Annals of Nuclear Energy 76 (2015) 218–225

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

Experimental investigation of slosh parametric instability in liquid filled vessel under seismic excitations

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ARTICLE INFO

Article history:
Received 26 April 2014
Received in revised form 23 September 2014
Accepted 26 September 2014
Available online 17 October 2014

Keywords:
Parametric instability
Sloshing
Mathieu equation
Shake table test
Seismic excitations

ABSTRACT

Present investigation aims to analyze parametric instability at free surface of liquid in rectangular vessel under seismic excitations close to primary resonance mode. Analytical solution is discussed and stability chart is plotted to highlight different regions of stability and instability. The analysis is based on solving the Mathieu equations derived from incompressible and inviscid fluid. Shake table tests are performed to evaluate the instability behavior under vertical seismic loads. The shake table tests are carried out in a vessel of aspect ratio $h/L = 0.5$. Comparison of test results with analytical solution is presented. The analytical solutions are obtained without considering damping effect leading to more conservative results compared to the experimental results.

1. Introduction

In Liquid Metal Fast Breeder Reactors (LMFBR) sodium is widely used as a coolant in Nuclear Power Plants (NPP) owing to its favorable properties. The coolant is housed in the main vessel and has a large free surface area which is highly prone to oscillate under external excitations viz. seismic events. During seismic excitations, the free surface of coolant experiences standing/moving wave motion known as sloshing (Abramson, 1996). Sloshing is a complicated phenomenon with strong nonlinearity and its behavior depends on the external excitation, tank geometry and liquid properties (Ibrahim et al., 2001). Depending on the frequency and amplitude of external excitation, the coolant in the vessel can undergo large amplitude oscillations exerting hydrodynamic loads on the container. Dynamic loads during sloshing can damage the main vessel leading to failure of the structure and coolant leakage. Besides sloshing in main vessels of NPP, a clear understanding of sloshing characteristics is also essential in spent fuel storage pool structures. Such structures should assure the safety of the stored spent fuels and prevent over flow of contaminated cooling water over the surrounding areas without entering into unexpected instability during sloshing. All liquid-filled structures should assure the safety of the structure and liquid free surface against design earthquake loads. Thus the problem of sloshing has attracted many researchers and engineers targeting to understand the complex behavior of sloshing and to design the structures to suppress it.

Analytical approaches and related asymptotic solutions to predict sloshing motion have been explored by several investigators (Faltinsen, 1974; Abramson, 1996; Hill, 2003; Ibrahim, 2005). Sloshing analysis is also carried out employing wide varieties of numerical formulations using finite element method (Haroun, 1980; Aslam, 1981; Liu and David, 1982; Cho and Lee, 2004), finite difference method (Chen et al., 1996; Frandsen, 2004) and smooth particle hydrodynamics (Shao et al., 2012; Wang et al., 2013). Experimental and numerical studies have been performed to find sloshing frequencies, sloshing heights and hydrodynamic pressure for liquid metal reactors by Sakurai et al. (1989) and Chang et al. (1989). Numerical simulations have been carried out to find the hydrodynamic loadings on vessels in a sodium fast reactor by Chellapandi et al. (2012). Comparison of sloshing in flexible tanks accounting fluid structure interaction with simplified mechanical models has been discussed (Nicolici and Bilegan, 2013). Sloshing studies related to spent fuel storage pool structures have been carried out by Choun and Yun (1999), Mitra and Sinhamahapatra (2007). Extensive studies have been done revealing the important aspects of sloshing phenomenon considering pure horizontal excitations as primary; meanwhile the sloshing under vertical excitations is considered secondary.

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http://dx.doi.org/10.1016/j.anucene.2014.09.056
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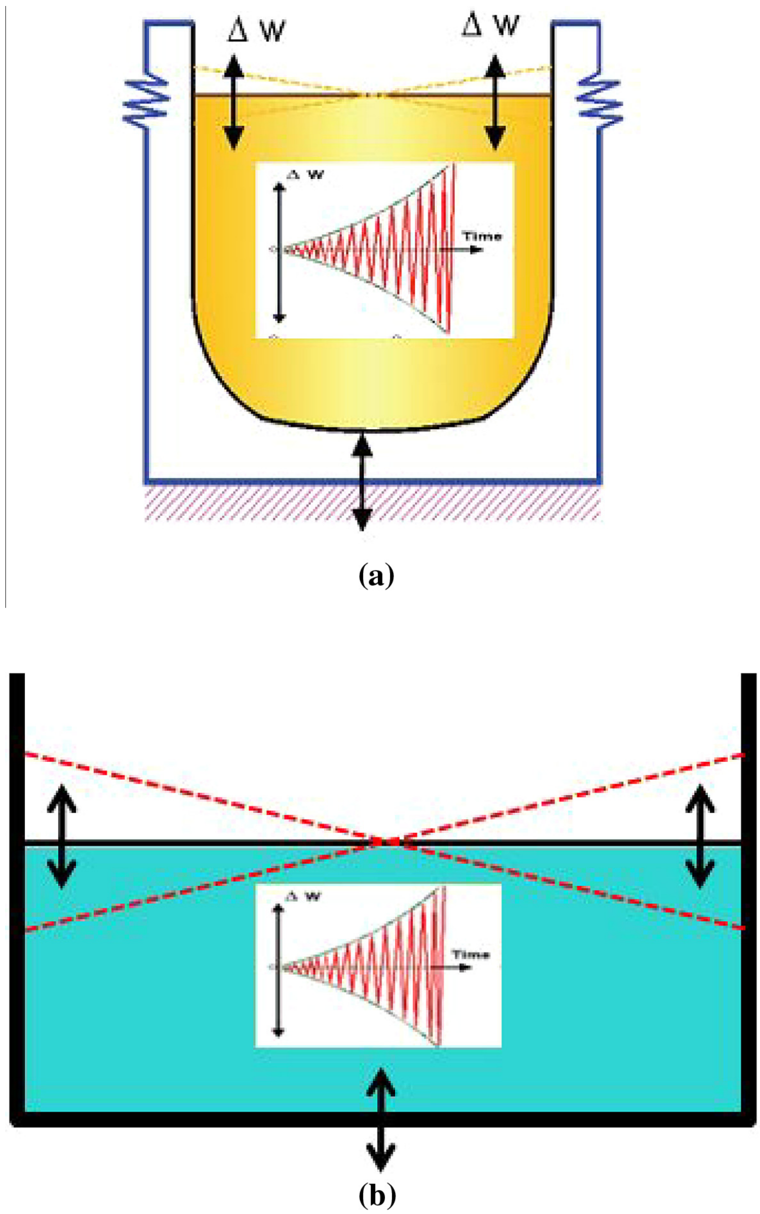

Fig. 1. Schematic of liquid free level oscillations under vertical excitation in NPP (a) Sodium free level oscillation under vertical excitation in PFBR (b) Liquid free level oscillation under vertical excitation in rectangular tank.

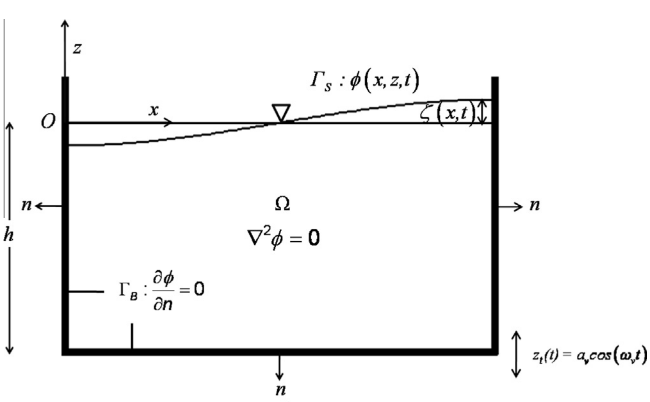

Fig. 2. Sloshing tank and its boundary conditions.

Under vertical excitations, liquid free surface can undergo unbounded out of plane displacements called parametric instability or parametric resonance. Liquid free surface undergoes parametric instability when the external excitation is equal to integral multiple of natural frequency of the system. Although parametric instability is secondary, the system may undergo failure near the critical frequencies of parametric instability, which cannot be neglected in NPP where utmost safety is required. Benjamin and Ursell (1954) investigated the problem theoretically and concluded that the response of the plane free surface of fluid under vertical excitation is governed by Mathieu equation (Mc Lachlan, 1957). Khandelwal and Nigam (1981) have studied the parametric instability of liquid free surface in rectangular tanks analytically. Dodge et al. (1964), Miles (1984) have studied the liquid surface oscillations under vertical excitation in cylindrical tanks. The parametric instability in liquid filled cylindrical shells has been addressed by Chiba et al.