Mechanical Systems and Signal Processing 101 (2018) 274–291

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Water level response measurement in a steel cylindrical liquid storage tank using image filter processing under seismic excitation

Sung-Wan Kim [a,*], Hyoung-Suk Choi [a], Dong-Uk Park [a], Eun-Rim Baek [a], Jae-Min Kim [b]

[a] KOCED Seismic Simulation Test Center, Pusan National University, 49 Busandaehak-ro, Mulgeum, Yangsan, Kyungnam 50612, Republic of Korea
[b] Department of Marine and Civil Engineering, Chonnam National University, 50 Daehak-ro, Yeosu, Jeonnam 59626, Republic of Korea

ARTICLE INFO

Article history:
Received 16 December 2016
Received in revised form 13 August 2017
Accepted 22 August 2017

Keywords:
Water level response
Shaking table test
Cylindrical liquid storage tank
Image filter processing

ABSTRACT

Sloshing refers to the movement of fluid that occurs when the kinetic energy of various storage tanks containing fluid (e.g., excitation and vibration) is continuously applied to the fluid inside the tanks. As the movement induced by an external force gets closer to the resonance frequency of the fluid, the effect of sloshing increases, and this can lead to a serious problem with the structural stability of the system. Thus, it is important to accurately understand the physics of sloshing, and to effectively suppress and reduce the sloshing. Also, a method for the economical measurement of the water level response of a liquid storage tank is needed for the exact analysis of sloshing. In this study, a method using images was employed among the methods for measuring the water level response of a liquid storage tank, and the water level response was measured using an image filter processing algorithm for the reduction of the noise of the fluid induced by light, and for the sharpening of the structure installed at the liquid storage tank. A shaking table test was performed to verify the validity of the method of measuring the water level response of a liquid storage tank using images, and the result was analyzed and compared with the response measured using a water level gauge.

1. Introduction

Liquid storage structures are used in various forms in a wide range of fields, ranging from small-scale water tanks (e.g., domestic and commercial water storage tanks and heat storage tanks used for heating and cooling devices) to large-scale storage tanks (e.g., fuel storage tanks for ships and aircraft, fuel and oil storage tanks for various industrial facilities, and fuel storage tanks for power plants). In particular, in the case of the fuel storage tanks used for important facilities, damage to the society at large can occur when the safety is not secured, and thus, performances relevant to various design loads are required.

When a dynamic load such as an earthquake is applied to a liquid storage structure, the hydrodynamic pressure acting on the structure and the dynamic behavior of the structure can be significantly amplified due to the interaction between the liquid inside the structure and the storage structure. Considerable damage can occur to the liquid storage tank when the interaction between the fluid and the structure is not appropriately considered. This was observed in the 1964 Niigata

* Corresponding author.
E-mail address: swkim09@pusan.ac.kr (S.-W. Kim).

http://dx.doi.org/10.1016/j.ymssp.2017.08.035
0888-3270/

earthquake, the 1964 Alaska earthquake, and the 1966 Parkfield earthquake. The investigation of the cause of the damage revealed that the hydrodynamic pressure could be considerably amplified compared to a rigid body structure model. Therefore, it was found that a method that analyzes a liquid storage structure by modeling it as a rigid body is not safe. In addition, for the aforementioned earthquakes, more damage was observed in a liquid storage tank that had not been fixed on the ground, indicating that the lifting of the liquid storage structure that had not been fixed on the ground had a significant effect on the safety of the liquid storage facility. Since the aforementioned study, many other studies have been conducted on the fluid-structure interaction [1,2], and the regulation states that the fluid-structure interaction should be considered during the design of a water tank structure, and that the effect of lifting should be considered in the case of a liquid storage facility that is not fixed on the ground [3].

The hydrodynamic pressure that occurs in a liquid storage tank due to the fluid-structure interaction can be divided into the convective pressure, which is relevant to the sloshing movement of the free water surface of the fluid, and the impulsive pressure, which is the pressure component due to the fluid that moves along with the wall of the structure. To understand the hydrodynamic pressure and the resultant behavior of the structure, various numerical analysis and experiment methods have been developed [4,5]. Many studies have been conducted on the fluid-structure interaction for a liquid storage structure due to the ground motion [6,7]. The hydrodynamic pressure that acts on the wall of a flexible water tank structure is significantly amplified by the fluid-structure interaction and is divided into the convective pressure component, the impulsive pressure component, and the interaction pressure component. The interaction pressure component refers to the pressure component that occurs due to the interaction between the flexible water tank structure and the fluid. It can be two to three times larger than the impulsive pressure component, and its distribution is also different from that of the impulsive pressure in a rigid body structure [8]. It has been reported that the pressure that is amplified by the fluid-structure interaction is mostly the impulsive pressure component, and that the interaction has a minor effect on the convective pressure component induced by sloshing [9]. The finite-element analyses and experiments that were conducted revealed that the fluid-structure interaction also has a small effect on the behavior of the free water surface of fluid in the case of linear analysis, but sloshing easily exceeds the linear limit even when the input ground motion is not large [10].

In the 2003 Tokachi-oki earthquake, a large-scale oil storage tank was damaged by sloshing due to the long-period earthquake, which resulted in a fire. This incident suggested that the effect of the second sloshing mode also needs to be considered [11]. With the recent increased demand for LNG storage facilities, analysis techniques considering the interrelation among the ground, structure, and fluid have been developed [12–14]. The effectiveness of the analysis models and methods developed in such studies can be verified using diverse methods, but verification needs to be performed through a shaking table test to accurately reflect the dynamic behavior of fluid [15–18]. To analyze the sloshing of the fluid in a shaking table test, the water level response is generally measured by installing a water level gauge at the ceiling. There are limited measurement points, however, as well as difficulty measuring, depending on the measurement method used. Moreover, it can cause severe noise. Therefore, a method for the simple and economical measurement of the water level response in a liquid storage tank is necessary. With the recent introduction of economical and high-performance image devices, the image-based water level response measurement has become an easily accessible method, and relevant studies on water level measurement have been conducted. A study was conducted on measuring the fluid behavior with the use of images by manufacturing a liquid storage tank using a transparent material [19,20], and another study was conducted on measuring the water level response with an infrared camera using the temperature difference between the liquid storage tank and the fluid. Other studies have measured the water level by directly installing a camera at the liquid storage tank, but the random noise caused by the fluid fluctuation and the fluid reflection by the light made the water level measurement difficult. While there were studies that measured the fluid velocity using PIV and PTV [21,22], not only would such a method require a transparent material; it would also allow the injection of special particles, which could then be illuminated by a laser. Thus, there is a need for a system and an analysis method for effectively measuring the water level of a full-scale liquid storage tank.

In this study, a method of measuring the water level in a liquid storage tank using images was suggested, and a commercial digital camcorder was used as a sensor for measuring the water level response, considering the ease of use and the economic feasibility. Template matching was used to measure the water level response, and the calculation was carried out at the subpixel using image transform function, which corrects the geometric movement and error between the image without deformation and the image with deformation. In addition, image filter processing was used for the reduction of the noise of the fluid induced by the reflection of light, and for the sharpening of the edge of the structure installed at the liquid storage tank. Therefore, a shaking table test was performed to verify the validity of the method of measuring the water level in a liquid storage tank using images, and the result was analyzed and compared with the result of the response using a water level gauge.

2. Water level estimation using images

2.1. Digital image processing

2.1.1. Template matching

Template matching is a method of calculating the similarity between a given template and an image in a specific space [23–26], and it is typically performed with respect to the single characteristic of an image. It searches a similar pattern