed of $N=4,000 \text{ min}^{-1}$. The normalized NPSH $\tau$ is defined by using the inducer tip speed $U_t$ as

$$\tau = \frac{\text{NPSH}}{U_t^2/2g}$$  \hspace{1cm} (5)

In addition, we measure the unsteady pressures at 4 locations, two of which locate just upstream of inducer with different azimuth locations and another two on the scroll casing wall as shown in figure 2, to detect the occurrence of flow instabilities. Sampling frequency of the measurements is 5,000 Hz. The observation of cavitation in the inducer is also conducted through the acrylic casing by using a high-speed camera with the frame rate of 2,000 frames/sec.

There should be some experimental uncertainty due to several imperfectly controlled factors such as water quality (gas content and cavitation nuclei population), stepwise adjustment of tunnel pressure, valve handling and so on. Therefore, it is difficult for us to quantify the experimental uncertainty, but we have checked the repeatability in some suction pipeline resistance cases instead.

3. Results and discussion

Figure 4 shows the suction performance curves of the test pump at the all examined flow rates of $\phi/\phi_d = 0.071, 0.286, 0.571$ and $0.857$ with the suction pipeline resistance of $\xi_c=4.38, 59.8$ and $591$. Please note that NPSH is defined at just upstream of the inducer not of the upstream valve, whereas the head loss due to the valve at this low flow rate is not very large. It can be seen that the suction performance becomes better by increasing $\xi_c$, especially at the very low flow rate of $\phi/\phi_d = 0.071$. As will be shown later, the cavitation surge is suppressed or weakened by increasing the upstream resistance which seems to be the reason why the head is recovered. Since the head curve has a convex shape against the flow rate as shown in figure 3, the time-averaged head might decrease slightly even with the small flow rate fluctuation. With the increase of flow rate fluctuation due to the development of cavitation surge, the decrement of the time-averaged head increases, which could be the reason for the head decrease due to cavitation surge. The instantaneous head may significantly decrease at the moment with huge development of cavity during the cavitation surge, which would also contribute to the head decrease.
Figure 4. Suction performance curves of test pump at the flow rates of $\phi/\phi_d=0.071$, 0.286, 0.571 and 0.857 with the suction pipeline resistance of $\zeta_s=4.38$, 59.8 and 591.

Figure 5 shows the results of suction performance test at the flow rate of $\phi/\phi_d=0.071$ with the suction pipeline resistance of (a) $\zeta_s=4.38$, (b) 59.8 and (c) 591. The top figure shows the suction performance curve which is the same as in figure 4, and the middle and the bottom figures show the results of FFT analysis of pressure fluctuation measured upstream of inducer and on the scroll casing wall respectively. The vertical axis is the normalized frequency $f/f_n$ ($f_n$: shaft speed frequency), the horizontal axis is the normalized NPSH $\tau$, and the colour contour shows the normalized amplitude of pressure fluctuation defined by $|\Delta\psi| = |p_s'/(\rho U^2_z/2)|$ for upstream of inducer and $|\Delta\psi| = |p_s'/(\rho U^2_z/2)|$ for on the scroll casing wall. We also check the cross-correlation of pressure signals at the same streamwise location with different azimuth angles, from which we identify if the fluctuation is caused by rotating instabilities or axial (surge-like) instabilities (zero phase angle).

With the decrease of the normalized NPSH $\tau$, the component with normalized frequency of $f/f_n \approx 0.01$ as depicted by (i) in the figures is observed upstream of inducer and on the scroll casing wall. It is confirmed that the inlet flow rate also fluctuates with the same frequency. From phase analysis of the pressure fluctuation and visual observation, this phenomenon is found to be cavitation surge. In the case with $\zeta_s=4.38$, the cavitation surge is observed in the wide NPSH range, and it is seen that the head gradually decreases with the decrease of NPSH during the occurrence of cavitation surge. The onset range of cavitation surge is slightly reduced for $\zeta_s=59.8$ and is remarkably reduced for $\zeta_s=591$ (only in $0.013<\tau<0.025$). However, another fluctuation with the normalized frequency of $f/f_n \approx 0.05$-0.1 and its second harmonics appear instead as depicted by (ii) in figure 5(c). With the decrease of NPSH $\tau$, the frequency of this component gradually decreases, and from the phase analysis it has been also found to be the surge mode. The amplitude of this instability is significantly small compared with the cavitation surge (i). This component may be related to the head performance since, at this flow rate, the slope of head curve is small although it is still negative. The further investigation is needed to clarify this phenomena and its impact on the system stability.
Figure 5. Suction performance curve (Top) and FFT analyses of upstream (middle) and downstream (bottom) pressure fluctuations at $\phi/\phi_d=0.071$ with the pipeline resistance of $\zeta_s = 4.38$, 59.8 and 591.

Figure 6 shows the occurrence map of cavitation surge. The onset region is expressed by the NPSH region between upper and lower curves for each suction pipeline resistance case. With the increase of the pipeline resistance, the occurrence region of cavitation surge could be narrowed. This well agrees with the finding of past theoretical analyses, i.e. onset condition shown by Eq. (1). Especially for $\zeta_s = 591$, the occurrence region of cavitation surge is extremely limited.

4. Conclusions

In the present study, the effect of the suction pipeline resistance on the cavitation surge of a turbopump with inducer has been experimentally investigated. The obtained results are summarized as follows.

(1) By increasing the suction pipeline resistance, the onset region of cavitation surge can be reduced. This agrees with the finding proposed by the past stability analyses. Especially, with the huge suction pipeline resistance, cavitation surge is remarkably suppressed/weakened.

(2) With the suppression of cavitation surge by increasing the suction pipeline resistance, the decrease
of the head is relieved. This indicates that the gradual decrease of head in the suction performance curve is partly associated with the occurrence of cavitation surge.

(3) With the suppression of cavitation surge, another surge-like instability with higher frequency appears although its amplitude is small. This phenomenon may be related to the performance curve like conventional surge phenomenon although the slope of head curve is small negative.

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