B202 PIV による矩形容器内の自励振動流れ場の解析

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Research on the Self-induced Sloshing Phenomena by Using PIV

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ABSTRACT The self-induced sloshing in a rectangular tank had been investigated experimentally by using Particle Imaging Velocimetry (PIV) technique. The instantaneous flow fields, time average results and phase average results of the PIV measurement were used to reveal the evolution of the vortical structures in the test tank. Based on the experimental result, resonated oscillation was suggested to be the mechanism of the self-induced sloshing, and the fluctuation of the inlet plane jet and the periodically shedding of the unsteady vortical structures were conjectured to be the excitation source of the self-induced sloshing.

Keywords: self-induced sloshing, vortex shedding, resonated oscillation, PIV technique

INTRODUCTION

Self-induced sloshing is a natural oscillation phenomenon that had been paid great attention by many researchers in the fields of civil engineering, petroleum industry and nuclear energy engineering. For example, in the Liquid Metal Fast Breeder Reactor (LMFBR), which is one of the major energy plants in the near future, the self-induced sloshing of the sodium coolant may occur in the reactor vessel. Such self-induced sloshing can result in high thermal stresses on the vessel walls, which may do severe damage to the vessel structures (Okamoto et al. 1998). So, the mechanism of the self-induced sloshing should be understood clearly in order to do an optimum safety design to prevent the self-induced sloshing of the sodium coolant in the reactor vessel.

Since the first systemically research on the self-induced sloshing in a rectangular tank reported by Okamoto et al. (1991), several investigations on the self-induced sloshing in a rectangular tank with circulating flow had been conducted experimentally and numerically in the past ten years. Although many important results had been got through these previous investigations, much work still needs to be done to understand the fluid dynamic mechanism of the self-induced sloshing more clearly. In particular about the evolution of the vortices and the turbulent structures in the sloshing flow field. In the present study, the self-induced sloshing flow field in a rectangular tank was measured by using a PIV system. By analyzing the instantaneous velocity distributions, time-average values and the phase-average results of the PIV measurement, the evolution of the vortices and the turbulent structures in the test tank were studied. Based on these PIV measurement results, the mechanism of the self-induced sloshing was suggested.

EXPERIMENT SETUP

Figure 1 shows the experimental setup used in the present research. The flow in the test loop was supplied from a head tank, which was continuously pump-filled from a lower tank. The water level in the head tank was maintained in constant by an overflow system in order to eliminate the effect of the pump vibration on the inlet condition of the test tank. The flow rate of the loop, which was used to calculate the representative velocity and Reynolds numbers, was measured by a flow meter. Honeycomb structures and a convergent section were installed in the upstream of the inlet of the test tank to insure the uniform

flow entrance. A valve was installed at the downstream of the test tank exit to adjust the water level of the free surface in the test tank.

Figure 2 shows the schematic view of the thin rectangular test tank. Water flowed horizontally into the test tank and flowed out at a bottom centered vertical outlet. During the experiment, the water level in the test tank was about $H=160\text{mm}$. The flow rate of the test loop was about 20 liter/min, which corresponded to the average velocity at the inlet of the test tank being about 0.333 m/s, and Reynolds number about 6,700 based on the height of the inlet ($b=20\text{mm}$).

Figure 1. The schematic of the experiment setup

Figure 2. The schematic of the test tank

For the PIV measurement, double pulsed YAG lasers (pulse frequency 15 Hz, power 20 mJ/pulse) were used to illuminate the flow field. Polystyrene particles (diameter 20-50 μ m, density is 1.02) were used as PIV tracers. A 1008 by 1018 pixels cross-correlation CCD array camera (PIVCAM 10-30) was used to capture the PIV images. For the PIV image processing, the cross correlation method (Willert et al., 1991) was used to obtain the average displacement of the ensemble particles instead of tracking individual particles. The PIV images were divided into 32 by 32 pixel interrogation windows, and the calculation was conducted on the 50% overlap grids. The post-processing procedures which including sub-pixel interpolation (Hu et al., 1998) and velocity outlier deletion (Westerweel, 1994) were used to improve the accuracy of the PIV measurement results.

RESULTS AND DISCUSSIONS

1. The flow patterns in the test tank

During the experiment, it was found that three different flow patterns could be observed in the test tank for the same system parameter setting, i.e. water level $H=160$ mm, inlet jet velocity $V=0.333$ m/s or flow rate of the test loop $Q=20$ l/min. They are Pattern A (Reverse Flow Pattern), Pattern B (First Mode Self-induced Sloshing Flow Pattern) and Pattern C (Second Mode Self-induced Sloshing Flow Pattern). Figure 3 and Figure 4

show the instantaneous velocity distributions and time average results of the PIV measurement for these three flow patterns.

It was found that, when the flow field in the test tank was in the pattern A (Fig.3(a) and Fig.4(a)), the water free surface in the test tank was found to be peaceful. The inlet jet was also found to be stable. However, when the flow field in the test tank was in Pattern B or Pattern C. The water free surface in the test tank was found to oscillated periodically, the inlet jet was also found to fluctuate up and down periodically. Such phenomenon was called self-induced sloshing (Okamoto et al. 1991). The differences between the pattern B and Pattern C are the oscillation frequency and oscillating wave of the water free surface in the test tank. For the pattern B, i.e. first mode self-induced sloshing, the water free surface in the test tank at right side and left side move up and down alternately. The oscillation phase angle of the free surface at the left side and right is out of phase. For the pattern C, i.e., second mode self-induced sloshing pattern, the water free surface in the test tank at right side and left side move up and down at the same time. i.e. the oscillation phase angles of the free surface at the left side and right of the test tank are in phase. In the meanwhile, the oscillation frequencies of the self-induced sloshing for pattern B and pattern C were also found to be different, which will be discussed in the following section.

a. pattern A b. pattern B c. pattern C
Figure 3. The instantaneous velocity distributions for the three flow patterns

a. pattern A b. pattern B c. pattern C
Figure 4. The time average velocity distributions of the three flow patterns

a. pattern A b. pattern B c. pattern C
Figure 5. Typical velocity power spectrum profiles for the three flow patterns

2. The velocity power spectrum profiles for the three flow patterns.

Figure 5 shows the velocity power spectrum profiles at the same point in the flow field (X=100mm, Y=100mm, Z=25mm) for the three flow patterns. For the flow pattern A (Fig.5(a)), the velocity power spectrum profile was found to be in random. None of the characteristic frequency can be found in the studied frequency range. However, when the flow field was in pattern B or pattern C (Fig. 5(b) and Fig. 5(c)), an obvious characteristic frequency can be identified in the velocity power spectrum profiles, which are 1.6Hz and 2.3Hz for the flow pattern B and pattern C respectively. By measuring the oscillation frequency of the water free surface, it was found that the characteristic frequencies in the velocity power spectrum profile are just the frequency of the self-induced sloshing of the flow field in the test tank.

Lamb (1932) had deduced that the eigenvalues of the water in a rectangular could be expressed as:

$$f^n = \frac{1}{2\pi} \sqrt{\frac{n\pi g}{W} \tanh\left(\frac{n\pi H}{W}\right)} \quad (1)$$

where n is the mode number, W and H are the width and height of the water in the tank.

For the present study case, i.e. H=160mm and W=300mm, the eigenvalues of the water in the test tank can be calculated by using equation (1), which are listed in the Table 1.

Table 1. the eigenvalues of the water in the test tank

n-th mode	Eigenvalues (Hz)
1	1.6
2	2.3
3	2.8
4	3.2
5	3.6

From the table 1, it can be seen that, the characteristic frequencies of the self-induced sloshing flow field for pattern B ($f_0=1.6\text{Hz}$) and Pattern C ($f_0=2.3\text{Hz}$) are the 1st mode eigenvalue and 2nd mode eigenvalue of the water in the test tank. So, the pattern B is called first mode self-induced sloshing pattern and the pattern C is called second mode self-induced sloshing flow pattern. The same result also had been reported by Okamoto et al.(1998)

3. Vortical structures in the test tank

It can be found that the vortical structures in the test tank are completely different for these three flow patterns. For the flow pattern A (Fig. 3(a) and Fig. 4(a)), just one big clockwise vortex can be found in the flow field. However, when the flow was in pattern B or Pattern C, two counter rotating vortices can be found from the PIV time average results, which were at the right side and the left lower corner of the test tank (Fig.4(b) and Fig. 4(c)). During the experiment, it was also found that when the flow was sloshing (pattern B or pattern C), the inlet jet fluctuated up and down periodically. Some smaller scale unsteady vortices can also be found shedding from the inlet jet periodically.

In order to investigate the effect of the periodically shedding of these unsteady vortices and the inlet jet fluctuation on the self-induced sloshing phenomena, the PIV phase average measurement had also been conducted in the present study. The phase average measurement results for the flow pattern B were shown on Figure 6. The phase angles of them are $\theta = 0, \pi/2, \pi$ and $3\pi/2$. The free surface water levels at the left side (inlet side) of the test tank were at its highest position, middle level (the free surface level is decreasing), lowest position and middle level (the free surface level is increasing) corresponding to these four phase angles respectively.

Figure 6. The phase average flow field of PIV result for the flow pattern B

Figure 7. Typical oscillating component fields for the flow pattern B and pattern C

Unlike the time average results, which can just reveal two steady vortices in the sloshing flow field, the unsteady vortex can also be revealed clearly in the flow field from the phase average measurement result. The unsteady vortex was found to change its position with the changing of the phase angle. When the phase angle increasing from 0 to π , i.e., the free surface water level at the left side of the test tank decreased from its highest position to its lowest position (from Fig.6(a), Fig.6(b) to Fig.6(c)); the unsteady vortex shed from the inlet jet and moved downstream. When the phase angle increasing from π to 2π , i.e., the free surface water level at the left side of the test tank began to increase from its lowest position to its highest position (from Fig. 6(c), Fig. 6(d) to Fig. 6(a)), the unsteady vortex was engulfed by the large steady vortex at the right side of the test tank, and another new vortex was found to roll up from the inlet of the test tank. Then, another new self-induced sloshing cycle began. As the phase angle changing, the inlet jet flow was also found to fluctuated up and down periodically.

Since the flow field in the test tank was found to be oscillating (sloshing) periodically when the flow field was in pattern B or pattern C. In order to reveal such oscillating movement, the oscillating movement component was extracted by subtracting the PIV time average result from the PIV phase average results. Typical results of oscillating movement for the pattern B and pattern C were shown on Fig. 7. The evolution of the vortical structures and the form of the oscillating wave can be seen clearly from these figures.

4. The mechanism of the self-induced sloshing

As mentioned above, for the same test tank and system parameter setting, i. e. water level $H=160\text{mm}$, inlet jet velocity $U=0.333\text{m/s}$ or flow rate $Q=20\text{L/min}$, three completely different flow patterns can be observed in the test tank. All of these three flow patterns are found to be stable. the transformation of the flow pattern was found to be determined by the inlet jet condition. Although the representative velocity of the inlet jet flow or the flow rate of the test loop is same, the velocity distribution, turbulence intensity level and momentum boundary layer thickness of the inlet jet flow may affect the flow pattern, oscillating mode and frequency of the self-induced sloshing.

From the above discussions, it can be seen that when the flow field in the test tank is sloshing, (pattern B and pattern C), the frequencies of the self-induced sloshing always equal to the eigenvalues of the water in the test tank. The same results were also found from the Sierras studies of Okamoto et al. (1991,1998). These mean that the self-induced sloshing has a very close relationship with the oscillation characteristics of the water in the test tank. So the resonated oscillation was suggested to be the mechanism for the self-induced sloshing.

It was well known that there are two necessary factors for the resonated oscillation, which are excitation source and frequency coupling of the excitation source with the eigenvalue of the oscillating body. From the above PIV measurement result, it can be seen that during the self-induced sloshing, the fluctuation of the inlet jet and the periodically shedding of the unsteady vortex from the inlet jet played a key role on the distribution of the flow pattern. The frequency of jet fluctuation and the periodically shedding of the unsteady vortex equals to the frequency of the self-induced sloshing (which means it can be coupled with the eigenvalue of the water in the test tank). So the inlet jet fluctuation and the periodical shedding of the unsteady vortex may be suggested to be the excitation source of the resonated oscillation (self-induced sloshing).

In the meanwhile, it should mention that the inlet jet fluctuation of the flow pattern B or Pattern C has very similar characteristics to the well known phenomenon of "edged tone" (Rockwell et al. 1979), which was a self-sustained jet oscillation phenomenon and caused by the interaction between the jet instability and the edge. So the relationship between the self-induced sloshing and "edged tone" phenomenon will be studied in the future work.

CONCLUSION

The self-induced sloshing in a rectangular tank was investigated experimentally by using PIV technique. The instantaneous flow field, time average value and phase average result of the PIV measurement were used to investigate the evolution of vortical structures in the self-induced sloshing flow field. Based on the experimental results, resonated oscillation was suggested to be the mechanism of the self-induced sloshing. Periodic fluctuation of the inlet jet and the periodically shedding of the unsteady vortices from the inlet jet were conjectured to be the excitation source of the self-induced sloshing.

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