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Effects of Flow Coefficient on Two-Bladed Inducer Alternate Blade Cavitation

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ABSTRACT

An experimental study has been conducted to investigate the effects of flow coefficient on two-bladed inducer alternate blade cavitation. Three flow coefficients (0.051, 0.057, and 0.062) and five cavitation number (0.070, 0.085, 0.100, 0.115, and 0.130) at each flow coefficient are studied. Five unsteady pressure transducers, four pneumatic pressure sensors, and a high-speed camera have been used for flow characterization. As flow coefficient decreases from 0.057 to 0.051, the cavitation number at which the maximum magnitude of alternate blade cavitation occurs and the maximum magnitude of alternate blade cavitation both increase. As flow coefficient increases from 0.057 to 0.062, the same trend appears. The cavitation number at which the maximum magnitude of alternate blade cavitation occurs and the maximum magnitude of alternate blade cavitation both increase.

INTRODUCTION

High speed centrifugal pumps, often used in the liquid rocket propulsion, can suffer from severe cavitation. Therefore, most modern turbopumps have an inducer, or an axial pump, at the main impeller inlet. The inducers often have large stagger angle and high solidity to be robust against cavitation. Thus, inducer increases the main impeller inlet pressure and decreases cavitation in the main impeller. Yet even the diminished cavitation in the inducer can still exert disadvantageous effects on the propulsion system. For example, inducer cavitation instability can cause severe vibration or system failure.

Cavitation instabilities have been categorized by their frequency, propagating direction, and spatial mode (Tsujimoto et al., 1997). Also, it has been shown that the number of inducer blades affects the type of cavitation instability. For a two-bladed inducer, a dominant cavitation instability is alternate blade cavitation (Huang et al., 1998). Under alternate blade cavitation, a larger cavity is developed on one blade, and a smaller cavity is developed on the other as shown in Fig. 1. This uneven cavity pattern is attached to the blades and thus appears steady in the rotating frame. Thus, pressure perturbation of shaft rotating frequency is strongly excited as in Fig. 2. To investigate the occurrence condition and the magnitude of the alternate blade cavitation, many experimental and numerical studies have been conducted (Huang et al., 1998; Kang et al., 2009). However, systematic investigation of alternate blade cavitation under various flow coefficients and cavitation numbers is still lacking.

Figure 1. Long and short cavity able to be observed at alternate blade cavitation on two-bladed inducer

Figure 2. Frequency spectrum of pressure perturbation with alternate blade cavitation

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Therefore, this paper experimentally examines two-bladed inducer alternate blade cavitation under various operating conditions. A two-bladed inducer is investigated under different flow coefficients and cavitation numbers. Unsteady pressure measurements are conducted for all experiments, and through Fourier transformation, the onset and post-onset behaviour of the alternate blade cavitation have been determined. Also, the cavities are visualized using high-speed camera to further analyse the effect of operating conditions on the alternate blade cavitation.

**EXPERIMENTAL SETUP**

Unsteady pressure measurements and visualization have been performed in the Seoul National University Water Tunnel (SNU-WT) test facility (Fig. 3). SNU-WT is designed to independently control the flow rate and inducer inlet pressure and can test various inducers and pumps of interest. To freely control the operating condition, following devices are used: a booster pump and control valve, which are used to control the flow rate up to 2,400 LPM; a vacuum pump attached to the water tank, which can decrease the inducer inlet pressure down to a minimum of 0.1 bar; a filtration chamber which ensures that particles larger than 1 micron are removed from the water tunnel inflow (Kim et al, 2019). Also, an acrylic transparent casing is installed in the inducer test section to provide optical access for the high-speed cameras. The two-bladed test inducer used in the experiments are shown in Fig. 4. Tests have been conducted for three values of flow coefficient \( \phi \equiv \frac{u_{axial}}{u_{tip}} = \frac{Q}{u_{tip}} \times 0.051, 0.057, \) and 0.062. At all flow coefficients, tests have been done under non-cavitating (cavitation number above 0.3) and cavitating conditions (cavitation number of 0.070, 0.085, 0.100, 0.115, and 0.130).

To measure unsteady pressure at the inducer inlet, five unsteady pressure transducers (Kulite HKM-375 model, 0–3.5 bar, 0.1% full scale accuracy) are flush-mounted at the inducer inlet casing 0.15 inducer diameter upstream from the inducer tip leading edge. Also, to determine cavitation number and to detect possible head breakdown of the inducer as the cavitation number decreases, four pneumatic pressure sensors (Druck PMP 5073 model, 0–2 bar, 0.04% full scale accuracy) are installed at 0.5 inducer diameter upstream and 1.0 inducer diameter downstream from the inducer tip leading edge, respectively. The unsteady pressure measurements are done at a sampling frequency of 2 kHz per channel via National Instruments PXIe-4492 module.

The cavitating inducer has been visualized with high-speed camera: Phantom v2640 (4,800 fps, 2,048 X 1,920 pixels per each frame) & NIKON AF-S VR Micro Nikkor ED 105mm f/2.8G lens. While the sampling frequencies for the unsteady pressure and video acquisition are much larger than the inducer rotating frequency, the unsteady pressure fluctuation and cavity structures are clearly resolved. The camera exposure time has been set a 0.2ms, and the inducer test section is illuminated via KOMI Cyclops I (90W, LED(White)) with front-lighting method.

![Figure 3. SNU water tunnel test facility](image1)

![Figure 4. Two-bladed test inducer (a) CAD model (b) Inducer on the test rig](image2)

**RESULTS AND DISCUSSION**

Typical unsteady pressure perturbation in frequency domain for a two-bladed inducer is shown in Fig. 5. Fig. 5(a) shows the frequency trace of non-cavitating condition, Fig. 5(b) shows the frequency trace when similar-size cavities are developed on both blades, and Fig. 5(c) shows the frequency trace under alternate blade cavitation (a larger cavity on one blade and smaller one on the other blade). From Fig. 2 and Fig. 5(c), the shaft rotating frequency is dominant under alternate blade cavitation. Therefore, the magnitude of the Fourier coefficient at the shaft rotating frequency is used to quantify the magnitude of alternate blade cavitation. Fig. 6 shows the magnitudes of the alternate blade cavitation for various cavitation numbers and \( \sigma \), the cavitation number at which the maximum magnitude of alternate blade cavitation occurs. As the flow decreases from 0.057 to 0.051, the cavitation number at which the maximum magnitude of alternate blade cavitation occurs and the maximum magnitude of alternate blade cavitation both increase. The results are consistent with the previous research (Tsujimoto et al., 1997; Pasini et al., 2018) which showed alternate blade cavitation appearing at higher cavitation number and having a larger magnitude at a lower flow coefficient. However, as the flow coefficient
increases from 0.057 to 0.062, again, the cavitation number at which the maximum magnitude of alternate blade cavitation occurs and the maximum magnitude of alternate blade cavitation both increase. This is a new finding.

To further analyze these two trends, cavities have been visualized. Figs. 7-9 show cavities for three different flow coefficients ($\phi = 0.051, 0.057, \text{and} 0.062$) under alternate blade cavitation. The figures show longer and the shorter cavities attached to the first and second blades, respectively. The cavity images under the cavitation number at which the test inducer shows the maximum magnitude of alternate blade cavitation are marked with red boxes.

For all flow coefficients, the maximum magnitude of alternate blade cavitation appears when the longer cavity’s trailing edge is formed near the leading edge of the following blade and the cavity collapses (Fig. 10). This phenomenon is consistent with the findings of Kang et al., 2009 & Franc et al., 2004, which are that i) the cavitation instability appears when there is an interaction between tip leakage vortex cavitation and the following blade; and ii) the cavity length is a key factor.

As the flow rate decreases from 0.057 to 0.051, the incidence at the blade leading edge increases (Kim et al., 2019), resulting in larger cavity for the flow coefficient of 0.051 at a given cavitation number. Thus, the lower flow rate increases cavitation number due to the increased incidence and larger cavity, which makes the inducer more susceptible to cavitation instability. However, between the flow coefficients of 0.057 and 0.062, the flow rate of 0.057 has smaller cavities than the flow rate of 0.062, as Figs. 6, 8, and 9 show. In this flow region, at the same cavitation number, smaller cavity is developed at the lower flow rate.

![Figure 5](image)

**Figure 5.** Normalized frequency spectrums of unsteady pressure perturbation for two-bladed inducer (a) Non-cavitating condition (b) cavitation condition with equal length cavity (c) cavitation condition with alternate blade cavitation

![Figure 6](image)

**Figure 6.** Magnitudes of alternate blade cavitation and $\sigma^*$ for 3 flow coefficients

<table>
<thead>
<tr>
<th>$\phi$</th>
<th>$\sigma^*$</th>
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<tbody>
<tr>
<td>0.051</td>
<td>0.100</td>
</tr>
<tr>
<td>0.057</td>
<td>0.070</td>
</tr>
<tr>
<td>0.062</td>
<td>0.085</td>
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Figure 7. Visualization of cavity for the case of $\phi = 0.051$

Figure 8. Visualization of cavity for the case of $\phi = 0.057$

Figure 9. Visualization of cavity for the case of $\phi = 0.062$
The existence of the critical flow coefficient, at which the tip leakage vortex cavitation is the smallest, can be explained as follows: as the flow coefficient decreases, blade loading increases and the velocity of the tip clearance flow also increases. This results in two competing effects regarding the generation of the tip leakage vortex cavitation. Firstly, because of the increased shear between the tip leakage flow and the main flow, vorticity at the shear layer increases and stronger vortex can be generated after the roll-up process. On the other hand, due to the increased velocity of the tip leakage flow, the distance between the succeeding vortex elements, which are generated via Kelvin-Helmholtz instability (whose roll-up is also described in Chen et al., 1991), increases and the vortices are getting harder to roll-up into a single vortex structure. Therefore, as the flow coefficient decreases, even though the effect of increasing vorticity will eventually be dominant, and the tip clearance vortex cavitation gets larger, critical flow coefficient could exist if the strengthened vortices are getting hard to roll-up. However, while the tip clearance vortex cavitation extents are similar for flow coefficients 0.051 and 0.062, the strength of the alternate blade cavitation is much larger at the flow coefficient of 0.051. This is due to the development of high-pressure region at the inducer throat area under low flow coefficient. At low flow coefficient, incidence increases, and high-pressure region is developed at the pressure side leading edge, which is at the inducer throat and causes the cavitation bubbles to collapse. This strong collapse of the bubble, or the occurrence of negative velocity divergence, just behind the leading edge of the adjacent blade induces axial flow and reduces the incidence of the adjacent blade, which is the driving mechanism of the alternate blade cavitation. Thus, the rapid collapse of the cavitation bubble at low flow coefficient according to the Rayleigh-Plesset equation results in stronger alternate blade cavitation compared to the high flow coefficient condition with the same cavity extent.

CONCLUSIONS

Alternate blade cavitation under three flow conditions have been measured and visualized in the SNU water tunnel test rig. For all 3 flow coefficients, the maximum magnitude of alternate blade cavitation occurs when the trailing edge of the longer cavity is formed near the following blade. For the flow coefficients of 0.051 and 0.057, the lower flow rate increases both the cavitation number at which the maximum magnitude of alternate blade cavitation occurs and the magnitude of corresponding cavitation. This is because the lower flow rate increases the incidence at the leading edge, resulting in the extended cavity length and collapse of the longer cavity and following blade. For the flow coefficients of 0.057 and 0.062, on the other hand, both the cavitation number at which the maximum magnitude of alternate blade cavitation occurs and the magnitude of corresponding cavitation increase as the flow rate increases.

References


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