CFD SIMULATION OF SLOSHING PHENOMENA INDUCED BY SEISMIC EVENTS. APPLICATION TO ALFRED

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Abstract

The pathway towards the validation of the CFD simulation of sloshing phenomena induced by seismic events is illustrated. The aim of the work is to qualify the CFD for the simulation of seismic induced sloshing effects of the primary coolant in a GEN-IV reactor. The scaling laws have been established so that the CFD validation could be supported by experimental campaigns using the SHAKESPEARE platform. In the first stage, a partially filled vertical cylinder was employed for experimental tests and numerical simulations under horizontal harmonic forcing. In the second stage, a mock-up inspired by the current design of ALFRED is built and operated in water. The validity of the numerical model is ascertained by comparison with the experimental results performed on artificial harmonic forcing. Finally, the CFD model is run applying existing seismic loads taken from a real significant earthquake. Considerations on the impact load on internal structures foreseen in ALFRED are extrapolated.

Keywords: *PASCAL, Seismic events, sloshing, CFD simulation, ALFRED*

Introduction

The work presented here was performed in the framework of the H2020 EURATOM PASCAL project [1]. Among other objectives, the PASCAL project addresses the following task, quoted in the proposal: *"To further enhance the modelling and computational readiness level of sloshing dynamics in compact liquid-metal filled pools and to retrieve the expected impact forces and dislocations on the involved components for a reference system (e.g. ALFRED)"*. The Advanced Lead-cooled Fast Reactor European Demonstrator (ALFRED) is one of the innovative concepts implemented in support of the LFR technology.

The sloshing phenomena appear when a vessel partially filled with a liquid undergoes some movement with the consequence that the free-surface acquires momentum and deforms in multiple different ways during the displacement. When the vessel is displaced or rotated, it applies an acceleration to the external border of the fluid. The fluid inside conforms itself to the vessel acceleration by developing an internal pressure gradient which is then converted in motion of the fluid. The fluid will show a motion relatively to the tank reference frame, inducing the free-surface deformation.

In the case of a forcing with a periodical component getting close to the natural frequencies of the tank, a coupling can appear and the liquid displacement may greatly exceed the forcing amplitude. In such a situation, it is feared that the force exerted by the fluid can put in danger the vessel stability or structural integrity.

Our purpose in the PASCAL project is to evaluate the effective possibility that sloshing can impact the resilience of a particular tank, i.e. the main vessel and internal components of the ALFRED demonstrator under seismic load. After understanding the basics of the phenomena, the underlying physics and the controlling parameters, this knowledge is used to define correctly an experimental campaign performed by the von Karman Institute for Fluid Dynamics (VKI) using the SHAKESPEARE facility [2]. Some constrains must be taken into consideration: the shaking table and related instrumentation capabilities, the possibility to numerically reproduce the experimental tests by means of Computational Fluid Dynamics (CFD) tools, and compare the numerical results with the experimental ones for validation. The CFD tool must be sufficiently versatile to allow for comparison with any experimental output data.

We briefly illustrate the rationales for the use of water in the experimental campaign. Ideally, the fluid should be Lead or Lead-Bismuth (LBE) but none of them are liquids at ambient temperature and it is too costly to build a sloshing experimental setup operating at high temperatures. Mercury (Hg) is the only heavy metal liquid at room temperature and relatively easy to purchase in sufficient quantities, but its specific weight limits the volume operable, while its opacity limits the instrumentation. Moreover, use of Hg is subject to health safety concern.

Water offers some very practical advantages: unlimited availability without particular safety concern, larger volume thanks to the lower density and more precise instrumentation. However, the density being much different from the Lead one, we must demonstrate why this is not an issue. Dimensional analysis will show that, in the present framework, water can be representative of Lead or LBE upon applying the correct scaling. This aspect is approached in the first section of the paper.

Next, the numerical simulation setting and the experimental set-up were discussed, followed by the illustration of the first satisfying numerical results and their comparison with the experimental ones. Then the CFD simulations of the ALFRED mock-up under artificial harmonic forcing and real seismic load from earthquakes were presented, with particular focus on the Romanian 1977 earthquake.

Dimensional analysis

For the sake of simplicity and guided by a rapid literature survey [3, 4], a cylindrical vertical tank partially filled with water is chosen and made it subject to periodic horizontal forcing in a single direction. According to the inviscid theory, when the container water filling height is at least 1.5 times its radius, then the effect of the bottom on the resonance frequency becomes negligible. Therefore, the largest transparent cylindrical vessel easily purchasable that can be operated by the SHAKESPEARE table has a diameter of ~60 cm.

The first asymmetrical natural frequency formula for the free-surface in a cylinder of radius R partially filled with a liquid makes use of the geometrical parameter k_{11}=1.841/R. The simplified frequency dispersion relation is then given by $\omega_{11}^2 = g \cdot k_{11}\left(1 + \sigma \cdot k_{11}^2 / \rho \cdot g\right)$, with ω_{11} the first asymmetrical pulsation (in Rad/s), g the gravity acceleration, ρ the fluid density and σ its surface tension.

The relative effect of the surface tension is smaller for larger radius and is already negligible for R= 30 cm. Since we want to get valid extrapolations for ALFRED whose vessel is a cylinder with several meters of diameter, in both cases, the dispersion relation simplifies to $\omega_{11}^2 = g \cdot k_{11} = 1.841\, g / R$ with the natural frequency given by $f_{11} = \omega_{11} / 2\pi = 0.667 / R^{1/2}$.

Numerical implementation and experimental reference configuration

In the following, the sloshing and its CFD implementation is briefly described. The CFD simulation is based on the Multiphase flow model and Volume of Flow (VoF) method. The laminar setting is adopted since the turbulence setup proved to be excessively dissipating. Convection and temporal discretization are second order. Adaptive refinement of the free-surface is applied. The input displacement data provided in the analytical form to the SHAKESPEARE table is imported in STAR-CCM+ and used directly. Translation motion is set by using the rigid body mesh moving method.

The main settings of the numerical model are: i) Trimmed mesh with base size 5mm; ii) Local refinement only boundary layer: 3 cells, 50% of mesh size; iii) Dynamic local refinement around the free surface: 2 levels, every 5 time-steps; iv) Time-step controlled by two CFL criteria with STAR-CCM+ default values: CFL limiter on the velocity (mean 0.5, max 5), CFL limiter on the free-surface velocity (0.4).

A typical sloshing simulation is completely controlled by a series of parameters: i) time-lapse of flow at rest (without forcing); ii) asymptotic forcing amplitude; iii) asymptotic forcing frequency as a multiple of the natural frequency; iv) number of periods to reach the asymptotic amplitude.

The experiment is measuring the free-surface position in correspondence with four vertical line probes located near the cylinder wall symmetrically on the reference axes with one axis in the forcing direction. The height of the free-surface in coincidence with a line-probe is obtained with high accuracy by measuring the mean vertical position in a small neighbourhood around the probe.

In order to refine, adapt and validate the CFD modelling, the experimental tests performed by VKI are used for comparison. The first experimental campaign investigated the behaviour of a cylindrical vessel with flat bottom of radius R=30 cm filled with water for 45 cm height. The vessel is fixed to the SHAKESPEARE seismic platform which will impose periodic horizontal displacements of various intensities, below the centimetre range, at a main frequency near the first asymmetrical natural mode f_0 = 1.236 Hz and the amplitude of the sinusoidal forcing A_f = 4 mm. The precise value of the natural pulsation is w_0 = 7.77 rad/s. Three tests have been shared for CFD validation purpose: i) 92% natural frequency (linear test), ii) 92.55% (near transition), iii) 92.75% (transition).

The free-surface height at four horizontal positions is monitored. In Fig.1, the comparison of the experimental test case at 92% of the natural frequency for 60 s is shown. While the numerical precision can still be improved, the comparison with the experimental data is already very good. The modulation of the signal is due to the interference of the forcing frequency with the natural one. The signal at the forcing frequency builds up very fast to constant amplitude, while the natural frequency signal is built up at the beginning and then shows slow exponential decay.

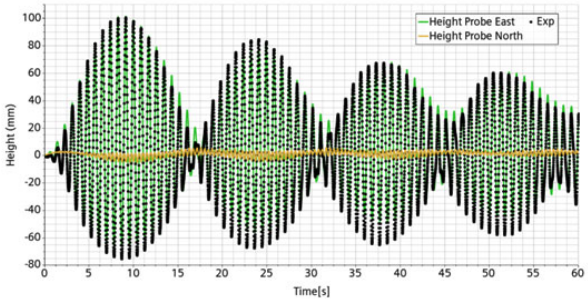


Fig. 1. Linear test 92%$f0$. Experimental-numerical free-surface height comparison

In [3], the asymptotic sloshing heights and the stability map of the first natural frequency mode are provided. The diagram of the solicitation amplitude versus frequency together with its regions of interest taken from [3] (see Fig.2) is used in our work to demonstrate experimental control and validate the numerical representation. Our numerical results for the cylinder radius 30 cm are anticipated in red.

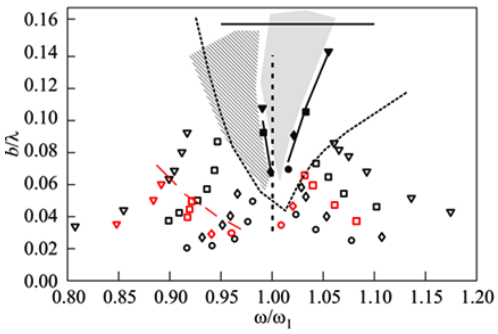


Fig. 2. Amplitude-frequency diagram for cylinder radius 7.8 cm and four different forcing amplitudes A_f/R: triangle for $A_f/R=0.267$, square for $A_f/R=0.0133$, rhombus for $A_f/R=0.0067$ and circle for $A_f/R=0.0033$. Dashed lines indicate the stability limit of the asymmetric planar wave. Our results are given in red.

The stability map suggests that there is a transition to chaotic behavior once the forcing frequency gets close to the resonance frequency. Chaos arises numerically when the frequency is set to $0.925f_0$, while in the experiment it appears at $0.9255f_0$. At $0.9275f_0$, the oscillation initially rises much higher numerically than experimentally, delaying the appearance of the orthogonal motion. However, the global behavior is quite similar. The numerical and experimental results in terms of free-surface height are shown in Fig. 3. Two pictures of the free-surface at $0.925f_0$ are shown on Fig 4.

Looking at what are the onset features of the transition, we simulate also the frequencies $0.923f_0$ and $0.924f_0$ and we notice that, with respect to the reference case at $0.92f_0$, the frequency increase to $0.923f_0$ has the effect of increasing the maximum amplitude and to delay the first modulation node. Increasing further the frequency to $0.924f_0$, the maximum amplitude is further increased and the first node further delayed, showing similar trend with the experiment. We can thus conclude that the bifurcation is captured within 0.1% of the frequency and it is particularly impressive considering that around the bifurcation the experiment is not fully reproducible, probably due to long time surviving slow internal coherent recirculation flows.

In the stability map shown in Fig. 2 the bifurcation for the corresponding amplitude arises at about 94.5% of the first asymmetrical mode. This means that the map is much less universal than expected, the main difference between the experiments being the cylinder radius. Because of this unexpected dependence of the stability map on the cylinder radius, we decided to investigate this aspect numerically. To get a better idea on the position of the transition curve with our larger cylinder, we performed a series of simulations at different amplitude and frequencies. More details about these simulated cases are given in the PASCAL project deliverable D13 [5]. The results are superposed on the stability map as given in [3] and shown in red in Fig. 2. For our larger cylinder, there is a clear extension of the chaotic region towards the lower frequencies. On the right side of the map the transition boundary between asymmetric planar and circular motion does not depend on the radius. However, the relative amplitude of the asymptotic wave is lower with the larger radius.

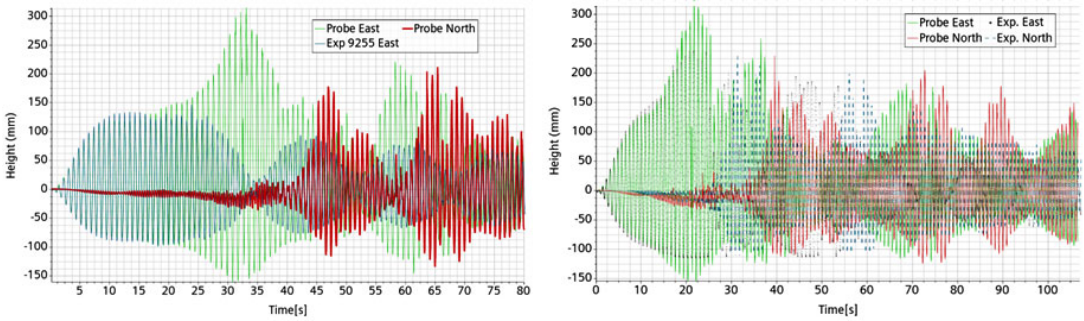


Fig. 3. Numerical-experimental free surface height, frequency at $0.925f_0$ and $0.9275f_0$

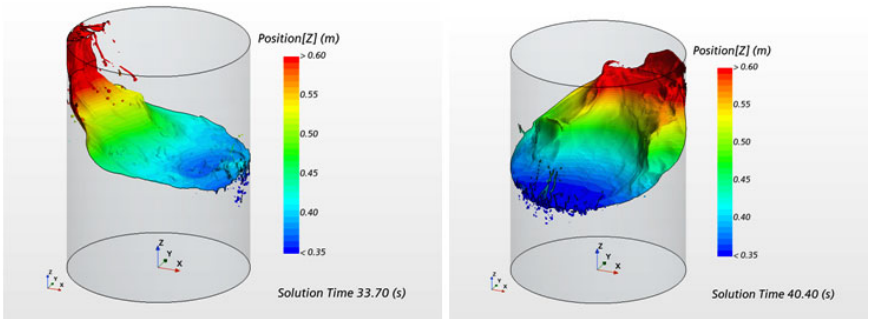


Fig. 4. Free-surface around the first north, $0.925f_0$ (left) and east, $0.9275f_0$ (right) peak amplitude

CFD modelling and validation of ALFRED mock-up under harmonic forcing

Thanks to the increased confidence with the experimental and the numerical setup and the information exchange between them, the investigation is pushed further and is switched from the simple test case of the cylinder to a more practically oriented one able to give relevant information about qualitative and quantitative effects that seismic induced sloshing could produce on ALFRED.

The CFD geometry of the ALFRED mock-up (see Fig. 5) consists of a vessel and three groups of three components distributed evenly at 40 degrees intervals: Steam Generators (SG) 60 mm diameter plain cylinders; Primary Pumps (PP) 50 mm diameter; Decay Heat Removal (DHR) with 5 mm thick walls. The probes position in the numerical model is indicated in Fig. 5 (right). The mean height over a small (~3mm radius) centered domain is effectively measured.

The simulated case has the following inputs: displacement provided by VKI with terminal amplitude 30 mm and frequency 1.08 Hz. The case is characterized by quite large flow displacement far from the linear behavior and with traveling waves indicating a more shallow-water behavior. The numerical (thicker) and experimental (thinner) elevation above the initial level at the probe location is shown on Fig.6 for 30s. The agreement is reasonably good. The maxima are slightly and progressively shifted, maybe because of a very slight delay in the response time of the sloshing table. The mock-up has small circular gaps between PPs, respectively SGs, and the plate, and of a perforated plate at the bottom of the PPs with many small holes in place of the PPs hydraulic resistance. These small-scale details control the flow between lower and upper plenum. The main vertical velocity in the gaps and in the PPs holes is given in Fig. 6, right. Velocities near the meter scale and a consistent mass transfer are measured.

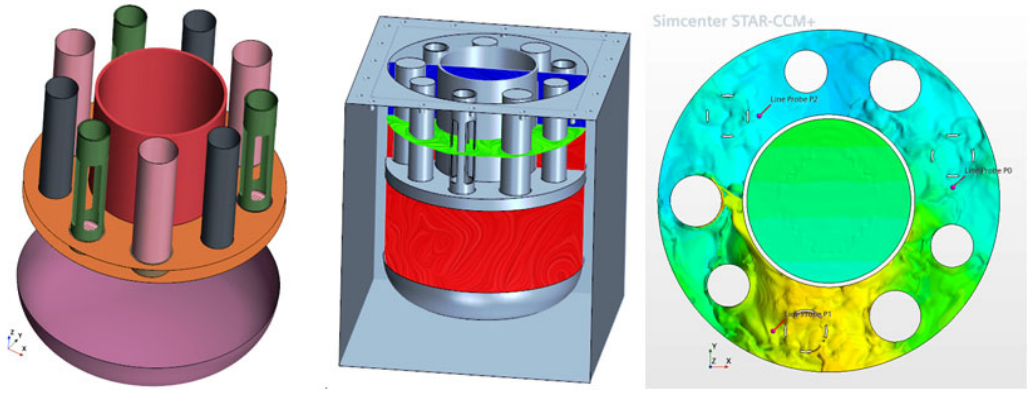


Fig. 5. Mock-up CFD model. Locations of the probes in the numerical model on the free-surface.

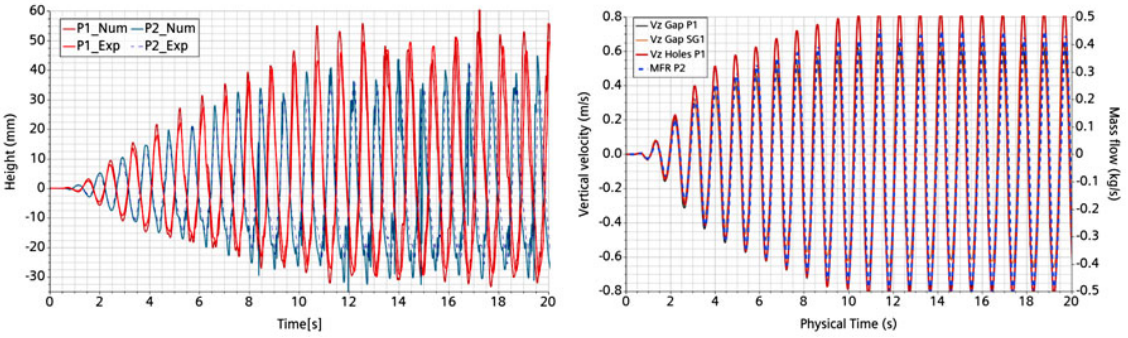


Fig. 6. Comparison between experimental (thinner) and numerical (thicker) elevation at probes P1 and P2 (left). Mean vertical velocity through the gaps and the pump pipe holes (right).

ALFRED mock-up simulation from the Romanian 1977 earthquake seismic load

With the numerical model of the ALFRED mock-up validated, it is used to evaluate the impact of seismic loads arising from significant real earthquakes. The detailed description of the CFD simulation analysis of such events was included in PASCAL project Deliverable D38 [6]. Here we focus on the ALFRED mock-up CFD simulation with input data from the earthquake that took place in Romania on March 4, 1977, magnitude 7.5, motivated by the fact that ALFRED is expected to be built in Romania.

The seismic data were registered by several stations more or less distant from the epicenter. The data chosen for the simulation were from the station with the highest Peak Ground Acceleration (PGA): distance 164 km, PGA 194 cm/s^2. The displacement data was downloaded from the ESM database [7]. Displacements along East-West (X-axis)), South-North (Y-axis) and Down-Up (Z-axis) were used. The data are constructed by successive integrations of the accelerations. The displacement data were previously treated and filtered, with the baseline being removed and a 2nd order Buttterworth filter with a low-cut frequency of 0.2 Hz and a high-cut frequency of 25 Hz being applied.

Since the acceleration is an invariant of the scaling, the acceleration data can be used directly provided that time is consistently contracted. The scaling law is that time scales like the square root of length. The length ratio between ALFRED and the mock-up is estimated at 18.4, making the mock-up flow of time going 4.29 times faster than the ALFRED flow of time. The applied forces scale with density and the volume, hence 1N on the mock-up represents about $10.4*18.4^3 = 65000$N on the real ALFRED.

The scaled displacement input was imposed to the mock-up. The simulation was run and the free surface height was monitored. The three components of the displacement with a maximum of 1 cm are shown on Fig. 7 (left) and the free-surface elevation at the probes up to 2 cm, rapidly decreasing, is shown on Fig. 7 (right). An animation of the ALFRED mock-up displacement and free-surface evolution can be found on the authors' home page [8].

The forces applied to the vessel and to the DHRs are given in Fig. 8. The forces measured in the simulation suffer from a strong numerical high frequency noise. This noise is enhanced by the adaptive mesh refinement performed each 5-time steps. In order to better understand the consequences of this issue, the signal is regularized by passing it 5 times to a 3 time-steps running mean, similarly to a Gaussian regularization. The peak value of the force on the vessel in the Y direction drops from 300 N to 70 N when regularized and the signal becomes more easily interpretable. The regularized force on the vessel in direction Y is strongly correlated to the acceleration (as can be seen in Fig. 9) with a ratio giving an equivalent mass about 33 kg, to be compared with the 40 kg water inventory. This ratio is interpreted in the following way. The water in the lower plenum weights 30 kg and is displaced mainly as a rigid body. The vessel displaces about 3 kg of water in the upper plenum, the remaining 7 kg being displaced by the internal structures, up to the free-surface evolution. After the event is over, a periodic forcing of about 1N initial amplitude and 2.5 Hz frequency remains and slowly decays. This contribution can be attributed to the sloshing effect. A very small residual sloshing of about 1 mm amplitude can be observed at the end of the simulation.

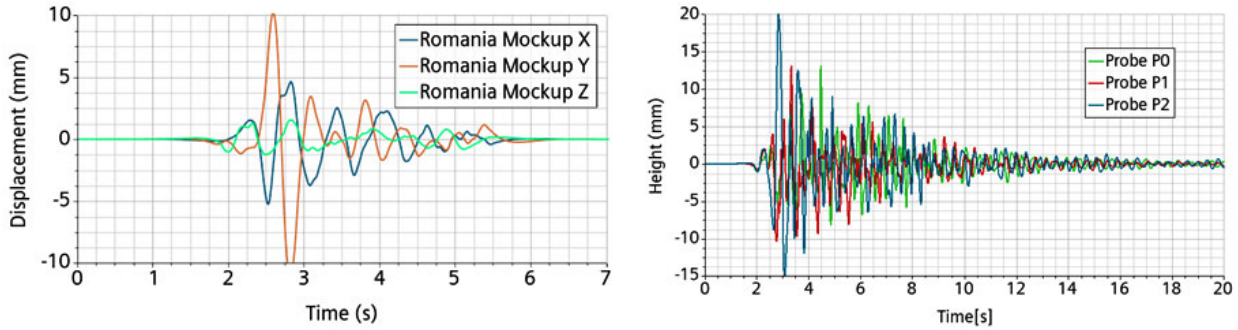


Fig. 7. Romania 1977 earthquake: Displacement imposed to the mock-up (left); Free-surface elevation (right).

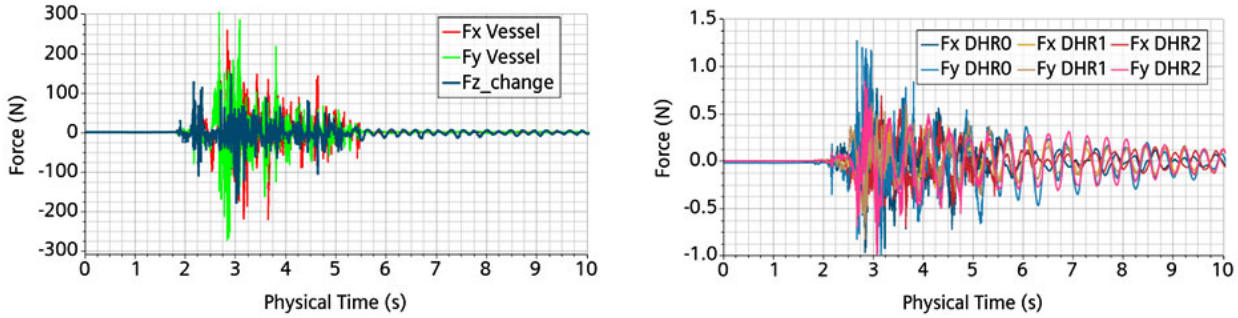


Fig. 8. Romania 1977 earthquake: Forces on the vessel (left); Forces on the DHR (right).

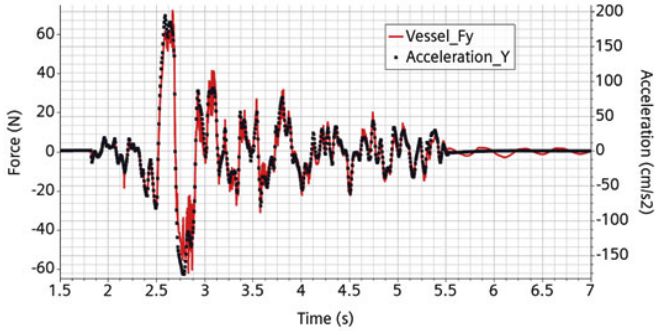


Fig. 9. Romania 1977 earthquake: Regularized force on the vessel and (minus) the imposed acceleration.

Conclusions

In the framework of the H2020 EURATOM PASCAL project, it has been demonstrated that the CFD qualifies as a versatile tool for the simulation and investigation of the sloshing phenomena. An experimental campaign was set up consisting in a water cylinder of 60 cm diameter with flat bottom, solicited by a harmonic horizontal linear forcing with frequencies spanning around the first asymmetrical natural mode. A very good numerical reproduction of the experimental flow could be obtained. There is a precise transition frequency across which the planar flow becomes chaotic with a fast and large initial amplitude growth up to wave breaking. The experimental bifurcation value is 0.9255 f_0. Numerically, the value is found in the range [0.924, 0.925] f_0 that is within 0.1% of the experimental value; therefore, this result is a clear validation of the CFD modelling. All the typical chaotic behaviours of the flow have also been captured by the simulation. The transition frequency is significantly different from the one expected from literature, above 94%, found with a smaller tank of 7.8 cm radius, meaning that the transition frequency changes with the tank radius in such a way that the chaotic region grows with the radius.

A more complex geometry intended to reproduce a mock-up of ALFRED was successively built. At first, we validated the numerical model using displacement input data provided by VKI and by making a direct comparison, still with result data provided by VKI, on the water level above three positions. Direct comparison provided a good matching. Finally, the CFD model was run applying seismic loads taken from the Romanian 1977 earthquake. The free surface height and forces on the vessel and internal structures were measured and interpreted. The practical aim of this work was to check whether a realistic but large seismic event could trigger a large sloshing dynamic potentially damageable for ALFRED system integrity: up to now, there is no indication that it could be the case. Under large seismic events, the damage risk is overwhelmingly dominated by the forcing from the highest acceleration frequencies of the earthquake. With regards to the forces acting on the vessel, the mock-up reacts essentially like a rigid body with the vessel withstanding about 33 kg of water ″added mass″ and the remaining 7 kg being split between the components and the upper plenum.

Acknowledgments

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