Experimental Study on Cavitation Instabilities of Small Turbopump for Rocket Engine* 

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A cavitation test was carried out for a fuel pump designated for a liquid rocket engine. The fuel enters the pump perpendicular to the direction of the shaft. Cavitation instabilities were investigated using an accelerometer installed on the pump casing and pressure transducers placed at the inlet and the outlet of the pump. Rotating cavitation appeared at a frequency faster than the pump rotational frequency, and cavitation surge appeared at a slower frequency. Cavitation surge appeared within the range of cavitation coefficients where rotating cavitation occurred. The frequencies of the rotating cavitation and the cavitation surge decreased as the cavitation coefficient and flow rate decreased, and were proportional to the rotational speed.

Key Words: Turbopump, Cavitation Instability, Fuel Pump, Rotating Cavitation, Cavitation Surge

Nomenclature

| Symbol | Definition |
|--------|------------|
| ACC    | acceleration amplitude |
| CS     | cavitation surge |
| f_RC   | frequency of rotating cavitation |
| g      | acceleration of gravity |
| H      | pump head |
| N      | rotational frequency of pump |
| p'     | pressure fluctuation |
| p_00   | total pressure at pump inlet |
| p_v    | vapor pressure |
| RC     | rotating cavitation |
| RMS    | root mean square |
| u_11   | inducer inlet tip speed |
| u_22   | impeller outlet tip speed |
| Δψ     | pressure fluctuation coefficient, 2p' / ρu_22^2 |
| μ      | fluid density |
| σ      | cavitation coefficient, 2g(NPSH) / u_11^2 |
| Ψ      | head coefficient, 2gH / u_22^2 |

1. Introduction

Pumps for liquid rocket engines rotate much faster than industrial pumps in order to reduce weight, so cavitation is inevitable. Inducers which are aimed to improve cavitation performance are installed upstream of the main impeller. However, cavitation instabilities such as rotating cavitation (RC), cavitation surge (CS), attached cavitation, surge mode oscillation, and so on have been observed in turbopumps.

It has been found that the speed of the RC is slightly faster than the rotational speed of the pump inducer blades.1-2) Tsujimoto et al.3) investigated various forms of oscillating cavitation at a three bladed inducer. The number of inducer blades affects the cavitation instability. RC is not observed at two bladed inducers4,5) but is observed at many three bladed inducers1-3,6-9) and at some four bladed inducers10,11)

CS has been studied by several researchers2,3,6,7) CS is observed by Zoladz6) at the oxidizer pump inducer of a Fastrac engine, and its frequency was 3(f_RC − N). In the CS observed by Zoladz6) there was no phase difference between two pressure signals measured around the circumference of the inlet of the inducer. However, generally, there is phase difference between two circumferentially located pressure signals in RC, and it means that the cell rotates with the inducer. However, Shimagaki et al.7) observed the phase difference in CS and addressed that CS rotates at 60% of the rotational speed of the inducer. Tsujimoto et al.3) observed the CS of (f_RC − N) component in a scale model of an LE-7 LOX pump inducer and reported that this component does not rotate. Hashimoto et al.3) tested an inducer similar to an LE-7 LOX main pump inducer and observed three CS components: (f_RC − N), 2(f_RC − N), and 3(f_RC − N).

Fast-response sensors such as pressure transducers, displacement sensors, and accelerometers are used in research on cavitation instabilities. In many experiments, fast-response pressure transducers2,5,8,10,11) installed at the inducer inlet have been used. In some cases, displacement sensors installed on the pump shaft have been used as well as an accelerometer9) installed on the pump casing. A six-component balance mounted on the shaft to measure forces and moments has also been used, in Coutier-Delgosha et al.11) In this paper, cavitation test results of a small fuel pump for a liquid rocket engine are presented and the cavitation instabilities are discussed.

2. Test Facility and Test Article

Hydrodynamic tests of pumps were performed at a pump test facility. The pump was driven by an electric motor. Cold
water was used as the working fluid. The facility was composed of a water tank of 3.3 m$^3$ volume, an electric motor of 200 kW power, a gear box, a torque meter, a flow control valve, and a flow meter. The pressure of the water tank was adjusted by a vacuum pump and compressed nitrogen gas. The outline of the facility is shown in Fig. 1.

An accelerometer and a few fast-response pressure transducers were used to investigate the cavitation instability of the pump. The accelerometer was installed on the volute casing, that is, on the housing of the bearing on which the axial force of the pump is supported. Two pressure transducers, 120 degrees apart, were installed at the inlet pipe of the pump. Additionally, one pressure transducer was installed at the outlet pipe. The pressure transducers were mounted flush to the inner walls of the pipes.

The turbopump under development is applicable to a gas generator cycle liquid rocket engine with about 70 kN of thrust. The propellants are liquid oxygen and kerosene. The turbopump is composed of an oxidizer pump, a fuel pump, and a turbine, all aligned along a single axis. The test article is a fuel pump of the turbopump assembly. The pump is composed of an inducer, a centrifugal impeller, inlet casing, and volute casing. The specific speed of the pump is 0.19 in non-dimension (or, 80 in dimension of rpm, m$^3$/min, m) and the nominal rotational speed is 27,000 rpm. The nominal cavitation coefficient of the pump is 0.12.

The fuel flows into the pump, perpendicular to the direction of the shaft. Six ribs are circumferentially installed in the flow passage of the pump inlet casing, supporting uniform inflow and the structural strength of the casing. The rotational speed of the pump was kept constant during the test. It was 20,300 rpm in most cases of this study, and in one case 17,000 rpm was added to observe the effect of rotational speed. The pump under test is shown in Fig. 2, where the fast-response sensors are also marked.

The impeller has twelve blades: six main blades and six splitter blades. The inducer, with three swept-back helical blades, has the following features: flow coefficient of 0.09, inlet tip blade angle of 8.8 degree, ratio of the tip clearance to the inlet blade height of 0.024, and tip solidity of 4.0.

It should be noted that there are two differences between this study and other studies in terms of the experimental setup. First, the fluid enters the pump perpendicular to the direction of the shaft in this study, while it enters axially in most cases. Second, the fast-response pressure transducers were installed far upstream from the inducer (3.5 times the inducer diameter from the inducer inlet tip) due to the configuration of vertical inflow, whereas transducers are installed very close to the inducer (less than half the inducer diameter) in most cases.

3. Results and Discussion

The non-cavitating performance of the pump is presented in Fig. 3. The flow ratio is the ratio of the measured flow coefficient to the nominal flow coefficient. The head coefficient linearly decreases with the flow ratio, within the measured flow range. The cavitating performance curves of the pump, measured at three flow rate conditions, are presented in Fig. 4. The head, remaining constant with a decreasing cavitation coefficient, abruptly decreases near the critical cavitation coefficient. The cavitation tests are processed until the
head breaks down by more than 25%. The head-breakdown cavitation coefficient decreases with a decreasing flow rate.

The spectrum of the acceleration on the pump casing, at the flow ratio of 1.01, is presented by a contour plot in Fig. 5, where N is the pump rotational frequency of 20,300 rpm, or 338 Hz. The components of the rotational frequency 1N and its harmonics are observed, and their frequencies keep constant with the cavitation coefficient because the rotational speed of the pump remains constant during the tests. Two interesting components are observed. One component, slightly faster than the pump rotational frequency, is observed at $\sigma = 0.051 - 0.088$. This component is called the rotating cavitation (RC). Additionally, the components with repeated frequencies, or adding ($f_{RC} - N$) to the 1N and its harmonics, are observed. Another component, slower than the rotational frequency (about half of the rotational frequency), is observed at $\sigma = 0.060 - 0.076$. This component is called the cavitation surge (CS), and is identical to the CS of Zoladz. A discussion about the frequencies of RC and CS is found later.

The amplitudes of the acceleration associated with three interesting components in Fig. 5 (RC, CS, 1N) are plotted as a function of the cavitation coefficient in Fig. 6. The acceleration amplitude of the RC has the maximum at about $\sigma = 0.076$, and that of the CS has the maximum at $\sigma = 0.062$. The 1N component has dips at the cavitation coefficient of the appearance and the disappearance of RC, and shows a sharp decrease at the head breakdown. The peak acceleration amplitude of the RC at $\sigma = 0.076$ is the highest of the three interesting components.

The frequencies corresponding to RC and CS in Fig. 5 are shown in Fig. 7. RC appears at the frequency ratio of $f/N = 1.11 - 1.23$, and its frequency decreases as the cavitation coefficient decreases. CS appears at $f/N = 0.43 - 0.58$, and its frequency also decreases as the cavitation coefficient decreases. $3(f_{RC} - N)$ is also plotted, and it coincides well with the CS frequency. The component with $3(f_{RC} - N)$ frequency is also observed in several other studies.

Cavitation instabilities like RC and CS are detected by fast-response pressure transducers as well as the accelerometer. The spectrum of pressure fluctuation at the pump inlet is shown in Fig. 8. RC and CS, which are observed from the acceleration signal, are also detected. Considering the vertical inflow to the pump, the ribs in the inlet flow passage, and the distance between the pressure transducer and the inductor, it is surprising to observe RC from the pressure fluctuation at the inlet. The spectrum of pressure fluctuation at the pump outlet is shown in Fig. 9, where RC is not ob-
served, but a weak sign of CS is detected. The frequency of 6N is prominent through the cavitation coefficient.

The cross spectrum of the adjacent pressure signals at the pump inlet was analyzed, but the phase was zero even at RC, which implies that the cell of RC does not rotate any more at the measured section. The phase for the CS was also zero. From the frequency of CS, or 3(fRC - N), it seems that CS results from the interference between the RC frequency and the rotational frequency of pump. However, the origin of CS is not clarified in this study; further investigation is necessary to identify the origin.

The root mean square (RMS) of the acceleration and the pressure fluctuations is shown in Fig. 10. The acceleration and the outlet pressure fluctuation abruptly increase near the head breakdown. However, the inlet pressure fluctuation decreases continuously as the cavitation coefficient decreases.

The effect of the flow rate on the cavitation instability is investigated. The spectrum of acceleration at a low flow condition, with a flow ratio of 0.89, is shown in Fig. 11, where RC and CS are also observed. The cavitation coefficient range of the occurrence of RC and CS at flow ratio 0.89 is wider than at flow ratio 1.01. The spectrum at a high flow condition, with flow ratio of 1.11, is shown in Fig. 12, where RC is detected but not CS. The cavitation coefficient range of the occurrence of RC at flow ratio 1.11 becomes narrower than at flow ratio 1.01. In summary, the cavitation coefficient range of the occurrence of RC gets narrower as the flow rate
increases. The frequencies of RC and CS are plotted as a function of the flow ratio in Fig. 13. At the same cavitation coefficient, the frequencies of RC and CS decrease as flow rate decreases. Brennen\textsuperscript{12)} also addresses that the decrease of cavitation surge frequency with decreasing flow rate seems certain to be the result of an increasing volume of cavitation and increasing compliance as the blades are loaded up at lower flow ratios.

The effect of the rotational speed is also investigated. The frequencies of RC and CS at two rotational speeds are shown in Fig. 14, where the two data agree well. The figure suggests that the frequencies of RC and CS are proportional to the rotational speed.

4. Conclusion

From the acceleration and the pressure fluctuation at nominal flow rate condition, it is observed that the rotating cavitation occurs at $\sigma = 0.051–0.088$ and the cavitation surge occurs at $\sigma = 0.060–0.076$. The cavitation surge occurs during the occurrence of the rotating cavitation. The rotating cavitation frequency is 1.11–1.23 times of the rotational frequency, and decreases as the cavitation coefficient decreases. The cavitation surge frequency is 0.43–0.58 times the rotational frequency, and also decreases as the cavitation coefficient decreases. The cavitation coefficient range of the occurrence of the rotating cavitation gets narrower as the flow rate increases. The frequencies of rotating cavitation and cavitation surge decrease as the flow rate decreases, and are proportional to the rotational speed. Further investigation is necessary to identify the origin of cavitation surge.

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