Effects of Shaft Vibration on Occurrence of Asymmetric Cavitation in Inducer

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In the present study, I investigate the effects of shaft vibration on asymmetric cavitation, which is one of the instability phenomena on cavitating 3-bladed inducers. Inducer tests under various unbalance conditions are performed to clarify the effects of shaft vibration. The following results are obtained. (1) The amplitude of shaft vibration has a strong effect on the occurrence of asymmetric cavitation, and in an inducer with a large vibration amplitude, asymmetric cavitation easily occurs. (2) The phase of the small-tip clearance caused by shaft vibration coincides with the position of the small cavity. In this study, it is shown that suppression of shaft vibration amplitude is extremely important in preventing harmful asymmetric cavitation.

Key Words: Inducer, Cavitation, Vibration of Rotating Body, Pump, Asymmetric Cavitation

1. Introduction

An inducer is a type of axial impeller used with a turbopump that is required to run under ultralow inlet pressure, in which the occurrence of cavitation cannot be avoided. An inducer, usually installed before a centrifugal impeller, is used for the suction of fluid at ultralow inlet pressure and functions to increase the pressure sufficiently for a centrifugal impeller with a low suction performance to work with sufficient suction. With such a high-performance inducer, a pump can discharge high-pressure fluid while, generally, satisfying stringent requirements for suction performance. Currently, an inducer is used with a turbopump with rocket engines.

The inducer is capable of suction to a certain extent despite the occurrence of cavitation; however, it has the problem of causing unstable phenomena due to cavitation. Because unstable phenomena significantly affect the operational reliability of a turbopump, many studies have been conducted to analyze such phenomena and their solutions. Consequently, the following findings have been obtained. (1) There are many types of unstable phenomenon, such as cavitation surge, rotating cavitation and asymmetric cavitation. (2) A stepped inner diameter of the casing in the inducer inlet is effective in controlling rotating cavitation. (3) Theoretical analyses of unstable phenomena are in progress. However, because there are problems in analyzing three-dimensional and complicated flow involving cavitation, there are still unresolved issues for further studies.

I have analyzed the factors that affect the determination of whether asymmetric cavitation (AC) occurs. AC is an unstable phenomenon that occurs in inducers with three blades. In this phenomenon, the cavity of each blade becomes of uniform size as pressure is reduced and then stabilizes into a disproportionate size owing to some indetermined factors. Because unbalanced forces are applied to the inducer blades, the amplitude of shaft vibration, which is synchronized to the rotational speed, increases.

I faced a problem that there are two types of turbopump, in one, AC occurs, and in the other, AC dose not occur, although the pumps were fabricated using the same design. Initially, I thought that there are some unknown factors that determine the occurrence of AC. However, although I conducted various studies, I could not identify any specific factors for the occurrence. It may well be that AC is caused by some factor based on a rotating axis, because it may appear motionless if it is possible to observe from a certain point on the rotating axis. Accordingly, I conducted a test that involves the amplitude of unbalanced vibration to determine whether the amplitude significantly
affects the occurrence of AC.

Hashimoto et al.\(^{(7)}\) indicated previously that shaft vibration is considered to affect occurrence of AC. However, there has never been a report in which the amplitude of shaft vibration is investigated to determine its effect on the occurrence of AC.

I will describe in this paper the results of this investigation, along with my conclusions.

2. Symbol

\(Q/Qd\) : Ratio of \(Q\) (flow rate in test) to \(Qd\) (design flow rate according to rotational speed)

\(Q/Qd = \phi_{1t}/\phi_{1td}\)

\(\theta\) : Phase of maximum vibration amplitude at rotating coordinates

\(\sigma\) : Cavitation number

\(\sigma = (P_1 - P_v)/\rho W_1^2/2\)

\(P_1\) : Static pressure at inducer inlet

\(P_v\) : Vapor pressure

\(\rho\) : Fluid density

\(W_1\) : Relative velocity at inducer inlet tip

\(V_1\) : Axial velocity at inducer inlet

\(U_{1t}\) : Tip velocity at inducer inlet

\(\phi_{1t}\) : Flow coefficient at inducer inlet tip

\(\phi_{1t} = V_1/U_{1t}\)

\(\psi\) : Head coefficient

\(\psi = (P_{2T} - P_{1T})/(\rho U_1^2)\)

\(P_{2T}\) : Total pressure at inducer outlet

\(P_{1T}\) : Total pressure at inducer inlet

\(\psi_n\) : Head coefficient just before it decreases at \(\sigma = 0.055 \sim 0.06\)

3. Test

3.1 Test facility

The in-house inducer test facility is used for the test. Its outline is shown in Fig. 1. The test facility is a closed loop, using water as the testing fluid, in which the inducer is driven by an electric motor and circulates the water through a tank.

Rotational speed and flow rate are controlled by the opening of the outlet valve as a test condition and inlet pressure is reduced by using a vacuum pump.

3.2 Inducer/casing

The inducer shape and specifications used in the test are shown in Fig. 2 and Table 1, respectively, and the configuration of the casing is shown in Fig. 3. The inner diameter of the casing at the inducer inlet is wider than that of the inducer tip. Such a casing configuration at the inducer inlet is based on the results of the study by the group led by Dr. Kamijo\(^{(4)}\) and is effective in preventing rotating cavitation, although this is not the subject of the present study. Because the casing configuration is used, no occurrence of rotating cavitation was observed in the vicinity of the designed flow rate. In addition, the use of the configuration was effective in preventing rotating cavitation in all the tests; consequently, I was able to conduct all the tests paying careful attention to only AC.

3.3 Test method

The test was conducted by actively increasing shaft vibration amplitude to confirm the effect of shaft vibration on AC. I simply increased the shaft vibration by adding a
mass to unbalance the inducer. As shown in Fig. 4, I designed a tip nut for use at the point where the amount of mass unbalance is added. I chose four different amounts of unbalance between $+0$ and $+65.8$ g and conducted tests. The casing was made of transparent acrylic for observation of cavitation during the test. Shaft vibration was measured by a laser displacement sensor set outside the acrylic pipe. The exact location of the sensor, as shown in Fig. 4, was the hub side at the outlet where there is a smaller effect from the foam of cavitation.

4. Test Results and Analytical Insights

4.1 Amplitude of shaft vibration and its effect

The test flow rate was set based on $Q/Q_d = 1.01$ as a reference point in consideration of the fact that the actual inducer operating point is one percent higher than the designed value.

Figure 5 shows the test result obtained by changing the amount of mass unbalance added at $Q/Q_d = 1.01$. Usually, the occurrence of AC lowers the inducer head. The occurrence of AC was confirmed by the lowering of the head and visually observing the progress of cavitation. Figure 5 shows that no AC occurred in the case that the amount of unbalance added is $+0$ g, and the more the mass of unbalance added is increased, the more AC occurs in a wider range of cavitation number. This clearly shows that there is a significant correlation between the amplitude of shaft vibration and the occurrence of AC.

Figure 6 shows the result of the investigation of the occurrence of AC when flow rate is changed. In Fig. 6, the symbol ○ indicates the conditions under which AC occurs and × indicates otherwise. Although test data at $Q/Q_d > 1.07$ were not obtained due to the upper limit of the test facility, it is shown, within the scope of the test conducted, that the more the unbalance added increases, the more AC occurs in a wider flow rate range. As shown in Fig. 5, this result also indicates that there is a significant correlation between the amplitude of shaft vibration and the occurrence of AC.

Figure 7 shows how shaft vibration amplitude increases with the increase in the amount of unbalance added at $Q/Q_d = 1.01$ as a typical case. The vibration amplitude shown in Fig. 7 indicates a single amplitude and the amplitude in cavitation number ($\sigma > 0.06$) under which no AC occurs. At $Q/Q_d = 1.01$, AC occurs under the condition of more than $+21.5$ g, as shown in Figs. 5 and 6. This indicates that if there is shaft vibration of
more than approximately 200 µm, AC can occur because the amplitude under the condition of +21.5 g is approximately 200 µm. I have found that the AC occurs even at the relatively small vibration ratio of approx. 0.24 against tip clearance (The detailed threshold of the formation under this condition was not determined because no test was conducted under the condition between +0 g and +21.5 g).

It seems that the following mechanism is the reason that shaft vibration amplitude affects the occurrence of AC: Shaft vibration, the objective of this study, means the rotation of the axis due to unbalance and the corresponding vibration frequency synchronized to rotational speed. In this case, the tip clearance of the three blades rotates such that it is fixed in an unbalanced dimension. The dimensions of cavities are subject to the influence of the fluid that flows back to the inlet through the tip clearance. Therefore, it is thought that an unbalance in tip clearance causes an unbalanced backflow, consequently, the dimensions of the cavities become unbalanced and the unbalance induces the occurrence of AC. The higher the vibration amplitude, the larger the difference in tip clearance, and it is thought that the probability of the occurrence of AC increases.

It has been determined experimentally that increases in the height of the casing step at the inducer inlet and tip clearance prevent the occurrence of AC. On the basis of this knowledge obtained through this study, I presume that the reason for this is that increasing the aforementioned factors means a decrease in the amplitude of shaft vibration compared with increasing tip clearance, thus, the occurrence of the AC is prevented.

4.2 Phase of rotor vibration and its effect

I evaluate the relationship between the phase of shaft vibration and the distribution of unbalanced cavities due to AC. As stated earlier, it has been thought that an unbalance in tip clearance due to shaft vibration causes an unbalance in the dimensions of the cavities. On the basis of the value obtained from the measurement of shaft vibration amplitude, I searched for a phase where tip clearance maintains its minimum on the circuit of the inducer and compared the phase with the distribution of cavities confirmed through observation.

I show the result of the test conducted at \( Q/Q_d = 1.04 \). The reason I selected this condition is as follows: Figure 8 shows a comparison of suction performance for added unbalances of +0 g and +21.5 g. As shown in Fig. 6, no AC occurred under the condition of +0 g, whereas AC occurred under the condition of +21.5 g at \( Q/Q_d > 1.01 \). Because the magnitude of the occurrence of AC under the conditions of +21.5 g at \( Q/Q_d = 1.04 \) (the conditions under which AC occurs in a specific cavitation number) is similar to those for turbopump operation, I decide to show the results of the tests under these conditions.

As shown in Fig. 8, even in a region of cavitation number lower than that below which AC occurs, the cavitation shows instability compared with that under the condition of +0 g. A small shaft vibration in the whole of the suction performance curve seems to show a stable performance.

Figure 9 shows the amplitude and phase (at an angle where tip clearance becomes minimum) of shaft vibration under the conditions of +0 g and +21.5 g at \( Q/Q_d = 1.04 \). Figure 10 (a) shows a method of setting the phase \( \theta \), which is defined such that \( \theta = 0^\circ \) is set at the cardinal point of blade 1 and that \( \theta \) increases in the reverse direction of rotation.

As shown in Fig. 10 (b), the amplitude of shaft vibration is always as small as 50 µm under the condition of +0 g; thus, no AC occurs and no large change in vibration is observed until the condition of cavitation breakdown.

Meanwhile, because the amplitude of shaft vibration is as large as 200 µm under the condition of +21.5 g, AC occurs, and the amplitude and phase change. Because
the effect causing AC disappears at low cavitation number which causes AC to disappear, the amplitude returns to almost the original conditions. Specifically, the amplitude under the condition of $+21.5\, \text{g}$ changes with cavitation number from point A to point B (at the time of the occurrence of AC) to point C. The phase at point A is located near the leading edge of the blade 1. Because no AC occurs at point A, no large unbalance grows in the cavity. However, it was observed that the cavity at blade 3 is smaller than that at the other blades. Because AC occurs at point B, a definite difference in the dimensions of the cavity is formed. It was confirmed through observation that the cavity formed at blade 3 is small as well as that at point A. It was demonstrated that the phase at the location of the small tip clearance corresponds to the location near the trailing edge with a small cavity.

In addition, the following facts can be deduced from Fig. 10 (b).

a) From the difference between point $+0\, \text{g}$ and point A in the polar diagram: The effects of vibration amplitude and phase caused by unbalanced power are due to the increase in the amount of unbalance added.

b) From the difference between point A and point B in the polar diagram: The effects of the vibration amplitude and phase caused by fluid dynamics on to the inducer are due to the occurrence of AC.

c) From the difference between point B and point C in the polar diagram: The effects of the vibration amplitude and phase caused by the disappearance of fluid dynamics on the inducer are due to the nonoccurrence of AC.

5. Conclusion

An inducer test was conducted to confirm the effects of shaft vibration on AC formed in the inducer. The following are the results of the test.

1. There is a significant correlation between the amplitude of the shaft vibration and AC. The bigger the amplitude becomes, the more AC is formed.

2. The phase where the tip clearance becomes minimum due to amplitude corresponds to the location near the trailing edge of the small cavity.

Consequently, it is clear that not only the design of the inducer and casing but also the reduction in shaft vibration during operation is required in order to avoid the occurrence of AC.

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