Influence of Rotational Speed of an Inducer on the Propagation Velocity of Super-synchronous Rotating Cavitation

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Abstract. The phenomenon that a cavity rotates faster than the rotational speed of the pump in the direction of rotation is called super-synchronous rotating cavitation (super-S RC). It is known that super-S RC is often observed in rocket turbopumps, but that it is rare to be observed in industrial pumps. Therefore, we form a hypothesis that its occurrence is related to the rotational speed of the pump. In this study, experiments of an inducer were conducted at four rotational speeds at Kakuda Space Center in the Japan Aerospace Exploration Agency. The pressure fluctuation and the rotor vibration were measured, and the propagation velocity ratio of super-S RC and the frequency of unsteady cavitation in the super-S RC were determined at each rotational speed. As a result, when the cavitation number is the same, the propagation velocity ratio is almost the same regardless of the rotational speed of the inducer. It means that the faster the rotational speed, the faster the unsteady cavitation oscillates in the inducer despite the condition of the same cavitation number. It indicates that rotating cavitation does not occur under a certain rotational speed because of the limitation of the frequency of unsteady cavitation, which is known in hydrofoil.

1. Introduction
Cavitation is a phase change phenomenon from liquid phase to gas phase by reduction of pressure. It is often observed in high-speed fluid machinery such as pumps and causes vibration, noise, and a decrease of efficiency. Cavitation instabilities in pumps is classified into the two types, cavitation surge [1] and rotating cavitation [2]. In particular, the phenomenon that a cavity rotates faster than the rotational speed of the pump in the direction of rotation is called "Super-synchronous rotating cavitation" (super-S RC). There are many reports about super-S RC in the inducer of rocket turbopumps. The rotational speed of the rocket turbopump in which the super-S RC have been observed are from 13,000 to 30,000 rpm in the actual machines [3,4,5], and from 4,000 to 10,000 rpm in the water experiments[6,7,8]. However, it is generally rare to be observed in industrial pumps, which rotates at low rotational speed. For this reason, we assumed that its occurrence involves the rotational speed of pumps.

In this study, the experiments of the inducer were conducted in order to compare the differences in the characteristics of super-S RC by the difference of rotational speed. The experiments were performed...
using the water cavitation tunnel at Kakuda Space Center, the Japan Aerospace Exploration Agency (JAXA).

2. Apparatus and procedure

2.1. Test section and test facility

Figure 1 shows the test inducer. The test inducer was designed to be similar to an oxygen turbopump inducer with three blades. Its tip diameter is 152 mm. The tip clearance is 0.75 mm. The water cavitation tunnel is shown in figure 2. The test inducer is driven at constant rotational speed by a DC motor and electrical control system, and the rotational speed was measured by a magneto-type detector. The temperature of loop water is held constant by the heat exchanger. The flow rate is changed by flow control valves and is measured by an ultrasonic flow meter. The inlet pressure is controlled by a pressurization-depressurization piston. The pressure fluctuation was measured by pressure transducers to investigate the behavior of cavitation instability. The rotor vibration of the shaft was measured by eddy current type displacement sensors. The rotor vibration and the pressure fluctuation were recorded with an FM data recorder. This sampling frequency was 10 kHz.

![Test inducer](image1.png)

Figure 1. Test inducer.

![Water cavitation tunnel at JAXA Kakuda Space Center](image2.png)

Figure 2. Water cavitation tunnel at JAXA Kakuda Space Center.

2.2. Procedure

To compare differences by rotational speed of the inducer, the experiments were conducted at four rotational speeds (3000, 4000, 5000, 6000 rpm) and the constant flow rate ($Q/Q_d = 1.10$, where $Q_d$ is design flow rate) while the inlet pressure was reduced gradually from 0.30 MPa to 0.02 MPa. In this study, cavitation number $\sigma$ was used for the parameter which shows the possibility of cavitation. It is defined as follow:

$$\sigma = \frac{p_{in} - p_v}{0.5 \rho U^2}$$

(1)

Where $p_{in}$ is inlet static pressure [Pa], $p_v$ is saturated vapour pressure [Pa], $\rho$ is density of liquid [kg/m$^3$] and $U$ is inflow relative velocity on inducer tip [m/s]. Cavitation number is a dimensionless parameter that represents the ease of occurrence of cavity. The smaller the cavitation number, the larger the cavity, and when cavitation number is the same in the same flow field, similar cavities are generated. Head coefficient is defined as in equation (2).

$$\psi = \frac{(p_{out} + 0.5 \rho v_{out}^2) - (p_{in} + 0.5 \rho v_{in}^2)}{\rho u_t^2}$$

(2)

Where $p_{out}$ is outlet static pressure [Pa], $v_{out}$ and $v_{in}$ are axial flow velocity at the outlet and inlet [m/s], $u_t$ is inducer tip velocity [m/s].
3. Results and discussion

3.1. Suction performance

Figure 3 shows the difference in the suction performance of each rotational speed. There is not much difference in head coefficient $\psi$ between rotational speeds 3000 rpm to 6000 rpm. The pressure could not be reduced until head drop at 3000 rpm and 4000 rpm due to the equipment capacity. However, almost the same head drop is shown at 5000 rpm and 6000 rpm. At 5000 rpm, severe head oscillation is caused by strong oscillation of outlet pressure before the head is dropped, the cause of which is currently under investigation.

![Figure 3. Suction performance.](image)

3.2. Comparison of the power spectrum

Figure 4 shows the power spectrum of rotor vibration at the inducer for four rotational speeds, respectively. Rotational frequency $f_N$ of each rotational speed is 50, 66.6, 83.3, 100 Hz. The power spectra show peaks at a little higher frequency than rotational frequency, which are the frequency of super-S RC $f_{rot}$. Figure 5 shows the power spectrum in the red square of figure 4 (c) in the narrowed vertical axis range. Weak and scattered peaks are observed in figure 5, which is estimated to be weakened by severe pressure oscillation in the outlet pipe system through analysis of other data. However, these peaks can be considered super-S RC in terms of frequency. The values of these weak peaks are shown by open circles or bars in following graphs in order to distinguish it from the clear $f_{rot}$.
Figure 4. Power spectrum of the rotor vibration.

Figure 5. Power spectrum of red area of 5000 rpm.

Figure 6 and 7 show the change of propagation velocity ratio and frequency of unsteady cavitation in super-S RC. The propagation velocity ratio and frequency of unsteady cavitation are given by $f_{rot}/f_N$ and $f_{rot} - f_N$. Regardless of the rotational speed of the inducer, the propagation velocity ratio is the same when the cavitation number is the same. And the faster rotational speed, the faster unsteady cavitation oscillates despite the condition of the same cavitation number.

Figure 6. Comparison of the propagation velocity ratio $f_{rot}/f_N$ of super-S RC.

Figure 7. Comparison of the frequency of unsteady cavitation $f_{rot} - f_N$ in super-S RC.
Figures 8, 9 and 10 show the area of cavitation number, propagation velocity ratio and frequency of unsteady cavitation, respectively. However, at 3000rpm, the decompression limit was reached during the occurrence of super-S RC, so the lower limit value of super-S RC is unknown, and it is represented by a dotted line. When focusing on the inception of super-S RC, it is found that cavitation numbers and propagation velocity ratios of each rotational speed are close, and the frequency of unsteady cavitation is approximately proportional. Therefore, a certain propagation velocity ratio or cavitation number seems to be the trigger of super-S RC. Moreover, usually in a hydrofoil, the longer the cavity length is, the slower the cavity oscillates. This is the oscillation characteristic of unsteady cavitation, which is well-known in hydrofoil experiments [9-12]. There should be a lower limit on the frequency of unsteady cavitation since there is an upper limit on the cavity length in the hydrofoil. The similar characteristics are supposed to appear in the inducer. From the above, it is shown that the range of frequency of unsteady cavitation in super-S RC is smaller when the rotational speed of the inducer is slower. Therefore, it is supposed that super-S RC does not occur under a certain rotational speed.

Figure 8. The area of cavitation number.

Figure 9. The area of the propagation velocity ratio.

Figure 10. The area of the frequency of unsteady cavitation.

4. Conclusion
In this study, experiments of an inducer were conducted at four rotational speed and the influence of the rotational speed of an inducer on super-S RC was investigated. The results are summarized as follows. The head coefficient is almost the same. In addition, almost the same head drop is shown at 5000 rpm and 6000 rpm.
The propagation velocity ratio is almost the same at the condition of the same cavitation number regardless of the difference of the rotational speed of the inducer.

At the beginning of super-S RC, the propagation velocity ratio and cavitation number of each rotational speed are the same. Therefore, the upper limit of the occasion of super-S RC seems to be determined by the propagation velocity ratio or cavitation number. Additionally, the same propagation velocity ratio in the inception means that cavity oscillates in higher frequency in high rotational speed condition than in the lower rotational speed condition in the inception of super-S RC.

At the end of super-S RC, there should be a lower limit on the frequency of unsteady cavitation since there is an upper limit on the cavity length. Therefore, it is supposed that there is a lower limit of the rotational speed where super-S RC is caused.

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