Nuclear Engineering and Design 332 (2018) 99–110

Contents lists available at ScienceDirect

Nuclear Engineering and Design

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

Seismic sloshing effects in lead-cooled fast reactors

M. Jeltsov*, W. Villanueva, P. Kudinov

KTH Royal Institute of Technology, Stockholm, Sweden

ARTICLE INFO

Keywords:
LFR
CFD
Seismic sloshing
FSI
Gas entrapment
Seismic isolation

ABSTRACT

Pool-type primary system can improve the economy of lead-cooled fast reactors. However, partially filled pool of heavy liquid metal poses safety concerns related to seismic loads. Violent sloshing during earthquake-initiated fluid-structure interaction can lead to structural failures, gas entrapment and potential core voiding. Seismic isolation systems can be used to reduce the structural stresses, but its effect on sloshing is not straightforward.

This paper presents a numerical study of seismic sloshing in ELSY reactor. The purpose is to evaluate the effects of seismic isolation system on sloshing at different levels of earthquake. Sloshing is modeled using computational fluid dynamics with a volume of fluid free surface capturing model. Earthquake is simulated using synthetic seismic data produced in SILER project as a boundary condition. Simultaneous verification and validation of the numerical model using a dam break experiment is presented.

The adverse resonance effect of seismic isolation system is demonstrated in terms of sloshing-induced hydrodynamic loads and gas entrapment. Effectiveness of seismic isolation system is discussed separately for design and beyond design seismic levels. Partitioning baffles are proposed as a potential mitigation measure in the design and their effect is analyzed.

1. Introduction

In this work we focus on the assessment of dynamic loads on the reactor vessel structures in case of seismically induced sloshing of heavy liquid metal coolant. LFR (Lead-cooled Fast Reactor) is identified by the GIF (Generation IV International Forum) is one of the six most promising reactor designs that can advance the civil nuclear power to the next level (U.S. DOE Nuclear Energy Research Advisory Committee and The Generation IV International Forum, 2002; International Forum, 2009). There are several LFR designs under development worldwide (Alemberti, 2016). Most of them feature pool-type primary system that accommodates the main reactor components, i.e. core, pumps, SGs (Steam Generators) and coolant. Such configuration of partially-filled pool of high-density liquid raises concerns related to seismicity and coolant sloshing.

Nuclear power plants have to be designed to withstand severe internal and external natural and man-made hazards, including earthquakes (Roesset, 1998). The level of safety demanded of an earthquake-resistant design depends on the potential consequences which, in nuclear applications, are severe. In addition to the public safety concerns there is a monetary issue for the plant owner. Comprehensive review of earthquake-related problems specific to nuclear reactors can be found in (Roesset, 1998; Housner and Hudson, 1966; Newmark and Hall, 1978; Stevenson et al., 1984; Campbell et al., 1998).

When a structure or a piece of equipment is subjected to earthquake motions, its base tends to move with the ground on which it rests. If this component is sufficiently rigid, it moves with the motion of its base, and experiences the dynamic forces similar to those associated with the base accelerations. Since this motion is relatively rapid, it causes stresses and deformations in the item considered. However, if the component is flexible, large relative motions or strains can be induced in the component because of the differential motions between the masses of the component and its base. In order to survive the dynamic motions, the element must be strong enough as well as ductile enough to resist the forces and deformations imposed on it. In assessing the seismic response, it should be considered that the seismic actions are in addition to those already existing, i.e. dead load, live load, thermal effects, etc. (Newmark and Hall, 1978) The dynamic behavior of nuclear island structures is affected in several ways by the liquid pools (Housner, 1957; Housner, 1963; Zhengming et al., 2007). Mass of the liquid reduces the natural frequency compared to empty structures. Wave propagation in liquids and their slamming on the structures contributes to hydrostatic and dynamic stresses acting on the pool walls.

Pools with free surfaces can experience sloshing. Since LFRs use high density liquids as coolants, sloshing has to be carefully accounted for in the design and safety analysis (Ma et al., 1982; Chang et al.,

---

* Corresponding author at: Division of Nuclear Engineering, Department of Physics, School of Engineering Sciences, KTH Royal Institute of Technology, Roslagstullsbacken 21, Stockholm SE-106 91, Sweden.

E-mail addresses: jeltsov@kth.se (M. Jeltsov), walter@safety.sci.kth.se (W. Villanueva), pkudinov@kth.se (P. Kudinov).

https://doi.org/10.1016/j.nucengdes.2018.03.020
Received 5 December 2017; Received in revised form 13 March 2018; Accepted 14 March 2018

Nomenclature

Abbreviations

ALE	Arbitrary Lagrangian-Eulerian
BDBE	Beyond Design Basis Earthquake
CDF	Cumulative Distribution Function
CFD	Computational Fluid Dynamics
CFL	Courant–Friedrichs–Lewy
DBE	Design Basis Earthquake
ELSY	European Lead-cooled SYstem
FRS	Floor Response Spectrum
FSI	Fluid-Structure Interaction
GIF	Generation IV International Forum
HRIC	High-Resolution Interface-Capturing
LFR	Lead-cooled Fast Reactor
LNG	Liquefied Natural Gas
LRB	Lead-Rubber Bearing
MPS	Moving-Particle Semi-implicit method
OBE	Operational Basis Earthquake
RANS	Reynolds-Averaged Navier-Stokes
RIA	Reactivity-Initiated Accident
SG	Steam Generator
SI	Seismic Isolation
SL-1	Stationary Low-power reactor number One
SPH	Smooth-Particle Hydrodynamics
SILER	Seismic-Initiated event risk mitigation in LEad-cooled Reactors
US NRC	United States Nuclear Regulatory Commission
VOF	Volume Of Fluid

1988). Sloshing means any motion of the free surface, i.e. interface between a gas and a liquid, in its container (Ibrahim, 2005). Sloshing can be caused by internal (e.g. vortices, chemical reactions) or external disturbances (e.g. seismic events, motion of tanker ships and trucks). Increased mechanical loads during sloshing-induced FSI (Fluid-Structure Interaction) can lead to structural failures, i.e. plastic deformation when exceeding the yield stress and rupture when exceeding the ultimate tensile strength. This phenomenon can be particularly critical in the upper part of the LFR primary vessels where lead-argon interface intersects with many reactor internal structures important for safe operation (e.g. decay heat removal heat exchangers, steam generators (SGs), core barrel, above core structures). Moreover, upward moving liquid in the waves can cause high pressure impacts on the reactor roof (Zhengming et al., 2007). The SL-1 (Stationary Low-power reactor number One) reactor accident in US can be used as an illustration of the magnitude of forces created by liquid motion, although in this case it was not induced by seismic sloshing. Sudden enormous power excursion caused water to accelerate 0.76 m upwards and struck the vessel head at 49 m/s with a pressure of 690 bar causing the 12,000 kg steel vessel to jump 2.77 m before it dropped into its prior location (Kunze, 1962). Another potential consequence of violent sloshing, in addition to mechanical damage, is the gas entrapment at the disturbed liquid-gas interface. Transport of the gas to the core region can lead to (i) RIA (Reactivity-Initiated Accident) due to locally positive void reactivity coefficients in LFRs, or (ii) local dry-out of the fuel rods (Jeltsov and Kudinov, 2011; Jeltsov et al., 2018).

One of the mitigation strategies in case of an earthquake is to use an SI (Seismic Isolation) system. SI system is based on special devices dispositioned between the ground and the superstructure (e.g. nuclear reactor building) that would accommodate larger displacements and absorb energy (see examples in (Perotti et al., 2013; Kumar et al., 2015)). The increase in period/decrease in frequency in the motion of the structure compared to the ground, however, brings the system closer to liquid resonance conditions (Jeltsov et al., 2015; Nezo and Carrasco, 2007; Lo Frano and Forasassi, 2010).

The goal of this paper is to improve the understanding of the sloshing phenomena in the primary system of an LFR. An important aspect studied is the effect of SI system on the sloshing response. The paper starts with an overview of sloshing analysis methods and discussion of selected works in literature (Section 2). Then the design of ELSY (European Lead-cooled SYstem) reactor concept and the seismic cases are presented (Section 3). In order to increase confidence in this “predictive-mode” study, serious efforts are spent on solution verification and validation (Section 4). Main results include description of sloshing response in ELSY primary system in terms of hydrodynamic loads and gas entrapment. Implications of using SI system at different earthquake levels is discussed (Section 5). Finally, a simple mitigation measure is proposed and analyzed.

2. Overview of sloshing modeling approaches

Earliest sloshing analysis approaches include mass-spring and tank-liquid analogies (Housner and Hudson, 1966; Housner, 1957; Housner, 1963; Ibrahim, 2005). These approaches were suitable for linear (superposition of waves of different components) sloshing that occurs at small external perturbations. Seismic sloshing response, however, is mostly non-linear with large excitation amplitudes. The situation is more complex when the excitation is close to the natural frequency of sloshing.

Development and use of CFD (Computational Fluid Dynamics) codes based on finite element methods on FSI problems with special attention to the non-linear free surface motion and the tank buckling dates back to early 1980s. In general, there are two approaches to model free surfaces (Mahaffy, 2014). First involves construction of a Lagrangian grid to define and track the interface. This model provides high accuracy for continuous free surface problems but requires re-meshing. Second one is based on fixed grid Eulerian methods which allow for capturing discontinuous and breaking interfaces but require special treatment to maintain sharp interfaces.

One of the first numerical tools used for FSI problems in nuclear field is the fluid-structure analysis code FLUSTR based on Arbitrary Lagrangian-Eulerian (ALE) formulation that can model the fluid flow and solid behavior simultaneously (Ma et al., 1982; Chang et al., 1988; Liu, 1981; Liu and Ma, 1982). ALE provides means for separate treatment of and interaction between fluid and structural domains. ALE method was also used to study the structural response and lead sloshing during a safe shutdown earthquake in the ELSY reactor where it was found that the presence of internal components reduces sloshing (Lo Frano and Forasassi, 2012). The effect of different configurations of baffles on the liquid sloshing in the AP1000 top water tank and in a partially-filled cubic tank have been numerically investigated using ALE models in (Eswaran et al., 2009) and in (Zhao et al., 2014; Zhao et al., 2017; Zhao et al., 2017), respectively.

A sub-class of Lagrangian methods are meshless particle-based methods. These schemes represent a fluid by a large number of calculation points (particles) moving with flow where the partial differential operators appearing in the Navier-Stokes equations are modeled by the interactions between particles. Examples include SPH (Smooth-Particle Hydrodynamics) (Gingold and Monaghan, 1977) and MPS (Moving-Particle Semi-implicit) methods (Koshizuka and Oka, 1996). SPH analysis of a dam break and centralized liquid sloshing experiments have shown that the method predicts the general flow fields reasonably well but requires special attention to accurately model the viscosity and wall effects (Vorobyev et al., 2011). Development of an SPH method using schemes from MPS framework is described in Gotoh et al. (2014) and Hwang et al. (2014).

Most common examples of Eulerian methods are the VOF (Volume