Unsteady Behavior of Asymmetric Cavitation in a 3-Bladed Inducer

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Abstract
Blade stresses of 3-bladed inducer were measured under various cavitation numbers. At the transition point from asymmetric cavitation to cavitation surge, the asymmetric cavitation pattern moves irregularly. The blade stress near the leading edge fluctuates between zero and a value observed under the non-cavitating condition. Under the firing test of LE-7A engine for H-IIA rocket, similar phenomenon was observed through the measurement of shaft vibration. The result of the firing test is also shown for comparison.

1. Introduction
Cavitation instabilities such as rotating cavitation and cavitation surge are one of the major concerns in the turbopump inducers for rocket engines (Acosta 1958, Kamijo et al. 1977, Young 1972). In addition to these cavitation instabilities, asymmetric cavitation with uneven cavities on each blade is often observed in 3-bladed inducer at relatively low cavitation number (Kamijo et al. 1977, Tsujimoto et al. 1997). Asymmetric cavitation causes a large amplitude synchronous shaft vibration, although the blade stress fluctuation does not occur since the relative flow is steady. The mean blade stresses, i.e. time averaged blade stresses, near the leading edge are largely different among three blades because of the asymmetry of the cavities on each blade (Azuma et al. 2001).

Present paper reports a phenomenon in which the pattern of the cavity on each blade changes irregularly with keeping the asymmetric cavitation pattern. The characteristics of this phenomenon were examined through the measurements of the pressure fluctuations on casing wall and the blade stress fluctuations. In addition, this phenomenon was observed in the firing test of LE-7A engine for H-IIA rocket. The result of this firing test is also shown in the present paper.

2. Nomenclature

\( D \) = inducer diameter
\( f \) = frequency of pressure fluctuations or blade stress fluctuations
\( f_n \) = shaft rotational frequency
\( p_1 \) = pressure at inlet
\( p_{1t} \) = total pressure at inlet
\( p_2 \) = pressure at outlet
\( p_v \) = vapor pressure
\( \Delta p \) = pressure fluctuation (Zero-to-Peak) or pressure difference
\( U_t \) = peripheral speed of inducer tip = \( \pi D f_n \)
\( v_1 \) = axial velocity at inducer inlet = flow rate / inlet area
\( \beta \) = blade angle
\( \beta_t \) = tip blade angle (\( \beta_{t1} \): inlet tip blade angle, \( \beta_{t2} \): outlet tip blade angle)
\( \mu \) = pressure gain = \( \partial \psi / \partial \sigma \)
\( \rho \) = density
\( \sigma \) = cavitation number = \( (p_1 - p_v) / (\rho U_t^2/2) \)
\( \sigma_m \) = mean stress of blade [MPa]
\( \Delta \sigma \) = blade stress fluctuation (Zero-to-Peak) [MPa]
\( \phi \) = flow coefficient = \( \dot{m} / U_t \)
\( \phi_f \) = design flow coefficient
\( \psi_s \) = static pressure coefficient = \( (p_2-p_1) / (\rho U_t^2) \)
\( \psi_{ts} \) = pressure coefficient = \( (p_2-p_{1t}) / (\rho U_t^2) \)
\( \Delta \psi \) = coefficient of pressure fluctuations = \( \Delta p / (\rho U_t^2) \) (Zero-to-Peak)

3. Experimental Apparatus and Procedure

3.1. Experimental apparatus

The cavitation tunnel used in the present study is shown in Fig. 1. This tunnel is a closed loop tunnel, and the base pressure and hence cavitation number is adjusted by using a vacuum pump connected to the top of the pressure control tank. Tap water is used as the working fluid after degassing. Main shaft of the inducer is driven by an inverter motor with a cogged belt. A slip ring is installed at the end of the main shaft to take out the signal from the strain gauges on inducer blades.

3.2. Test inducer

The principal dimensions of test inducer are shown in Table 1, with a sketch of the test section in Fig. 2. The inducer was originally designed for LE-7A liquid hydrogen turbopump but it was replaced by a new design inducer. The inducer has three helical blades with swept back leading edge, and the sweep angle at the tip is 56 degrees. The tip diameter of the inducer is 174.0 mm. The inlet blade angle is 6.4 degrees and outlet blade angle is 11.1 degrees at the tip. Design flow coefficient is \( \phi_d = 0.067 \). Each blade is named Blade 1, Blade 2 and Blade 3 in the order as shown in Fig. 3.

3.3. Procedure of the experiment

In Fig. 2, the details of the test section and the locations of the pressure sensors on the casing wall are shown. The casing is made of transparent acrylic resin so that the cavity on the blade can be observed with the aid of stroboscopic light. Radial tip clearance is 0.35 mm, and the casing has a 0.5 mm step at 5 mm upstream of the leading edge. Therefore, the upstream diameter of the casing (175.7 mm) is larger than that at the inducer (174.7 mm).

Two pressure sensors are flush mounted on casing wall at 32.6 mm upstream of the inducer inlet with angular distance of 90 degrees. At the inducer outlet, one pressure sensor is flush mounted on casing wall. The resonance frequency of these pressure sensors (KYOWA, PGM-5KC) is 34 kHz. Blade stresses are measured by the strain gauges installed at the root near the leading edge on pressure surface. The locations of strain gauges are shown in Fig. 3.
4. Experimental Results

4.1. Classification of various cavitation instabilities  

Figure 4 shows the performance curves for various cavitation numbers. Pressure coefficient decreases suddenly at relatively high flow coefficient at smaller cavitation number.

Figures 5 (a), (b) and (c) show the cascade plot of the spectrum of inlet and outlet pressure fluctuations and blade stress fluctuation, respectively, for various cavitation numbers. The flow coefficient is $\phi = \phi_d = 0.067$, and rotational speed is 3000 rpm (i.e. rotational frequency $f_n = 50$ Hz). The component with 150 Hz ($=3f_n$) observed in Fig. 5 (a) and (b) is blade passing frequency. In the spectrum of the blade stress fluctuation (Fig. 5 (c)), we can observe the component with 50 Hz ($=f_n$) with constant amplitude whose frequency does not depend on the cavitation number. From the examination of the measurement equipment, it is considered to be the components caused by the electrical noise of the inverter motor or slip ring. Therefore this component will be ignored hereafter.

(1) In the range of $\sigma = 0.040$–0.060, the components ($f_{R.C.}$) with 60–64 Hz ($f_{R.C.}/f_n=1.2$–1.3) in the spectrum of inlet pressure fluctuation and with 10–14 Hz ($f_{R.C.}/f_n=0.2$–0.3) in the spectrum of blade stress fluctuation are observed. Judging from the phase differences of those components measured at various circumferential locations, it is found that this component is caused by the rotating cavitation rotating in the same direction of the impeller with one cell. The component denoted by “$3f_n-f_{R.C.}$” in Fig. 5 (a) is considered to be caused by the nonlinear interaction between $f_{R.C.}$ and $3f_n$. On the other hand, remarkable component is not found in the spectrum of outlet pressure fluctuation (Fig. 5 (b)) in the same range of cavitation number ($\sigma = 0.040$–0.060). This characteristic of rotating cavitation is also observed in other experiments (Kamijo et al. 1977, Fujii et al. 2002).

(2) In the range of $\sigma = 0.030$–0.040, a component with 50 Hz ($f/f_n=1.0$) is observed in the spectra of inlet and outlet pressure fluctuations. This is caused by asymmetric cavitation with steady unequal cavities on each blade. The photographs of the cavities under asymmetric cavitation are shown in Fig. 6. The blades with longer cavity (Fig. 6 (a)) and shorter cavity (Fig. 6 (b)) are found. With asymmetric
cavitation ($\sigma = 0.030 \sim 0.040$), no blade stress fluctuation is shown in Fig. 5 (c), since the relative flow is steady under this condition.

(3) In the range of $\sigma = 0.023 \sim 0.025$, a component with 5 Hz ($f_{C.S.}$) is observed in the spectra of inlet and outlet pressure fluctuations and blade stress fluctuation. The phase differences measured at various circumferential locations of this component are almost zero. Hence, this component is caused by cavitation surge ($f_{C.S.}/f_n = 0.1$).

At the transition point from asymmetric cavitation to cavitation surge ($\sigma = 0.025 \sim 0.030$), a component ($f_{M.A.C.}$) with 1 Hz $\sim$ 5 Hz is observed in the spectrum of blade stress fluctuation (Fig. 5 (c)). This component is examined in detail in the following sections.

4.2. Wave forms of blade stress fluctuation

In Fig. 7 (a)-(e), the wave forms of blade stress fluctuation for various cavitation numbers are shown. In these figures, higher frequency component exceed 100 Hz has been removed by a low-pass filter.

With equal length cavitation the blade stress does not fluctuate as shown in Fig. 7 (a), since the relative flow is steady. The stresses on three blades are almost the same. In Fig. 7 (b), the blade stresses under rotating cavitation are shown. Periodic blade stress fluctuations are observed on all blades, and the amplitude of fluctuation is almost the same for each blade. Under asymmetric cavitation the blade stress does not fluctuate as shown in Fig. 7 (c). However, the mean blade stress on each blade is largely different from that of equal length cavitation. The stress on Blade 1 and Blade 2 are almost zero, and the stress on Blade 3 is almost the same value as that under equal length cavitation. From the observation with the aid of stroboscopic light, the cavities on Blade 1 and Blade 3 are larger and the cavity on Blade 2 is smaller under this condition. It is considered that the pressure differences ($\Delta p$) between suction surface and pressure surface of Blade 1 and Blade 2 are larger and the cavity on Blade 2 is smaller under this condition. The situation is shown in Fig. 8.

Fig. 7 Wave forms of blade stress fluctuation for various cavitation numbers, $\phi = 0.067$, 3000 rpm

Fig. 8 Schematic sketch of the cavity under asymmetric cavitation
edge of Blade 1 and Blade 2 is small (Azuma et al. 2001).

As shown in Fig. 7 (d), the blade stress changes with time significantly at \( \sigma = 0.028 \) where the transition from asymmetric cavitation to cavitation surge occurs. The blade stress seems to be changing randomly. However, the stresses on two blades are almost zero and that of another blade is almost the same value as equal length cavitation at a certain instant. The situation is the same as the asymmetric cavitation. Therefore, it is considered that the pattern of the cavity on each blade under asymmetric cavitation changes irregularly with time at this cavitation number. We will call this phenomenon “movement of asymmetric cavitation.” This phenomenon was also confirmed by the observation with the aid of stroboscopic light. The component \( f_{MAC} \) caused by this phenomenon observed in the spectrum of blade stress fluctuation (Fig. 5 (c)) is rather broadband (1 Hz ~ 5 Hz), since the oscillation is not periodic.

In Fig. 7 (e), the blade stress under cavitation surge \( (\sigma = 0.023) \) is shown. The stresses on three blades are significantly fluctuating with almost the same phase. The amplitude of blade stress fluctuation is slightly larger than that under rotating cavitation, although the mean blade stress is smaller.

The mean blade stresses (i.e. time averaged blade stresses) at four cavitation numbers corresponding to those in Fig. 7 (a)-(e) are shown in Fig. 9 with the amplitudes of blade stress fluctuation. These values are obtained from the record as shown in Fig. 7. The amplitude of blade stress fluctuation caused by the movement of asymmetric cavitation is larger than those under rotating cavitation and cavitation surge.

4.3. Cavitation performance and mean blade stress

The mean blade stresses for various cavitation numbers including the start-up and shutdown in the case with \( \phi = 0.067 \) are shown in Fig. 10. The suction performance obtained simultaneously is also shown at the bottom of the Fig. 10. Under the asymmetric cavitation, large differences of blade stresses among three blades are found as shown in Fig. 7 (c). The pressure coefficient decreases about 3% in this case. At lower cavitation number where the movement of asymmetric cavitation...
occurs, the blade stress fluctuates significantly as shown in Fig. 7 (d).

The pressure coefficient under the asymmetric cavitation is smaller than that under cavitation surge. Therefore, pressure gain is negative ($\mu = \frac{\partial \psi_s}{\partial \sigma} < 0$) in the region of the movement of asymmetric cavitation. The negative value of pressure gain can make the system operation unstable (Young 1972). This can be the cause of the movement of asymmetric cavitation.

The blade stress fluctuation due to rotating cavitation is not included in Fig. 10 since the frequency components higher than 1 Hz have been removed by a low-pass filter.

5. Movement of Asymmetric Cavitation in a Firing Test

During the firing test of LE-7A engine for H-IIA rocket, the shaft vibration considered to be caused by the movement of asymmetric cavitation was observed in the liquid oxygen turbopump inducer. In Fig. 11, trajectory of the shaft displacement is shown in a polar coordinate rotating with the rotor. The direction of shaft deflection in rotating frame changes repeatedly with angular distance about 110 degrees. This phenomenon was also observed by Rosenmann (1965) in the experiment measuring the radial force of a 3-laded inducer. This is considered to be caused by the movement of asymmetric cavitation as explained in Fig. 12.

6. Conclusions

The blade stress fluctuation caused by an irregular movement of asymmetric cavitation is reported in detail. The blade stress at the root near the leading edge fluctuates between zero and the value at non-cavitating condition irregularly with typical frequency 1~5 Hz. This phenomenon should be avoided since the amplitude of stress fluctuation is very large. It occurs at a very small cavitation number at the transition between asymmetric cavitation and cavitation surge. It was correlated with the movement of asymmetric cavitation through the visual observation and blade stress measurement.

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