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Dynamic analysis of the nonlinear response of high density fuel storage racks

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ABSTRACT: High Density Spent Fuel Storage racks are steel structures designed to hold nuclear spent fuel assemblies removed from the nuclear power reactor. Weighing around 60 tons, they are 5m high free-standing structures resting on the floor of a 12 m depth pool and separated by only a few centimetres. Their underwater seismic response is a troubling safety issue, especially after Fukushima nuclear disaster. However, only limited basic guidelines have been provided as regulatory design criteria to date. The racks’ design deals with a very highly nonlinear behaviour, a transient dynamic response and a fluid-structure interaction problem. Industry is currently using available computer-aided finite element analysis software to solve the design problem in a cost-effective manner but some dispersion of results still exists. Hence, the nuclear regulatory authorities are requiring an evaluation of the current uncertainty associated to the assessment of rack displacements, rocking and maximum forces on supports. This paper discusses the main difficulties faced during the seismic analysis and presents an ad-hoc analysis methodology based on the hydrodynamic mass concept which takes advantage of a simplifying thermal analogy. The methodology, implemented in ANSYS FE Mechanical is hereby described for a reduced scale 2-rack model where the coupling effect of water in the dynamic motion of immersed racks is quantified and displacements and forces are provided. Finally, methodology assumptions are discussed and lessons learnt about the behaviour trends are summarized.

KEY WORDS: racks, free-standing; FEM; dynamic analysis; nonlinear; fluid-structure interaction; hydrodynamic mass.

1 INTRODUCTION
High Density Spent Fuel Storage (HDSFS) racks are used in the first step of the nuclear waste management process, during the wet storage of the irradiated assemblies. As shown in Figure 1, there may be numerous free-standing racks nestled in the depths of the spent fuel pool. They are designed to maximize the storage capacity of an existing pool, so the space between units is reduced as much as possible (i.e. in the order of a few centimetres).

The rack slenderness ratio determinates its seismic behaviour by taking side for either a rocking or sliding movement. The distinct geometries combined with a large spectrum of fuel distributions, types and earthquake accelerogram convert the design of racks into a singular engineering problem.

Equipos Nucleares, S.A. (ENSA) is a worldwide expert in racks design, manufacture and installation (Figure 2) \cite{1}\cite{2}\cite{3} and has recently launched a research project to improve the understanding of the rack response and to reduce the existing uncertainty in analysis.

2 CONTEXT AND DIFFICULTIES
The typical features that characterize HDSFS racks are summarized hereafter:
- unique and singular structure,
- tailored dimensions adapted to the spent fuel pool geometry,
- made of structural stainless steel and neutron-absorbing materials,
- installation in radioactive ambient with restricted access preventing from any ground fixation,
- free-standing structure just resting on the pool depths,
- multi-body analysis combining several racks with multiple fuel assemblies rattling inside its storage cells,
- submerged conditions (under 12 m water head),
- nuclear regulation imposing the highest seismic requirements.
3 DESCRIPTION OF THE DYNAMIC PROBLEM

The design of the rack system for seismic loading faces the three main challenges: a nonlinear response, a transient dynamic problem and a Fluid-Structure Interaction (FSI). These phenomena are reviewed next.

3.1 Nonlinear response

It has been shown that the vibrating frequency of the free-standing rack decreases when the excitation increases due to the combination of rocking and sliding motions [4]. This feature is the best example of the high nonlinear behaviour of racks under seismic loads. Racks units suffer deformations and large amplitude displacements (e.g. sliding, rocking and lift-off) which constantly change the boundary conditions and alter the initial thickness of water gaps between racks. They may also cause the impact of fuel assemblies on the storage cell as well as between racks units.

These contacts represent the main source of nonlinearities as they create changing-status singularities affecting the stiffness of the system whether parts are touching or separated. Initial contact points can be cleared (e.g. uplifted support feet), and new ones can appear at each instant (e.g. physical contact between nearby racks or between a rack and the pool walls). After the non-interpenetration contact event, the two solids may slide relative to each other along the interface. New forces appear in the surface of contact in agreement with new boundary conditions: a normal reaction and a frictional force opposite to the movement. The value of these forces is uncertain and depends on the surface material stiffness and its friction coefficient.

As a result of these nonlinearities, the successive finite displacements are not commutable. Hence, unless the 3D seismic components are applied simultaneously, nonlinear displacements are not accurately predicted. This issue is overcome through a transient analysis along the whole duration of the seism where the outputs at the end of a calculus step are taken as initial conditions for the next step.

3.2 Transient dynamic problem

The seismic analysis requires the resolution of a system of equations which involve time-dependent variables. Due to the nonlinearities inherent to the racks system, the response of the rack system does not satisfy the superposition principle and the equation of motion must be solved by direct numerical integration. Direct integration methods attempt to satisfy equilibrium with finite precision at discrete points in space and time. In other words, individual numerical calculations have to be computed to solve the ordinary differential equation of motion at a series of discrete points in time which are small relative to loading duration.

It is therefore necessary to implement an iterative numerical method to solve the Finite Element (FE) equations of motion at multiple time steps. The basic equation of motion is given by Equation 1:

\[ [M][\ddot{u}(t)] + [C][\dot{u}(t)] + [K][u(t)] = \{F(t)\} \]  

where \([M]\), \([C]\) and \([K]\) are the mass, damping and stiffness matrices of the structural system respectively and \{\(\dot{u}(t)\)\}, \{\(\ddot{u}(t) = d\dot{u}(t)/dt\)\} and \{\(\ddot{u}(t) = d^2\dot{u}(t)/dt^2\)\} are vectors containing the translational and rotational degrees of freedom of the structure and their respective velocities and accelerations. \{\(F(t)\)\} is the time-dependent vector of forces applied at each of the degrees of freedom.

The literature proposes a huge number of well-developed step by step iterative algorithms. Their accuracy and stability directly depend on the time step parameter and on the order of the derivative. However, the higher accuracy of the simulation, the lower becomes the stability field [5]. Due to the nonlinear behaviour of racks, only single-step, implicit, unconditional stable methods are suited to the rack seismic analysis.

3.3 Fluid-Structure interaction (FSI)

Besides the buoyancy vertical force, the presence of water determines the dynamic response of the racks and fuel assemblies. During a seismic event, the ground acceleration is transmitted from the pool to the racks by friction on feet and by compression throughout the water volume. In particular, the inertial effects derived from this water acceleration lead to coupling forces between the racks, and between the racks and the pool walls. It is noted that this FSI has to be considered for every submerged element, including the fuel assemblies inside their cells and for the racks themselves inside the spent fuel pool.

The magnitude of the FSI phenomena can be explained by the geometrical relationships inside the pool. Racks have a prismatic shape with large faces (the area of a rack face is in the order of 10 m²) separated by relatively small water gaps (in the order of 50 mm). As a result, the motion of a rack boosts the fluid pressure within the water gaps and alters the balance of the complete system. This effect has an important impact on the dynamic behaviour, particularly on the natural frequencies.

The previous hydrodynamic pressure should be ideally calculated through Navier-Stokes equation for the 3D turbulent flow, but this is difficult and computationally expensive even in simple cases. Cost-effective analyses assume some simplification in water behaviour, ignore fluid damping and sloshing effects, and use the hydrodynamic mass approach. The concept of hydrodynamic mass is defined as the equivalent mass of water vibrating with the rack and it represents the dynamic external effect of the surrounding water volume [6]. In brief, the fluid is treated as a virtual extension of the structure changing its effective mass. Thus, Equation 1 becomes:

\[ [M + m_{\text{hydro}}][\ddot{u}(t)] + [C][\dot{u}(t)] + [K][u(t)] = \{\dot{F}(t)\} \]  

where the added matrix \(m_{\text{hydro}}\) is referred to as hydrodynamic mass and represents the added masses associated to each rack itself (diagonal terms) and the inertial coupling among the multibody system (off-diagonal terms). Since this matrix multiplies the acceleration vector \(\ddot{u}(t)\), it assigns a proper weight to each rack acceleration.
both hydrodynamic masses and transient displacements are assessed here for a reduced scale 2-rack model. This illustrative application is aimed to validate the accuracy of the numerical results with experimental data from a future physical model test [7]. The general features of the mock-up shown in Figures 3 and 4 are summarized in Table 1.

Table 1. Description of the testing racks

<table>
<thead>
<tr>
<th>Racks</th>
<th>2 units</th>
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<tr>
<td>Clearance</td>
<td>40 mm</td>
</tr>
<tr>
<td>Length</td>
<td>1919 mm</td>
</tr>
<tr>
<td>Width</td>
<td>696 mm</td>
</tr>
<tr>
<td>Height</td>
<td>1774 mm</td>
</tr>
<tr>
<td>Weight</td>
<td>2300 Kg</td>
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At this point, it is of utmost importance to realise that the potential fluid flow shows a complete analogy with the steady-state heat conduction phenomena. In other words, the previous CFD problem is similar to a thermal problem governed by identical equations but other variables: hydrodynamic pressure is equivalent to temperature, acceleration is equivalent to heat flux, and fluid density is equivalent to the inverse of the heat conductivity. Thus, evaluate hydrodynamic pressures over faces and walls turns into getting a temperature distribution. For a given problem, the thermal approach offers a high accuracy and a computational time economy.

Consequently, the associated hydrodynamic masses can be assessed through the thermal FE model presented in Figure 5. Such a model allows to take into account the 3D fluid motion (i.e. heat flux under and above the rack body). The pool and racks external faces are assumed to be non-deformable. The clearance volume around racks is discretised in heat conduction ANSYS elements type SOLID 70.

Figure 3. Sketch of the pool screwed to the vibration table.

Figure 4. Detail of the 2 free-standing racks juxtaposed inside the pool.

4.1 Computation of the hydrodynamic masses through a thermal approach

In a first approach, the terms of the hydrodynamic mass matrix could be directly obtained by accelerating a rack and assessing the resulting hydrodynamic pressures over the racks faces and the pool walls. This scheme is easy to understand but difficult to implement due to the complex fluid behavior.

Alternatively, some cost-effective simplifications can be undertaken. If free surface sloshing is neglected and the water is assumed as inviscid and irrotational, the relationship between the acceleration of the rack and the associated hydrodynamic pressure can be defined via the potential flow theory. In addition, if also the fluid compressibility is neglected, the velocity potential function \( \Phi \) satisfies the Laplace equation \( \nabla^2 \Phi = 0 \) and the pressure field can be determined via the Bernoulli equation. Boundary conditions are given by the acceleration of the in-water structures so the fluid acceleration is therefore equal to the normal acceleration of the wet interface, and zero in the free surface (no sloshing assumption). This mathematical problem has been solved for simple configurations so analytical formulations are currently available for small relative oscillation amplitudes of two coaxial cylinders in 2D [8], two coaxial squares in 2D [9], and two coaxial rectangles in 3D [10]. However, for more complex geometries, a Computational Fluid Dynamics (CFD) model of the enclosed fluid domain remains necessary.
interaction. The procedure is repeated for each rack unit, in a manner that the added hydrodynamic mass (M_{hyd}), in the direction ‘i’ corresponding to a specific rack acceleration in the direction ‘j’ (\ddot{u}_j) is computed as the surface integral through the i-normal face of the temperature produced by a heat flux emitted from the j-normal faces.

According to the concept, a symmetrical system should lead to a symmetrical hydrodynamic mass matrix. This can be verified in Table 2 which presents the hydrodynamic masses in the x-direction added to each structure under a unitary acceleration in the x-direction of each structure. The hydrodynamic masses in other directions could be also assessed using the same procedure.

<table>
<thead>
<tr>
<th></th>
<th>M_{xx, rack1}</th>
<th>M_{xx, rack2}</th>
<th>M_{xx, pool}</th>
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<tr>
<td>\ddot{u}_{x, rack1}</td>
<td>6435</td>
<td>-1591</td>
<td>-5965</td>
</tr>
<tr>
<td>\ddot{u}_{x, rack2}</td>
<td>-1591</td>
<td>6435</td>
<td>-5965</td>
</tr>
<tr>
<td>\ddot{u}_{x, pool}</td>
<td>-5965</td>
<td>-5965</td>
<td>15302</td>
</tr>
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where “\ddot{u}_{x, index}” refers to structure where the unitary x-acceleration is applied (in m/s²) and “M_{xx, index}” represents the x-component (in kg) of the hydrodynamic mass corresponding to such an x-acceleration. For example, when the rack1 is accelerated in the x-direction (\ddot{u}_{x, rack1}=1 m/s²), the water induces a x-force over this rack 1 equivalent to increasing its mass (M_{xx, rack1}= 6435 kg).

It should be noted that the terms of the hydrodynamic mass matrix are affected by any relative displacement of racks. The variation throughout time in the thickness of the water gaps around the racks changes the geometrical relationships and therefore the hydrodynamic pressures field. The implemented methodology assumes that the water coupling forces limits the relative displacement between racks, so hydrodynamic mass matrix is assessed only once and just for the initial configuration. The numerical results will show that racks moves nearly in phase, so it seems acceptable to keep the hydrodynamic masses constant during the whole transient analysis.

4.2 Transient dynamic analysis of the seism

Once the hydrodynamic masses associated to each rack have been evaluated, they are entered into the dynamic FE model of Figure 6. Due to the complexity of the transitory analysis and the computation cost, the model should be as simple as possible: the cellular structure is represented through a unique beam, the fuel assemblies are grouped in a vertical rigid body, the base plate is shaped as a rigid shell and the total mass is discretised in 7 lumped points. Nevertheless, a reliable model has to maintain the original dynamic properties (i.e. natural vibration frequencies), so the stiffness of different elements must be carefully adapted. In addition, it should be built in 3D in order to reproduce the real spatial motion which cannot be approached by a 2D superposition principle as the behaviour is highly nonlinear.

It should be noted that the pool structure is considered as an infinitely rigid solid and therefore modelled by a unique node which is connected to the racks by the following ANSYS elements:

- CONTA 178, to model the free-standing condition: elastic contacts and Coulomb model of friction (coefficient = 0.50)
- MATRIX 27 with forced-distributed-surface contact (MPC), to add the coupling hydrodynamic masses and spread the hydrodynamic pressure over the entire rack faces.

As outlined in Section 3.2, a transitory analysis with full direct integration becomes necessary to accurately solve Equation (2) throughout the entire seismic event. Hence, a generalized \alpha-method, available in ANSYS as ‘HTT’ algorithm, has been used to analyse the nonlinear behaviour of the racks under the 12 sec duration design earthquake shown in Figure 7, which reaches peaks of acceleration up to 8.75 m/s².
4.3 Numerical results: displacements and forces

This section provides the most relevant results characterizing the racks’ behavior in terms of base and top displacements (Figure 8), relative displacements (Figure 9 and Figure 10), vertical lifting of a foot (Figure 11) and reaction force on a foot (Figure 12).

Racks follow, in some way, the pattern of the ground motion which explain the big displacements as far as 40 cm, are shown in Figure 8. However, as per Figure 9 the relative displacement between a rack and the pool remains in the order of some centimetres for both top and base levels. The same comment can be drawn from Figure 10 regarding the relative displacement between the 2 racks. Nonetheless it should be noted that the relative displacements at the top level are much more instable with higher amplitudes than at the base level. It is the evidence of a non-negligible rocking behaviour around their axis. These oscillations are also visible for a single rack in the differential displacement of the top with respect of the base green line (labelled ‘TOP-BASE’) in Figure 8.

It is noted that both types of relative displacements remain below the initial gap, so no horizontal collision is expected to occur. Indeed, as far as the racks get closer, the clearance becomes lower and the hydrodynamic masses should be updated as outlined in Section 4.1, which should exponentially increase the coupling forces and further reduce the predicted displacements.

Regarding the vertical behaviour, Figure 11 shows multiple uplifting events of a singular foot up to 15 mm. For the given earthquake and case study, they are produced by the already
mentioned rocking behaviour. Even if the rack did not completely take off, the return movement cause strong impacts of 50 kN as seen in Figure 12.

5 CONCLUSIONS AND FUTURE WORK

This paper has pointed out the main difficulties involved in the design of high density spent fuel storage racks. In order to address the latter, a successful analysis methodology based on a few simplification assumptions has been proposed to determine their seismic behaviour when immersed in water. Main results regarding the transient displacements and impact forces have been given for a specific geometry. The following conclusions can be drawn for predesign purposes:

- Reduced clearance leads to an important coupling effect between racks which are otherwise independent.
- The terms of the hydrodynamic mass matrix explicitly show how the coupling forces are established between racks and between racks and pool.
- In particular, the relationship between the area of the face and the thickness of the water gaps is key in the importance of the fluid-structure coupling.
- For the study case, these values reach up to 300% of the rack self-weight. It means that the submerged racks behave as if they weighed 6435 kg extra when they are accelerated.
- The fluid-structure coupling becomes stronger when the gaps between racks become lower. Such a effect pushes the ensemble towards a rigid solid motion where both racks move nearly in phase.
- Small relative displacements would allow the use of a constant hydrodynamic mass matrix throughout the transient analysis which can save much computation time.
- The rack slenderness ratio determinates its rocking or sliding behaviour for a given configuration, seismic time-history and friction coefficient.

Further steps seek to assess the accuracy of the outlined analysis methodology and refine the current settings if possible. For this purpose, a physical model test will follow to validate the correlation between the computed results and the experimental data, and to evaluate the uncertainties inherent to the water assumptions, to the FE modelling and to the numerical time-integration algorithm. Multiple testing configurations are planned aiming at performing a sensitivity analysis of the governing parameters as well as quantifying the influence of changes in variables such as the initial clearance, the friction coefficients, the seismic time-history features, the fuel load distributions, etc. on the response.

In a final stage, a statistical analysis will be performed and guidelines for a probabilistic design provided. The ultimate goal is to be able to predict the behaviour patterns of any kind of racks configurations, with stochastic features, under different loading conditions through low cost analysis and with a bounded error.

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