Experimental Thermal and Fluid Science 88 (2017) 423–433

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Tracking free surface and estimating sloshing force using image processing

Ufuk Tosun [a], Reza Aghazadeh [b,c], Cüneyt Sert [b], Mehmet Bülent Özer [a,*]

[a] Mechanical Engineering Department, TOBB University of Economics and Technology, Ankara, Turkey
[b] Mechanical Engineering Department, Middle East Technical University, Ankara, Turkey
[c] Department of Aeronautical Engineering, University of Turkish Aeronautical Association, Ankara, Turkey

ARTICLE INFO

Article history:
Received 27 December 2016
Received in revised form 20 June 2017
Accepted 22 June 2017
Available online 23 June 2017

Keywords:
Sloshing
Image processing
Modal expansion

ABSTRACT

Ultrasonic level sensors are commonly used to measure the motion of the free surface in fluid sloshing. They are used to measure the elevation of the free surface at a single point. The sloshing forces are generally measured with load sensors, which require two sets of measurements, with and without the fluid in the tank. This paper develops a method, which tracks the free surface motion during sloshing with a camera and uses the captured images to estimate the forces due to sloshing in a rectangular tank. One of the major assumptions is that the displacement input which causes sloshing is one dimensional and the resulting sloshing motion is two dimensional. For the method to correctly estimate the sloshing forces along the displacement input direction, sloshing should be around the resonant sloshing frequency. This new method can track the motion of the complete free surface rather than a single point. It estimates the sloshing forces using image processing and potential flow theory, without the need for a load cell measurement. Free surface shapes and sloshing force estimates obtained by image processing are compared with those measured by the sensors. Good agreement is observed for low amplitude sloshing around fundamental resonance frequency.

© 2017 Elsevier Inc. All rights reserved.

1. Introduction

The number of studies which focus on understanding sloshing dynamics using numerical modeling as well as experimental techniques is increasing in recent years. In terms of numerical simulations sloshing is a highly non-linear and therefore difficult problem to solve. Experimental investigation is still one of the main methods for understanding sloshing dynamics.

The reason for the interest in sloshing dynamics is due to sloshing forces effecting several engineering systems. One such important field is transportation. As the liquefied natural gas (LNG) transportation is gaining momentum, it is becoming more important to understand sloshing loads in partially filled containers for the safety of the cargo ships [1]. Sloshing dynamics is also critical for stability of space vehicles [2] and road tankers [3,4]. Another application where sloshing effects engineering systems is in fluid height measurements, especially in fuel level tracking systems [5]. Also, understanding sloshing dynamics is important in the use of sloshing dynamic vibration absorbers. Increased number of research articles are being published about using sloshing forces to decrease structural vibration with the interest in decreasing seismic and wind response of engineering structures [6–8].

A typical sloshing experimental setup is composed of several components. An important one is the actuator sub-system which is used to move the container. Another sub-system is the container and the liquid in it. The container can be in different geometries such as rectangular prism, cylindrical, etc. with different types fluids in it varying from water to non-Newtonian liquids. Sensors are also an important part of the sloshing experiments. They are used to measure and monitor the targeted sloshing parameters. Parameters such as pressure, free surface motion, sloshing force, etc. Finally, these sensors are connected to a data acquisition system where data is stored for further processing.

The actuator sub-system in a sloshing experiment is the component which is used to move the container and provide controlled sloshing. The experimental setup can be designed differently depending on the desired sloshing motion, such as rolling [9–11], translational [12,13] or both simultaneously (such as Stewart platforms with six degrees of freedom) [14–17]. In literature, translational motion actuation systems can be as basic as a crank-rocker mechanism attached to an electric motor or lathe for sinusoidal input to the container [12,13]. To study Faraday

* Corresponding author.
E-mail address: bulent.ozer@gmail.com (M.B. Özer).

http://dx.doi.org/10.1016/j.expthermflusci.2017.06.016
0894-1777/© 2017 Elsevier Inc. All rights reserved.

waves, low amplitude, high frequency sinusoidal displacement excitation can be obtained from an electromagnetic shaker [18].

Pressure is probably the most common parameter measured in sloshing tests. It is generally measured with pressure sensors mounted on holes at the desired locations of the container walls. They are commonly used in array form [9–11,13,15,17,20] so an understanding of a pressure distribution can be gained across one dimension of the container. The effects of sampling and post processing of the measured pressure data [16,17] and the use of different types of pressure sensors [19,21] (piezo-resistive or piezo-electric) for accurate measurement of peak pressures were studied in literature.

Another important parameter in sloshing experiments is the wave height. In literature, wave height is generally measured using capacitance wave probes, which are floating sensors on the free surface and the capacitance value of the sensor changes as the free surface moves [12,22,23]. One disadvantage of capacitive measurement is the fact that it is a contact measurement method and sensors may affect the surface measurements. Another method for wave height measurement is ultrasonic. This method uses reflection of ultrasonic waves from the free surface and calculates the distance from the sensor using the time of flight information. This method has the advantage of being contact-free. Breaking waves and temperature sensitivity problems of this measurement method is investigated and post-processing algorithms are suggested to eliminate these unwanted effects [5]. In a different study laser triangulation sensor was used to track the motion of the free surface [18]. In order for the laser beam to reflect from the fluid surface acrylic paint was added to the fluid. A general summary of free surface measurement methods is given in Table 1 with the advantages and disadvantages of each one.

Another common method to study the free surface motion is to use optical cameras. In several studies snap shots captured by a camera are used for qualitative comparison of the free surface characteristics predicted by the numerical solution with the experimental results [9,16,22,24]. Even though there are several studies that used cameras for qualitative comparison, to the best of authors' knowledge numerical extraction of free surface characteristics from camera images has not been pursued.

One of the most important parameter in sloshing dynamics is the sloshing force, which is the net force acting by the sloshing fluid on the container walls. It is an important parameter which can be critical during transportation if sloshing resonance occurs. It is also a critical parameter in sloshing vibration absorbers. For the sloshing forces to decrease the structural vibrations, not only the amplitude of the sloshing force but also its phase with respect to the motion of the structure is critical. However, the measurement of net sloshing force on the container is not straightforward. Despite its obvious importance, only a very limited number of studies attempted to measure the sloshing force. A summary of sloshing force measurement methods is listed in Table 2. In the work of Reed et al. [25], net sloshing force on the container walls was measured by a load cell placed between the moving platform and the container. However, data measured by the load cell also includes inertial forces due to the mass of the container. Therefore, two force measurements, with and without the fluid, need to be performed with the same inputs, and the measured forces need to be subtracted from each other to get the force due to sloshing liquid only [25].

This study aims to utilize the camera images in sloshing experiments as a quantitative data measurement tool. An image processing method is proposed to identify the free surface. The identified waveform of the free surface is converted into a Fourier series form. The Fourier series representation of the free surface is used for calculation of the velocity potential utilizing multi-dimensional modal expansions. Using the calculated velocity potential of the sloshing motion, pressure distribution is obtained for each wall of the tank. Lastly, the surface integration of the pressure values provides the net sloshing force. The estimated forces turn out to be accurate if the sloshing occurs close to the natural frequency of the fluid body in the container (resonance sloshing).

Table 1
Summary of free surface measurement methods in sloshing experiments.

Sensor	Working principle	Advantages	Disadvantages
Capacitance wave probes	Senses changes in the capacitance between two electrodes as the fluid level between the electrodes changes.	• Highly accurate height measurement	• Invasive. • Complications occur when the fluid is highly conductive. • Single point measurement.
Ultrasonic measurement	Uses time of flight information of the ultrasonic waves	• Contactless	• Single point measurement. • May not work in violent sloshing.
Laser	Measures fluid level using the doppler principle on a laser beam	• Contactless	• Expensive. • May not work in violent sloshing. • Interface needs to be reflective. • Single point measurement.
Optical camera	Captures the video of sloshing and post processes it	• Contactless • Measures the height of full free surface	• May not work in violent sloshing. • Measurement is not real-time. Requires post processing.

Table 2
Summary of sloshing force measurement methods.

Sensor	Working principles	Advantages	Disadvantages
Load cell	Measures the force generated during sloshing.	• Accurate measurement	• Needs two measurements, with and without fluid.
Pressure sensor array	Estimates the fluid force by integration of pressures collected at different locations on the container walls.		• Requires several pressure sensors. • Force is an estimation due to integration.
Optical camera	To the best of author's knowledge, this method is proposed in this study for the first time. Uses the free surface shape captured by the camera and multimodal sloshing theory to estimate the sloshing force.	• One measurement to estimate the force. • Contactless	• Applicable for resonance sloshing. • Not a real-time measurement. Requires post processing. • Force is an estimation not a direct measurement.

متن کامل مقاله ← دریافت فوری

ISIArticles
مرجع مقالات تخصصی ایران

- ✓ امکان دانلود نسخه تمام متن مقالات انگلیسی
- ✓ امکان دانلود نسخه ترجمه شده مقالات
- ✓ پذیرش سفارش ترجمه تخصصی
- ✓ امکان جستجو در آرشیو جامعی از صدها موضوع و هزاران مقاله
- ✓ امکان دانلود رایگان ۲ صفحه اول هر مقاله
- ✓ امکان پرداخت اینترنتی با کلیه کارت های عضو شتاب
- ✓ دانلود فوری مقاله پس از پرداخت آنلاین
- ✓ پشتیبانی کامل خرید با بهره مندی از سیستم هوشمند رهگیری سفارشات