International Journal of Offshore and Polar Engineering (ISSN 1053-5381)
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Vol. 19, No. 4, December 2009, pp. 264–270

LNG Sloshing: Characteristics and Scaling Laws

T.-W. Yung, Z. Ding, H. He and R. E. Sandström
ExxonMobil Upstream Research Company, Houston, Texas, USA

Understanding the local behavior of sloshing pressure is essential for the design of LNG containment systems, particularly for operations in offshore environments. Extensive sloshing experiments have revealed that local pressures at temporal resolution on the order of 20 kHz and spatial resolution of 5 mm for scaled models up to 1:20 are stochastic; peak pressure varies dramatically from cycle to cycle even under a simple harmonic excitation in 1 degree of freedom. In addition, such pressures are strong functions of local geometry such as corrugations and raised invar edges, as well as physical and thermal conditions of the ullage. As such, the phenomenon is very challenging for predictions using existing numerical algorithms. To obtain proper design values for the containment system, scaled model tests must address the above parameters and appropriate scaling laws must be identified. In this paper, we assimilate fundamental aspects of sloshing from first principles to identify relevant dimensionless numbers necessary for the dynamic similarity of scaled model tests involving local pressures. Various experiments were carried out to support the relevance of such dimensionless numbers; this paper discusses experimental results and their implication in scaling.

INTRODUCTION

Impulsive loads that resulted from body entry into fluids have been extensively studied from the turn of the 20th century. von Kármán (1929) and Wagner (1932) employed potential flow theory to study the 2-D cylinder and wedge entry problem, respectively, by neglecting the effects of gravity. (Fluid acceleration during impact is much larger than that of gravity). The potential function was assumed to be $\phi = 0$ at the mean free surface $z = 0$. This condition was subsequently relaxed by many investigators, noticeably Zhao and Faltinsen (1993) and Zhang, Yue and Tanizawa (1996). Solutions obtained from these techniques are deterministic, i.e. the same initial and boundary conditions always lead to the same solutions.

Abramson, Bass, Faltinsen and Olsen (1974) reported sloshing pressure within a narrow cross-section of an LNG tank form that underwent harmonic oscillations. Their experiments showed that even under harmonic oscillations, the pressure variation is neither harmonic nor periodic, since the magnitude and duration of the pressure peaks varied from cycle to cycle. In essence, the sloshing pressures are stochastic and followed a Weibull distribution.

The recent availability of high-speed computing, visualization, data acquisition systems, massive data storage and miniature sensors has enabled us to gain insights on impact behavior that were simply unavailable before. Aided by these technological advancements, we offer our observation of the sloshing load characteristics in this paper.

Because of the stochastic nature and very high demand in temporal and spatial resolutions, numerical predictions of sloshing pressures from existing algorithms are of limited value for design, and model tests form a more credible design basis. In applying experimental observation to the design of prototype structures, the biggest challenge for the experimental approach is how to scale the model testing results to prototype scale, or, in this case, establish scaling laws for liquid sloshing. Very limited work has been published on scaling laws for sloshing. Early research carried out by a group of researchers (Abramson, Bass, Faltinsen and Olsen, 1974; Bass, Bowles and Cox, 1980) started by identifying dimensionless numbers from the Π theorem that could affect the scaling of sloshing impact pressure. These researchers conducted a limited series of tests to validate the relevance of these dimensionless numbers and concluded that viscosity and surface tension are of secondary importance and need not be included in scaling. Bass, Bowles and Cox (1980) also concluded that the compressibility effects need to be scaled properly, and the ullage pressures should be Froude scaled. In addition they suggested that ambient air being used in models was probably too stiff to represent LNG vapor at full scale, resulting in potentially unconservative estimates of impact pressure. Reviewers of that paper expressed similar views. However, since that paper judged the use of Froude scaling for the liquid motion to be sufficiently conservative, the procedures they recommended do not explicitly modify the vapor.

In recent work, Dias, Ghidaglia and Coq (2007) performed an analytical study of the sloshing problem using 3 types of 2-phase impact models. Their analysis led to a conclusion that both Froude's law and acoustic scaling are relevant to the sloshing problem. However, the authors also acknowledged that their approach exhibited a discrepancy between their formula for calculating impact pressures and some model testing results.

Yung, Sandström, He and Minta (2009) proposed a dimensionless number, the *Interaction index* (Ψ) by the consideration from first principles of a set of dimensionless field equations and the interaction of immixable vapor and liquid at the interface under various thermal conditions. They substantiated the importance of Ψ in sloshing by experiments with condensable and noncondensable vapor and water. They illustrated that ambient vapor/liquid properties and their interaction during an impact event characterized by Ψ can alter maximum pressures by as much as 2 orders of magnitudes up to the liquid's acoustic limit. This finding and previous related studies provide the basis for scaling laws governing LNG sloshing and are discussed below.

CHARACTERISTICS OF SLOSHING LOADS

For tank sloshing problems, the events governing design at high and partial fills are, respectively, jet impacts (Fig. 1) and breaking

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Received September 4, 2009; revised manuscript received by the editors October 21, 2009. The original version (prior to the final revised manuscript) was presented at the First ISOPE Sloshing Dynamics and Design Symposium, part of the 19th International Offshore and Polar Engineering Conference (ISOPE-2009), Osaka, June 21–26, 2009.
KEY WORDS: Sloshing, physics, scaling laws, similitude, Euler number, Froude number, Interaction index, hydrodynamics, liquid impact.