Ocean Engineering 94 (2015) 199–212

Contents lists available at ScienceDirect

Ocean Engineering

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

Comparative study on pressure sensors for sloshing experiment

Sang-Yeob Kim[a], Kyong-Hwan Kim[b], Yonghwan Kim[a,*]

[a] Department of Naval Architecture & Ocean Engineering, Seoul National University, Seoul, Korea
[b] Offshore Plant Research Division, Korea Research Institute of Ships & Ocean Engineering, Daejeon, Korea

ARTICLE INFO

Article history:
Received 18 September 2013
Accepted 30 November 2014
Available online 29 December 2014

Keywords:
Sloshing experiment
Pressure sensor
Piezoelectric sensor
Piezoresistive sensor
ICP sensor
Thermal shock

ABSTRACT

This study considers a comparative study on pressure sensors for the measurement of sloshing impact pressure. For the comparative study, four pressure sensors are used: one piezoresistive sensor, one piezoelectric sensor, and two integrated circuit piezoelectric (ICP) sensors. For the comparative study, the sensors are installed on tank wall and ceiling of a rectangular tank with narrow breadth. Several types of comparative studies are carried out, including the sensitivity to temperature differences between the sensors and test medium. The forced regular and irregular motions are applied to the tank with partial water filling, and pressure signals on the tank due to sloshing are measured at different filling conditions. The characteristics of the pressure sensors are discussed and the measured pressure signals are compared. The measured impact peaks are statistically analysed and the results are compared to observe the difference of sensors.

1. Introduction

Accurate prediction of sloshing load is important for the structural design of LNG carriers and LNG-FPSO. Recently, the size of floating bodies for LNG production and transportation has been getting bigger and bigger, while the number of LNG cargo tanks has been fixed. Sloshing, therefore, has become a primary interest in the design of LNG cargo tanks. There have been many efforts to evaluate sloshing load using theoretical and computational analyses, but experimental analysis is mainly recommended by ship classifications and industries (ABS, 2006; BV, 2011; DNV, 2006; Lloyd, 2009; Kuo et al., 2009). In recent times, a high-performance data acquisition and large storage systems allow to capture the sloshing impact with a high sampling rate. There are many studies based on experimental approach (Lugni et al., 2006; He et al., 2009; Maillard and Brosset, 2009; Yung et al., 2009). A real-scale impact test was carried out in MARIN (Brosset et al., 2009; Kaminski and Bogaert, 2009). Previous experimental studies were focused to the sloshing phenomena and to investigate a scale effect of sloshing. Many research activities have been highlighted in the Sloshing Dynamics Symposium of ISOPE, the International Offshore and Polar Engineering Conference. Very recently, the ISOPE sloshing benchmark test was carried out (Loysel et al., 2012), and the differences of the experimental results of various experimental facilities were observed.

In spite of the huge effort on experimental analysis, there are many uncertainties in the sloshing experiment. Recently, Souto-Iglesias et al. (2011) discussed about the uncertainty analysis of the experimental setup. In terms of experimental instruments, Choi et al. (2010) tested two piezoelectric sensors and discussed about effects of thermal shock, sensing diameter, and mal-mounting on the sloshing pressure. Pistani and Thiagarajan (2012) handled a motion platform, a pressure sensor, and a data acquisition system, thoroughly. The characteristics of instruments were observed in their study. Except those papers, it is not easy to find studies on errors analysis of experimental instruments in previous literatures.

In the present study, it is focused on sensitivities and characteristics of pressure sensor as the pressure sensor can be the most important instrument among the experimental instruments. The motion platform can be calibrated by measuring the displacement of input and output. The error of data acquisition system is relatively lower than the other instruments. A model tank can be the source of error, but the error can be minimized by the manufacturer. However, the error of pressure sensor in the sloshing experiment is not accurately estimated in current status. Linearity, hysteresis and resolution of pressure sensor can be evaluated, and a calibration can be done using a reference sensor or through an impact test in the air. But those cannot guarantee the accuracy of sloshing pressure as the sloshing impact is happened within very short time and the medium contacted to the sensor is suddenly changed from the gas to the fluid. The pressure sensor is not calibrated in that situation, usually.

There are various types of pressure-sensing technologies, such as piezoresistive, capacitive, electromagnetic, piezoelectric, optical, and potentiometric types. For measurement of sloshing load, the piezoelectric sensors are mainly applied, and three makers of pressure

---

[*] Correspondence to: Department of Naval Architecture & Ocean Engineering, Seoul National University, 1, Gwanak-ro, Gwanak-gu, Seoul, 151-744, Korea. Tel.: +82 2 880 1543; fax: +82 2 876 9226.
E-mail address: yhwankim@snu.ac.kr (Y. Kim).

http://dx.doi.org/10.1016/j.oceaneng.2014.11.014
0029-8018/

sensor are popular: KISTLER, KULITE, and PCB. Those are presented in Table 1. The sensors of KULITE are mainly piezoresistive type, while those of KISTLER and PCB are mainly piezoelectric type. Many pressure sensors used in the previous studies have small sensing diameters about 2.5∼5.5mm. The pressure sensor should be small as possible and have a high natural frequency as the large sloshing impact is happened on very small region within very short time. Moreover, the pressure sensor needs to be capable of measuring in two phase flows and large range of pressure magnitude.

The piezoresistive sensor uses the piezoresistive effect, which describes the changing resistivity of a semiconductor due to applied mechanical load. This type of sensor is stable to temperature differences between the sensor and the medium. It is good at measuring slowly-varying pressure. On the other hand, piezoelectric sensors use the piezoelectric effect, through which piezoelectric materials produce electric potential when a mechanical load is applied. This type of sensor is regarded as a mature technology with an outstanding inherent reliability. The piezoelectric material has high modulus of elasticity and thus has almost zero deflection and an extremely high natural frequency. Moreover, it has excellent linearity over a wide amplitude range. Therefore, the piezoelectric sensor is proper to the sloshing experiment. However, it is known that an additional signal change can be generated when the sensor touches medium with a different temperature. It can be a weak point to measure the sloshing pressure as there can be temperature difference between the gas and fluid. This sensor is not good at measuring static pressure which produces constant loss of electrons, a source of drift signals. Piezoelectric sensors can be separated into two groups. The first one is charge mode type sensors, which need an amplifier to measure pressure signals. The second is IEPE (Integrated Electronics PiezoElectric) or ICP (Integrated Circuit Piezoelectric) type sensors, which have an amplifier in the sensor. The charged mode type sensor is good for high temperature and the sensitivity of the sensor can be changed. However, it needs a huge amount of space when a large number of measuring points are required. ICP sensors have fixed sensitivity, but the measuring system is relatively simple. Therefore, ICP sensors are mainly used in many sloshing facilities.

In sloshing experiments, it has not been determined which type of pressure sensor is proper to be used to measure the sloshing impact pressure, yet. It is regarded that the piezoelectric sensor is better than the piezoresistive sensor in order to capture the impact pressure, which happens within 1–10 milliseconds. The present study aims to show the results of the comparative study to investigate the characteristics of pressure sensors. One piezoresistive sensor and three piezoelectric sensors including two ICP sensors are tested. Sensitivity to temperature differences between the sensors and medium is tested by exposing cold and hot water to the sensors. Sloshing pressures during the regular and irregular motions are measured. The experimental results are observed and the characteristics of pressure sensors are discussed.

2. Experimental setup

A two-dimensional rectangular tank is used for the tests. The model tank is made of transparent acrylic plate. The thickness of the plate is 20 mm. The media filled inside tank is air and water. The dimension of the two-dimensional rectangular tank and position of the pressure sensor are shown in Fig. 1. The dimensions are 800x600 × 150 mm. For regular and irregular impact tests, the pressure sensors are located on the front surface and top surface of the tank. The motion platform is a hexapod-type with six actuators, as shown in Fig. 2. The capacity of the platform is 1.5 t, and six-DOF regular and irregular motions can be generated.

Four pressure sensors are applied to the sensitivity test: 4005B, 701A, 211B5, 112A21. Those shapes are shown in Fig. 3 and the main features are summarized in Table 2. In order to test the

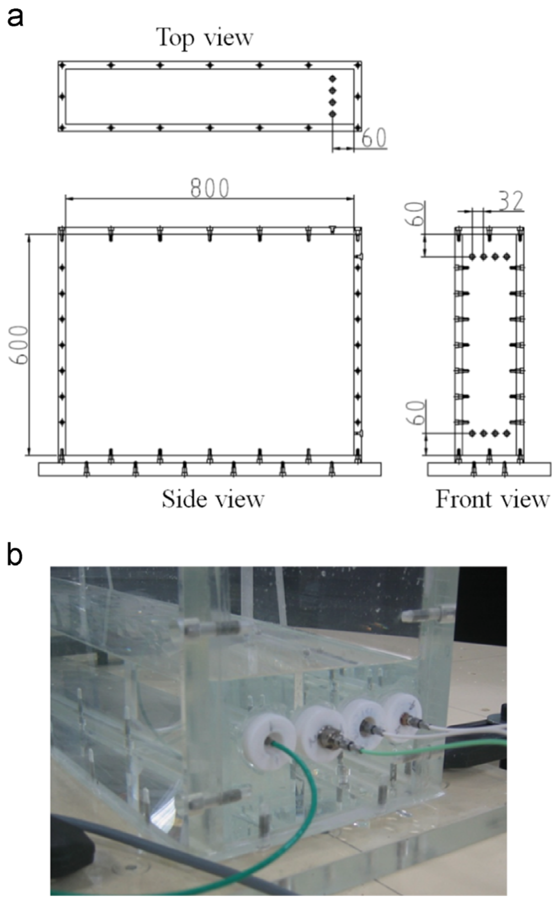

Fig. 1. Test model: (a) dimension of tank and positions of pressure sensor; (b) example of installed sensors.

Table 1
Main features of pressure sensors.

Group	Maker	Model	Diameter (mm)	Reference
Ecole Centrale Marseille	PCB	112A21	5.5	Loysel et al. (2012)
Exxon Mobile	KULITE	XCL-8M-100-3.5BARA	2.6	Yung et al. (2009)
GTT	PCB	112A21	5.5	Loysel et al. (2012)
MARINTEK	KULITE		∼2.5	Loysel et al. (2012)
Pusan National University	KISTLER	211B5	5.5	Choi et al. (2010)
Seoul National University	KISTLER	211B5	5.5	Kim et al. (2012)
Technical University of Madrid	KULITE	XTL-190	∼2.5	Souto-Iglesias et al. (2012)
University of Duisburg-Essen	KULITE	XTM-190	3.8	Loysel et al. (2012)
University of Rostock	PCB	M106B	11	Mehl and Schreier (2011)
University of Western Australia	KULITE	XCL-8M-100-3.5BARA	2.6	Pistani and Thiagarajan (2012)