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Sloshing design load prediction of a membrane type LNG cargo containment system with two-row tank arrangement in offshore applications

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Abstract

This paper addresses the safety of two-row tank design by performing the extensive sloshing model tests. Owing to the uncertainties entangled with the scale law transforming the measured impact pressure up to the full scale one, so called comparative approach was taken to derive the design sloshing load. The target design vessel was chosen as 230 K LNG-FPSO with tow-row tank arrangement and the reference vessel as 138 K conventional LNG carrier, which has past track record without any significant failure due to sloshing loads. Starting with the site-specific metocean data, ship motion analysis was carried out with 3D diffraction-radiation program, then the obtained ship motion data was used as 6DOF tank excitation for subsequent sloshing model test and analysis. The statistical analysis was carried out with obtained peak data and the long-term sloshing load was determined out of it. It was concluded that the normalized sloshing impact pressure on 230 K LNG-FPSO with two-row tank arrangement is higher than that of convectional LNG carrier, hence requires the use of reinforced cargo containment system for the sake of failure-free operation without filling limitation.

Keywords: Sloshing; Strength assessment; Two row arrangement; Cargo containment system; GTT NO96

1. Introduction

Sloshing phenomenon is deemed to be one of the most important design aspects when it comes to the reliable design of Cargo Containment System (CCS) of the offshore Liquefied Natural Gas (LNG) units, such as Floating Production Storage and Offloading (LNG-FPSO), Regasification Vessel (LNG-RV) or Floating Storage Regasification Unit (FSRU). Unlike seagoing LNG carriers where filling ratio is limited to remain above or below a certain filling level, offshore LNG units should be allowed to operate without any filling limitation. It entails a partial filling condition inside the cargo tank and the sloshing impact pressure induced by liquid cargo motion tends to increase compared to those under high or low filling conditions. The relatively large tank size and the above mentioned unlimited filling ratio requirements necessitate the CCS and inner hull structure be designed with care. Some proposed International Maritime Organization (IMO) type B tank for LNG-FPSOs to avoid the potential problems of membrane type cargo containment system under partial filling condition. IMO type B tank has independent inner tank made of either aluminum or stainless steel which is capable of containing the cryogenic liquid cargo without embrittlement. Owing to the use of metallic material for the cargo tank, IMO type B tank is considered to be tolerant of the sloshing impacts. However, the cost of type B tank is not comparable to membrane type CCS not to speak of its limited track record. Moreover, type B tank asks a lot more engineering works to guarantee the safety of hull structure which is vulnerable to embrittlement due to potential leak of the cargo. This is due to the partial secondary barrier concept which is realized by the drip tray with limited capacity.

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Normally, sloshing excitation and resulting impact pressure is known to become more critical when the vessel is exposed to the beam sea condition. The roll motion of the vessel is easily excited and it is highly likely to see resonance behavior between tank motion and liquid cargo motion, eventually leading to a critical situation. Especially, with traditional tank size, the resonance period of fluid-filled tank stays within the period range where ocean wave energy is high. In order to avoid the resonant liquid motion inside the cargo tank, one may consider changing the tank breadth forcing the tank resonance period to shift away from modal period of the wave spectrum. There has been some suggestions through which the violent internal liquid motion may be suppressed, such as the use of the anti-sloshing blanket system (Kim et al., 2013) or the application of wedged tank (Zhang, 2015). One of the most promising ways to achieve this could be a two-row tank arrangement. In this two-row concept, cargo tanks are to be arranged side by side by reducing their breadth by half. This leads to the tank natural period shifting far away from the modal period of the wave spectrum. Typically, the tank natural period in a two-row arrangement falls between 5 and 10 s depending on the filling level, which is far lower than the modal period of roll motion Response Amplitude Operator (RAO). Fig. 1 shows an example of a two-row tank design installed in an LNG-FPSO.

The difficulties entangled with the design of structurally reliable cargo containment system arise due to, fundamentally, the randomness of sloshing phenomenon. The liquid motion inside cargo tank is totally chaotic so that statistical approach is necessarily required to derive design sloshing impact load. To derive the design impact load, so called long-term approach has to be considered so that the probability distribution of the sloshing impact pressure acting on the tank wall throughout the entire life of the structure can be determined, from which the design load with a certain return period is to be chosen. However, unlike the case of derivation of the design bending moment amidship, the strongly nonlinear nature of the sloshing phenomenon prohibit the designer to rely on the transfer function concept because of the dominant influence of higher order effect, which becomes practically of no use once the order exceed 4 or 5. Thus, direct time domain approach, such as computational fluid dynamics or experimental method remain as the only feasible option. Computational fluid dynamics still does not seem to be mature enough to capture the complicated physical behavior of sloshing, such as sharp impact, fluid−gas interaction and so on, not to speak of the computational cost that one has to take for long-term analysis.

Fig. 1. Typical LNG-FPSO with two-row tank.

Many studies on sloshing have been performed since 1950's and the sloshing impact load prediction became an important issue in the design of LNG carriers since 1970's. Faltinsen and Timokha (2009) and many researchers (Kim, 2002, 2003, 2006, 2007; Gavory and de Seze, 2009, Kuo et al., 2009, Malenica et al., 2009; Pastoor et al., 2005; Rognebakke et al., 2009) studied numerically to investigate sloshing phenomena and resulting impact loads acting on tank walls. Recently some computational results using commercial general-purpose flow calculation programs, such as FLUENT, FLOW3D, STAR-CD and OpenFOAM, have been reported for the sloshing analysis (Hwang et al., 2008). Even though general purpose programs may not be proper for prediction of impact loads like in experiments, it was found that they can be used to identify relative magnitudes between different operating conditions or different designs (Ryu et al., 2009a, 2009b, 2009c).

Classification societies have published their own guidance notes on the safety assessment of membrane type cargo containment system, such as American Bureau of Shipping (2014), Bureau Veritas (2011), Det Norske Veritas (2014), Lloyds Register (2009). Different procedures have been taken by different classification societies possibly due to the complexity involved in the physics behind it. Traditionally, so called short-term approach which considers the sea states of the highest H_s on the wave scatter diagram only, was considered to be appropriate for the design sloshing load prediction. Later on, more extensive sloshing experiment revealed the fact that the largest impact pressure may occur in the sea states of lower H_s. The long-term approach is now considered to be standard procedure thanks to its capability to take into account higher impact pressure in lower sea state under partial filling condition (Rognebakke et al., 2009, Gervaise et al., 2009).

In this paper, the safety of two-row design was validated through extensive sloshing model test. Due to the uncertainties related to the scale law on the impact pressure, comparative approach was taken to derive the design sloshing load. The target design vessel was 230 K LNG-FPSO with tow-row tank arrangement and the reference vessel, for the purpose of the comparative approach, was 138 K conventional LNG carrier. Starting with the site-specific metocean data, ship motion analysis was carried out with 3D diffraction-radiation program, then the obtained ship motion data was used as 6DOF tank excitation for subsequent sloshing model test and analysis. Some sub-studies have been carried out to minimize the number of test cases, such as sea state selection, filling ratio grouping and so on. Finally, the statistical analysis was carried out with obtained peak data and the long-term sloshing load was determined out of it.

2. Reference vessel − 138 K LNGC

As stated earlier, the measured sloshing impact pressure from model test needs to be scaled up to the full scale one, but

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