Optics Communications 315 (2014) 91–96

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Small amplitude liquid surface sloshing process detected by optical method

Yang Miao*, Shaoping Wang

School of Automation Science and Electrical Engineering, Beihang University, Beijing, China

ARTICLE INFO

Article history:
Received 25 August 2013
Received in revised form
24 October 2013
Accepted 26 October 2013
Available online 12 November 2013

Keywords:
Liquid surface sloshing
Dynamics
Optical detection

ABSTRACT

A laser experimental set up to detect liquid surface sloshing wave excited by the instantaneous momentum was constructed. The sloshing parameters were determined by detecting the scattering light which is modulated by the surface sloshing wave. The analytical expressions which include the relationship between optical intensity and liquid surface sloshing wave and the expressions of the wave length as well as amplitude were derived theoretically. Optical patterns corresponding to static and sloshing liquid surface were obtained experimentally. The sloshing variation process including rising and damping was achieved. Both rising and damping processes are variable exponentially. The rising and damping coefficients and maximum amplitude as well as wavelength of the sloshing wave were also measured experimentally. The detection is nondestructive and real time.

1. Introduction

Sloshing is the free-surface oscillation of a fluid in a basin or partially filled tank, where the oscillations are typically excited. The sloshing phenomenon is an important consideration in several engineering fields such as aircraft and aerospace as well as petroleum transportation and reserve. Because the sloshing problem relates with many important fields, it has been studied by a host of researchers over the years. These studies are roughly classified as sloshing basic principle, computer simulation, experimental investigations and slosh damping devices. The sloshing problem was studied by using basic principle [1,2]. Experimental investigations on effect of tank sizes, flexibility of tank bottom wall and effect of frequencies in system were analyzed [3,4] to find the liquid sloshing effect. Papers [5–7] presented a series of computer simulation methods and the calculated results. Refs. [8–10] gave an important experimental results and comparison between experimental and numerical results. Cho et al. carried out a parametric study to find the effect of baffles for damping liquid oscillations [11]. Investing the detection of sloshing wave, one will find that pressure sensor [12] is widely used in the gauges and this pressure sensor is simple and practicable. The other sensor such as capacitance transducer whose capacitance relates with liquid surface height [13] is also adopted. But the defection of these sensors detection is a contact type. Usually, light is the best information carrier for non-contact measurement. The measurements based on this principle could be called as optical detection. Optical image technology such as camera [14] and particle image velocimetry [15–17] is extensively applied in the detection of sloshing wave. The basic principle of this technique is to achieve the measured wave image by using camera. Another optical measurement such as laser Doppler velocimetry [18] is based on Doppler Effect. The light wave shift related with the movement of the wave is the directive detecting parameters in this method. Laser light sheet [16] is also a practicable optical detection. The character of this technology is to project a laser sheet onto the tested wave and form a light line on the surface. Of cause, acoustic wave [19] can also be used as non-contact detection for sloshing wave, whose mechanism is similar to optics.Investing experimental studies for sloshing problem, one will find many measurements are in contact where pressure sensor was used to detect the sloshing. But optical detection is generally feasible to get the realization of non-contact measurement. Therefore, this detection for liquid surface sloshing, which is non-destructive and real time, will be presented. The instantaneous momentum caused by collision produces a small amplitude liquid surface sloshing. When the laser beam is incident upon liquid surface, the surface sloshing modulates the light phase and the scattering light from the surface will carry the sloshing information. The distribution of light scattered from sloshing surface was analyzed by Fourier optics. The sloshing process including rising and damping was observed by the scattering light patterns. The rising and damping coefficients and maximum amplitude as well as wavelength of the sloshing wave were also measured experimentally.

2. Description of experiment

The depiction of experimental set-up is shown schematically in Fig. 1, which includes excitation, sample cell, light source and light

* Corresponding author. Tel.: +86 13401195589.
E-mail address: miaoyang1985@126.com.cn (Y. Miao).

0030-4018/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.optcom.2013.10.079

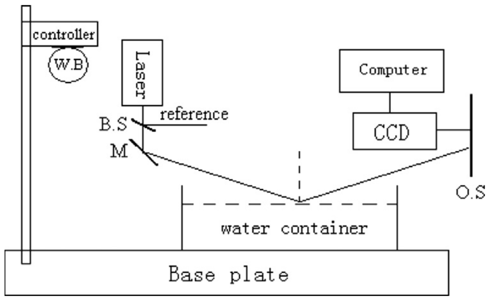

Fig. 1. Schematic diagram of experimental setup.

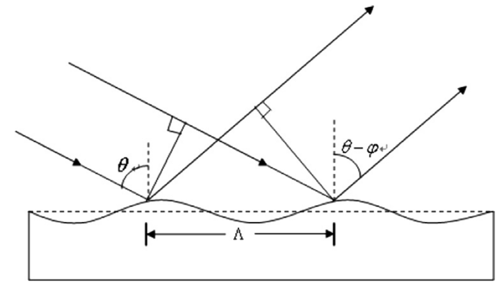

Fig. 2. Principle schematic diagram of sloshing modulation.

path, optical electronic detection and data processing system. A weight ball (W.B in Fig. 1) with 0.5 kg, whose height to the base plate is 500 mm, is hanged on the lower end of the controller. Liquid sample is a rectangular whose length and wide are 400 mm and 300 mm, respectively. The cell is on the base plate and the liquid is distilled water. The instantaneous momentum induces the liquid surface sloshing. A He–Ne laser beam is divided by using a beam splitter. One of the beams is used to monitor the laser output stability. The other is directly incident upon the water surface where the sloshing wave is traveling. As for the usual case of acoustic wave diffraction, it is needed that the acoustic wavelength is as approximately short as the light wavelength because a shorter acoustic wavelength causes a higher angular offset of diffraction light spots. However, the sloshing wavelength is in a few mini-meter order and the light wavelength is 632.8 nm. It is shown that the sloshing wavelength is much longer than light wavelength. In order to compensate this defect, a glancing light incidence and far observation distance are adopted. The incident angle is equal to 1.538 rad and the distance between the incident points to observation screen is about 8.5m, respectively.

For the oblique incidence, the shape of the illuminating area on the liquid surface is an ellipse whose major axis and minor axis are about 24 mm and 2.3 mm, respectively. The major axis is parallel to the sloshing wave traveling direction. The distance between the incident point to observation screen is about 8.5 m. A CCD imager is used to detect the scattering pattern on observation screen. The model is pike F-421B manufactured by AVT Germany. The CCD sensor is KAI-4022 and black response. The pixel size is $7.4\,\mu m \times 7.4\,\mu m$ and resolution is 2048×2048 respectively. The sampling rate is 16 fps and minimum exposure time is 70 µs. The camera focal length is 50 mm.

3. Sloshing modulation theory

The liquid surface sloshing wave will appear when the weight ball collides with the base plate. The light illumination area of the light on the surface is small because the laser beam is not expanded in the experiment. The sloshing wave in the illumination area can be supposed as simple plane one, although the wave is complex in large area on the surface. It is also supposed that the light beam and sloshing wave direction is adjusted in one plane. The principle schematic diagram is shown in Fig. 2 where θ is the incident angle, $\theta-\varphi$ is the light reflection angle on the wave surface, $\varphi/2$ is the local wave slope and Λ is the sloshing wave wavelength.The optical pattern on observation must be as similar as that of a phase grating diffraction in this case. However, if the wave in the area is complex, the Fourier decomposition should be used to derive the relationship between the pattern intensity and the sloshing wave. In order to ease the theoretical analysis and satisfy the experimental requirement, the principle diagram is simplified as Fig. 2 and the liquid surface sloshing in the case of small amplitude is briefly expressed as sinusoidal function. That is

$$Y=A\sin(\omega t-kx) \tag{1}$$

where Y is the longitudinal coordinate of the particle on liquid surface, A is the amplitude of the sloshing wave, $\omega$is the frequency, x is a position variable along the traveling direction of the wave on liquid surface,$k$is the wave number,and $k=2\pi/\Lambda$.

The incident optical function can be written as

$$u_i(x)=\exp(j\frac{2\pi\sin\theta}{\lambda}x) \tag{2}$$

where x is a position variable along the traveling direction of sloshing wave on liquid surface, λ is the light wavelength and j is the imaginary unit.

If the light beam is incident upon the liquid surface, its optical phase will be modulated by liquid surface sloshing. Because light velocity is far greater than that of sloshing wave, the optical phase modulation function $\phi(x)$can be written as

$$\phi(x)=\frac{2\pi}{\lambda}[(2A\cos\theta)\sin kx] \tag{3}$$

Combining Eqs. (1) and (3), one may readily have, based on Fourier optics [20], the scattering light intensity expression as

$$I^{(0)}(\phi)=\sum_{n=-\infty}^{+\infty} J_n^2(\frac{4\pi A\cos\theta}{\lambda})(\frac{\sin(w[\frac{\cos\theta}{\lambda}\phi-\frac{n}{\Lambda}])}{w[\frac{\cos\theta}{\lambda}\phi-\frac{n}{\Lambda}]})^2 \tag{4}$$

Where J_n is the first kind Bessel function, order n and n is integer. w is the width of laser beam on the liquid surface along the traveling direction of sloshing wave. $\cos(\theta-\phi)=(x_0/L)$, where n is a position variable on the observation screen and L reprints the distance between the incident point and the observation plane.

3.1. Liquid surface sloshing wavelength

The expression (4) is a series which shows the intensity of the scattering light caused by the sloshing wave. The intensity distribution is series of spots. Each term of the series includes double factors and one is$\left(\frac{\sin(w\,[(\cos\theta/\lambda)\phi-(n/\Lambda)])}{w\,[(\cos\theta/\lambda)\phi-(n/\Lambda)]}\right)^2$ which describes the position of the nth spot. From this factor, the interval space between adjacent spots can be written as

$$\Delta x_0=\frac{L\lambda}{\Lambda\cos\theta} \tag{5}$$

where Δx_0 reprints the interval space. The parameters Δx_0, $\lambda$and θ can be measured directly and then the wavelength of the liquid surface sloshing wave can be determined by the Eq. (5).

It should be pointed out that the light intensity between two successive spots is overlapping if their distance is becoming narrower and narrower. The two spots will not be resolved if the distance is smaller than Rayleigh criterion. In our experiment, according to the principle of grating, the half width of the spot can be simply calculated $\lambda L/w$ which is smaller than the interval space between adjacent spots shown in Eq. (5). This means the