IASMiRT

SMiRT 26
50 Anniversary Berlin/Potsdam

Transactions, **SMiRT-26**
Berlin/Potsdam, Germany, July 10-15, 2022
Division V

COUPLED NONLINEAR ANALYSIS FOR EVALUATION OF SEISMIC DEMANDS ON ELECTRICAL EQUIPMENT SUBJECTED TO HIGH–FREQUENCY GROUND MOTIONS

Sugandha Singh[1], Abhinav Gupta[2]

[1]Assistant Professor, Jaypee University of Information Technology, Waknaghat, Himachal Pradesh, India (sugandha.singh@juitsolan.in)
[2]Director, Centre for Nuclear Energy Facilities and Structures (CNEFS), North Carolina State University, Raleigh, NC, USA

ABSTRACT

In–cabinet response spectrum (ICRS) is needed in the seismic qualification of safety related electrical equipment in a nuclear power plant. To qualify equipment, the seismic demands at different frequencies are calculated in terms of ICRS which are then compared with seismic capacities (obtained from shake table tests or experience data). Conventionally, seismic demands on equipment are evaluated by multiplying the GMRS at the site with empirically obtained amplification factors for the structure and the electrical cabinet. The amplification factors are dependent on the height of the floor at which cabinet is placed and the type of the cabinet. The amplified spectrum is called in–cabinet response spectrum (ICRS) which gives the seismic demands on the devices like relays. Such an approach does not consider the effect of various factors such as building–cabinet interaction, geometric nonlinearities, location of equipment, etc., on ICRS. The ICRS calculated using the conventional approach have been found to be excessively conservative preventing many commercially available equipment from being considered for use in nuclear power plants and thereby increasing the cost. This study compares the ICRS obtained using coupled multiple degrees of freedom (MDOFs) building–cabinet–equipment system along with geometric nonlinearity with the corresponding ICRS obtained from uncoupled analysis of building, cabinet, and equipment. It is observed that the seismic demands on electrical equipment are lower from a nonlinear coupled analysis cases as compared to linear uncoupled analysis.

INTRODUCTION

During a seismic event, a nuclear power plant must safely shutdown and maintain the important functions needed to ensure the safety. The safe shutdown of a nuclear power plant depends on proper functioning of safety–related digital control systems and equipment such as relays. However, safety–related equipment are sensitive to high–frequency accelerations. Due to the observation of high–frequency content observed in recent earthquakes in Central and Eastern United States, South Korea, etc., it is important to evaluate the seismic demand of such equipment and compare with its capacity determined from shake table tests or experience data. From observations of previous high–frequency earthquakes in different regions of the world, various electrical systems tripped even though they were seismically qualified to continue operation during and after the earthquake. In general, the displacement induced by high–frequency ground motions are small and do not cause structural damage (EPRI 2007, 2014). However, the high–frequency seismic waves that propagate through the system may interfere with the functionality of electrical instruments mounted on cabinets and control panels.

Shake table tests are conducted to evaluate capacity of acceleration–sensitive equipment (EPRI, 2014; EPRI, 2015). Sine sweep tests conducted for the various equipment to determine the capacity against high frequency accelerations in the range of 16–48Hz. Seismic demands on equipment are evaluated by multiplying ground motion response spectrum at the site with amplification factors for building height and the cabinet types (EPRI, 2015). The amplification factors are determined empirically. The use of empirical amplification factors may lead to unnecessarily large seismic demands making equipment unusable nuclear power plants. Furthermore, this approach does not include various factors such building–cabinet–equipment interaction, geometric nonlinearities such as gap between anchor bolts and cabinet base plate, etc.

Various experimental (Vlaski et al., 2013; Vlaski et al., 2019) studies indicate that the high–frequency accelerations do not propagate up to the equipment. Further, analytical (Herve et al., 2014; Singh and Gupta, 2021) studies show that geometric nonlinearities such as a gap between the anchor bolt and the cabinet base plate filter out the high–frequency accelerations resulting in much lower seismic demands. In the study conducted by Singh and Gupta (2021) it is also observed that such small gaps may cause localized impacts at the cabinet base, thus amplifying equipment demands at higher frequencies. The preliminary study conducted by Singh and Gupta (2021) involved representation of both building and cabinets as single degree of freedom (SDOF) system. Moreover, this study does not address the building–cabinet interaction by conducting uncoupled analysis. It is observed in various studies (Burdisso et al., 1987; Dubey et al., 2019) that linear coupled analysis of structure and equipment may result in more than 50% reduction of spectral amplitudes of the floor which may lead to further reduction in seismic demand on equipment.

In this study, the results of coupled and uncoupled linear as well as nonlinear analysis are discussed for an example multiple degree of freedom (MDOF) building and MDOF cabinet model. The seismic demands on equipment are found by evaluation of in–cabinet response spectrum (ICRS) from the total acceleration observed in the cabinet.

CABINET BEHAVIOUR

The seismic demand on an equipment depends on various factors such as the dynamic properties of the electrical cabinet, the mounting arrangement, the location of equipment in the cabinet, etc. (Gupta et al., 1999; Gupta et al., 2019). As discussed in various studies, a significant mode governs the ICRS which can be either a global mode or a local mode (cabinet door/panels, internal frame, etc.) or a combination of both. The significant mode may not necessarily be same as the fundamental mode of the cabinet which depends on the location of the equipment. Furthermore, the mounting arrangement may also affect the behaviour of the cabinet by introducing a global rocking mode thus leading to change in the ICRS (Yang et al., 2002; Han et al., 2018).

Due to the recent occurrences of high–frequency ground motions in various parts of the world, the effect of geometric nonlinearities on the ICRS (Vlaski et al., 2013; Herve et al., 2014; Singh and Gupta, 2021; Vlaski et al., 2019) is also explored in experimental and analytical studies. It is observed in experimental tests that high–frequency accelerations may not necessarily propagate to the equipment leading to reduction in seismic demands on them. Since high–frequency ground motions induce small displacements, the analytical studies conducted by Herve et al. (2014) and Singh and Gupta (2021) hypothesized that the high–frequency accelerations may filter out due to small gap between cabinet base and the floor. The spectral accelerations in ICRS, thus, are much less than those obtained from a linear analysis. However, if the floor displacement is more than that of the gap between floor and anchor bolt, it can lead to impact being induced at every cycle thus leading to higher spectral accelerations that exceed those obtained from a linear analysis. The cabinet behaviour observed in these studies is based on uncoupled analysis of SDOF representation of both the building and the cabinet which does not take into account the mass interaction. The gap between the floor and cabinet is modelled as shown in fig. 1.

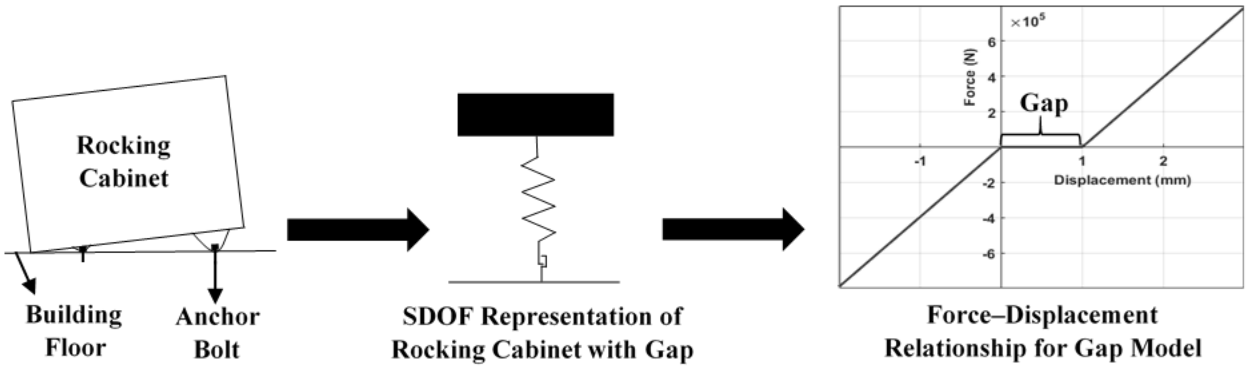

Figure. 1. Nonlinear Gap Model for Rigid Body Rocking of Cabinet (Singh and Gupta, 2021)

COUPLED SYSTEMS

The interaction between nonstructural components and the building is discussed in various studies (Xu et al., 1999; Xu et al., 2004; Dubey et al., 2019). The observation from these studies shows that the amplitudes of floor response spectra decrease significantly as compared to uncoupled analysis of the system. The decrease in spectral amplitudes occur due to mass interaction between the tuned or nearly tuned modes of the building (primary) system and the modes of the equipment (secondary) system. In this study, the effect of mass–interaction on seismic demands for electrical equipment is analyzed. The equation of motion of a coupled primary–secondary system (Gupta and Gupta, 1998) is given by equation (1):

`

$$[M]\{\ddot{U}\} + [C]\{\dot{U}\} + [K]\{U\} = -[M]\{U_b\}\ddot{u}_g \quad \textbf{(1)}$$

where, $[M]$, $[C]$, and $[K]$ are the mass, damping and stiffness matrices of the coupled primary–secondary system; $\{\ddot{U}\}$, $\{\dot{U}\}$ and $\{U\}$ are acceleration, velocity, and displacement vectors of the coupled system; $\{U_b\}$ is the influence vector of coupled system and $\ddot{u}_g$ is the ground acceleration time history. Equation (1) can further be expressed as:

$$\begin{bmatrix} [M_P] & [O] \\ [O] & [M_S] \end{bmatrix} \begin{Bmatrix} \{\ddot{U}_P\} \\ \{\ddot{U}_S\} \end{Bmatrix} + \begin{bmatrix} [C_P] + [C_P^S] & [C_{PS}] \\ [C_{SP}] & [C_S] \end{bmatrix} \begin{Bmatrix} \{\dot{U}_P\} \\ \{\dot{U}_S\} \end{Bmatrix} + \begin{bmatrix} [K_P] + [K_P^S] & [K_{PS}] \\ [K_{SP}] & [K_S] \end{bmatrix} \begin{Bmatrix} \{U_P\} \\ \{U_S\} \end{Bmatrix} = -\begin{bmatrix} [M_P] & [O] \\ [O] & [M_S] \end{bmatrix} \begin{Bmatrix} \{U_{bP}\} \\ \{U_{bS}\} \end{Bmatrix} \ddot{u}_g \quad \textbf{(2)}$$

Where, $[M_P]$ and $[M_S]$ are uncoupled mass matrices of primary and secondary systems respectively; $[C_P]$ and $[C_S]$ are uncoupled damping matrices of primary and secondary systems respectively; $[K_P]$ and $[K_S]$ are uncoupled stiffness matrices of primary and secondary systems respectively; $[C_P^S]$ and $[K_P^S]$ are the damping and stiffness contributions of the secondary system for the primary system's connecting DOF; $\{\ddot{U}_P\}$, $\{\dot{U}_P\}$ and $\{U_P\}$ are the acceleration, velocity and displacement respectively of the primary system; $\{\ddot{U}_S\}$, $\{\dot{U}_S\}$ and $\{U_S\}$ are the acceleration, velocity and displacement respectively of the secondary system; $\{U_{bP}\}$ and $\{U_{bS}\}$ are the influence vectors for primary and secondary systems respectively.

After further simplification of equation (2), it can be shown that the stiffness and damping matrices become uncoupled. On the other hand, the mass matrix becomes coupled due to the interaction between primary and secondary systems. In this study, the effect of mass interaction along with the geometric nonlinearity is considered in a representative building–cabinet–equipment system.

METHODOLOGY

The primary system (building) is represented by a 10 degree of freedom (DOF) lumped mass model while the secondary system (electrical cabinet) is represented by a 6 DOF lumped mass model. The MDOF primary–secondary system is subjected to a high–frequency ground motion. The dynamic properties of the system are selected so that the modal frequency of the primary and secondary system coincide with the dominant frequency of the ground motion (16 Hz). To understand the effect of frequency content as well as amplitude, the ground motion is normalized to a peak ground acceleration (PGA) of 1g and 0.2g. Figure 2 shows ground motion response spectra normalized to 0.2g.

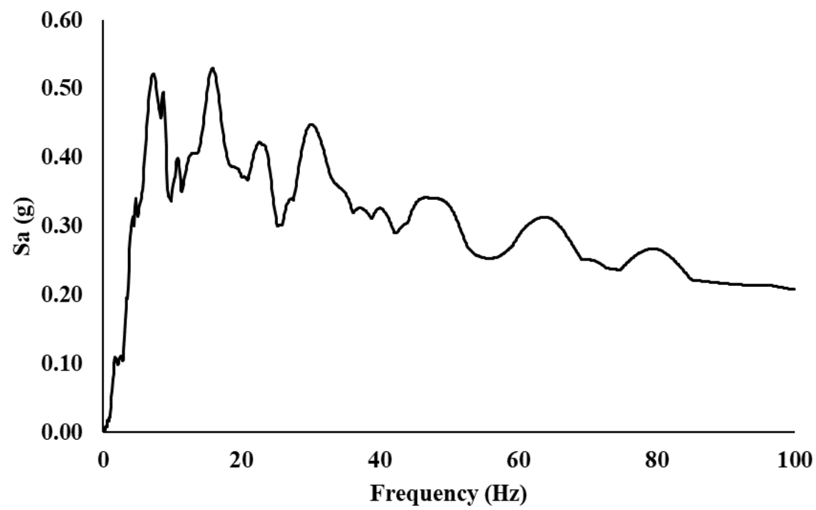

Figure. 2. Ground Motion Response Spectra Normalized to 0.2g and 1g

The modal frequencies of both primary and secondary systems are shown in Table 1. The secondary system is connected to the primary system at the 10th DOF. Both linear and nonlinear analysis are conducted. The geometric nonlinearity in the primary–secondary system is modelled as shown in figure 1. Only the connecting DOF of secondary system is modelled as nonlinear. The effect of the length of gap is also assessed in this study (1mm and 3mm). Both coupled and uncoupled analysis of the system are conducted to evaluate the effect of mass interaction between the primary and secondary systems. The modal damping ratio for all the modes in the coupled or uncoupled systems is assumed to be 5%. The ICRS at the first DOF and sixth DOF are generated from both uncoupled and coupled analysis and compared.

Table 1. Uncoupled Modal Frequencies of Primary and Secondary Systems

Primary System		**Secondary System**	
Mode	**Frequency (Hz)**	**Mode**	**Frequency (Hz)**
1	8.27	**1**	7.47
2	16	**2**	16.30
3	33.20	**3**	33.20
4	35.98	**4**	39.94
5	52.98	**5**	57.17
6	70.45	**6**	109.42
7	84.97		
8	95.85		
9	102.58		
10	117.35		

RESULTS

Coupled and Uncoupled Linear Analysis

Figures 3 and 4 show that due to the primary–secondary system mass interaction, the spectral amplitudes at both first and sixth DOF are lower for coupled analysis. The difference in spectral amplitudes is larger at the frequencies of tuned modes (16 Hz and 33.20 Hz) at the first DOF. However, at the sixth floor, only the fundamental mode (7.5Hz) contributes to the ICRS which shows significant difference in spectral amplitudes.

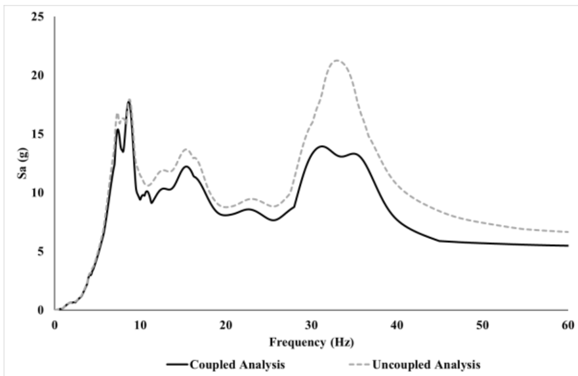

Figure. 3. Comparison of ICRS obtained at First Story of Secondary System from Coupled and Uncoupled Linear Analysis

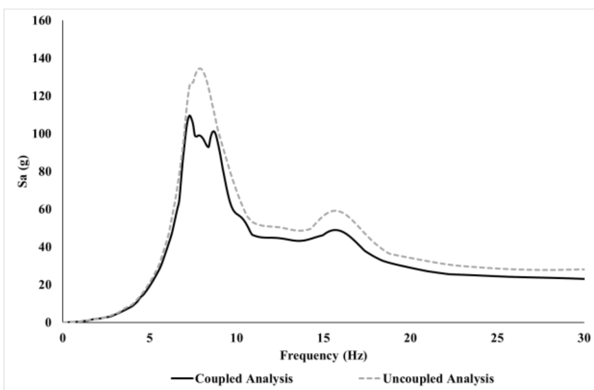

Figure. 4. Comparison of ICRS obtained at Sixth DOF of Secondary System from Coupled and Uncoupled Linear Analysis

Uncoupled Linear and Nonlinear Analysis

Figures 5 and 6 show the difference in spectral amplitudes of ICRS due to geometric nonlinearity compared with linear analysis. At first DOF, the high–frequency modes are dominant and shows higher amplitudes for nonlinear analysis as compared to linear analysis. However, at sixth DOF, the fundamental mode of the cabinet contributes to equipment response. Hence, the spectral amplitudes for nonlinear analysis are significantly lower than that of linear analysis.

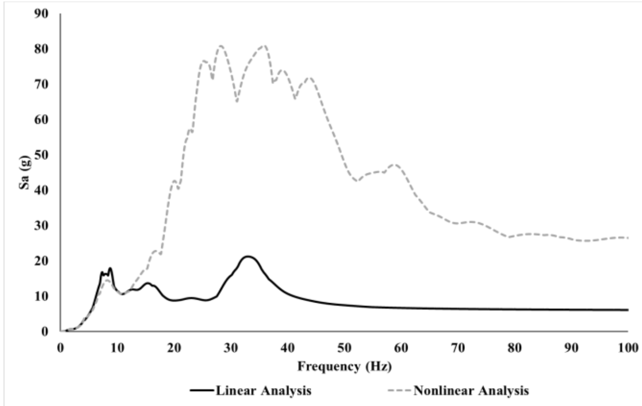

Figure. 5. Comparison of ICRS obtained at First DOF of Secondary System from Uncoupled Linear and Nonlinear Analysis

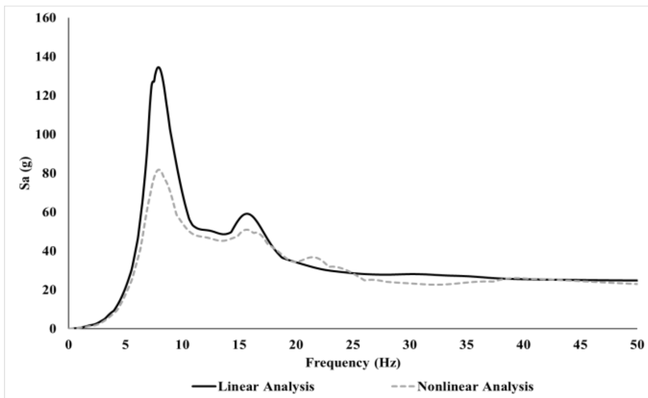

Figure. 6. Comparison of ICRS obtained at Sixth DOF of Secondary System from Uncoupled Linear and Nonlinear Analysis

Coupled and Uncoupled Nonlinear Analysis

Figures 7 and 8 show the effect of MDOF primary–secondary systems interaction on the nonlinear analysis. In coupled analysis, the effect of mass interaction occurs only when the gap closes. Since the high–frequency seismic motions induce small displacements, the gap closes for a very small duration. Hence, in coupled nonlinear analysis the effect of mass interaction is lower.

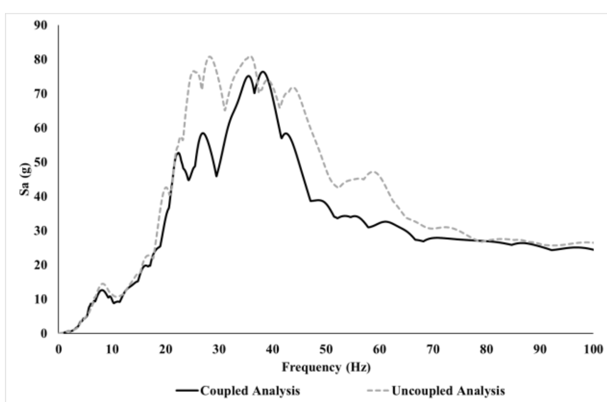

Figure. 7. Comparison of ICRS obtained at First DOF of Secondary System from Coupled and Uncoupled Nonlinear Analysis

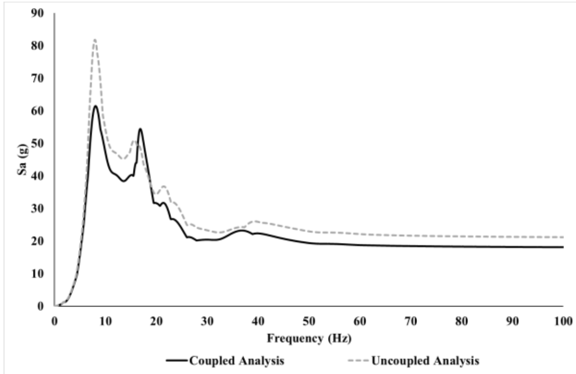

Figure. 8. Comparison of ICRS obtained at Sixth DOF of Secondary System from Coupled and Uncoupled Nonlinear Analysis

Amplitude Of Ground Motion

In this section, the effect of amplitude of ground motion is assessed on the coupled nonlinear analysis of the system. Previous results discussed the ICRS obtained from ground motion normalized to 1g PGA. As shown in figures 9 and 10, there is a significant difference between the ICRS spectral amplitudes obtained from 0.2g and 1g PGA. Such significant difference occurs due to the duration of free sliding of cabinet leading to reduced number of impacts, and lower velocity of impact at the cabinet base for 0.2g PGA ground motion.

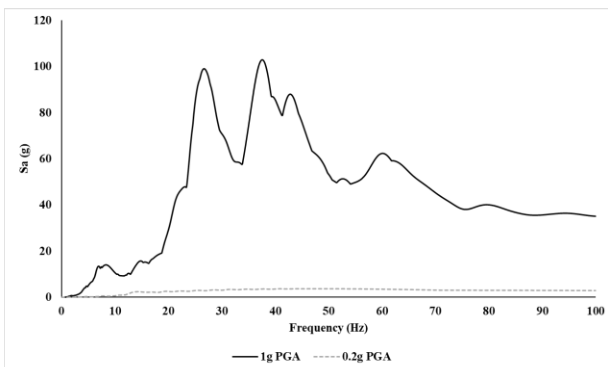

Figure. 9. Comparison of ICRS obtained at First DOF of Secondary System from Coupled Nonlinear Analysis Ground Motion Normalized to 1g and 0.2g PGA

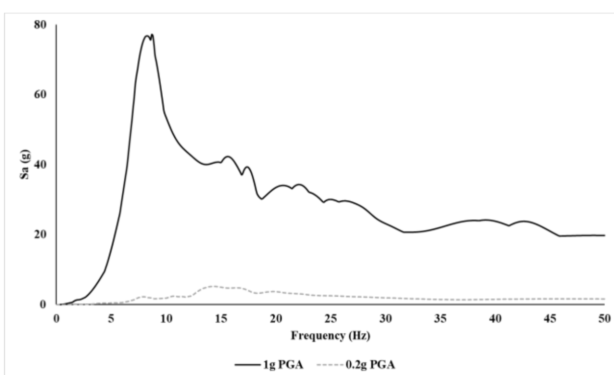

Figure. 10. Comparison of ICRS obtained at Sixth DOF of Secondary System from Coupled Nonlinear Analysis Ground Motion Normalized to 1g and 0.2g PGA

Gap Length

As shown in figures 11 and 12, the spectral amplitudes with 3 mm gap are lower as to compared to 1 mm gap model. These results indicate that the high–frequency ground motions are filtered out due to the gap. Moreover, as observed in results of Singh and Gupta (2021), a periodic pattern is observed in the ICRS. Such behaviour occurs due to the interference between transient and steady–state response whenever the gap closes.

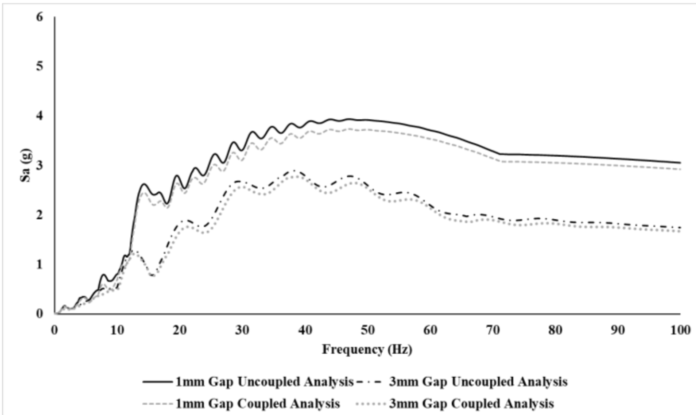

Figure. 11. Comparison of ICRS obtained at First DOF of Secondary System from Coupled and Uncoupled Nonlinear Analysis

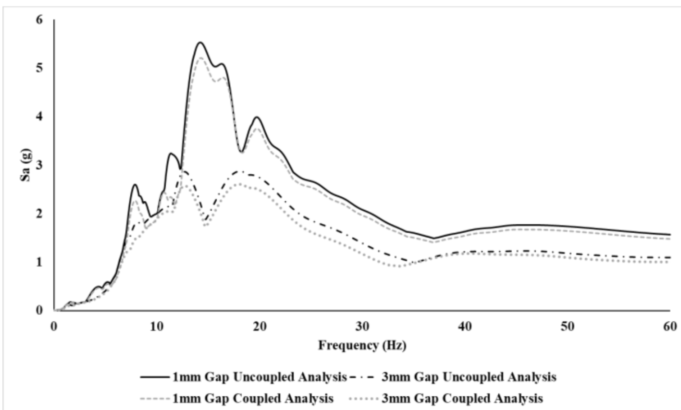

Figure. 12. Comparison of ICRS obtained at Sixth DOF of Secondary System from Coupled and Uncoupled Nonlinear Analysis

CONCLUSIONS

Understanding of seismic response of equipment is very important for proper functioning of nuclear power plants. In this study, the effect of various factors on the in–cabinet response spectrum is studied. The results show that coupled analysis yields lower spectral amplitudes as compared to uncoupled analysis due to the building–cabinet interaction. Furthermore, due to the localized geometric nonlinearity, the high–frequency accelerations are filtered out. However, if the floor displacement is more than that of the gap, the spectral amplitudes at higher frequencies are more than those obtained from a linear analysis. This effect is more prominent if the equipment is located near the first degree of freedom (where higher frequency modes are dominant). The results obtained from coupled nonlinear analysis, also show that the mass interaction between the building and the cabinet occurs only when the gap closes and the anchor bolt is in contact with the cabinet base. Since the displacement induced by high–frequency seismic motion is lower, the gap closes less often reducing the effect of mass interaction. Finally, the coupled nonlinear analysis is also affected by the amplitude of ground motion as well as the length of the gap. The spectral amplitudes reduce with the lower amplitude ground motion and larger gap lengths.

ACKNOWLEDGEMENT

This research was supported by Centre for Nuclear Energy Facilities and Structures at North Carolina State University. Resources for the Centre come from the dues paid by member organizations and from the Civil, Construction, and Environmental Engineering Department and College of Engineering in the University.

REFERENCES

Burdisso, R.A., Singh, M.P., (1987) "Seismic Analysis of Multiply Supported Secondary Systems with Dynamic Interaction Effects." *Earthquake Engineering Structural Dynamics*, Volume 15, Pages 1005-1022.

Dubey, A.R., Bodda, S., Gupta, A., Vasquez, J., Bhargava, D., (2019) "Reduction in Seismic Demand by Using Equipment-Structure Interaction," *In: Transactions of 25th Conference on Structural Mechanics in Reactor Technology (SMiRT-25), Charlotte, NC, USA,* August 4-9, 2019.

EPRI, (2007) "Program on technology innovation: The effects of high-frequency ground motion on structures, components, and equipment in nuclear power plants," Palo Alto, CA: 2007.1015108.

EPRI, (2014) "High frequency program: High frequency testing summary," Palo Alto, CA, 2014.3002002997.

EPRI, (2015) "High frequency program: Application guidance for functional confirmation and fragility evaluation," Palo Alto, CA, 2015.3002004396.

Gupta, A., Cho, S.-G., Hong, K.-J., Han, M., (2019) "Current State of In-Cabinet Response Spectra for Seismic Qualification of Equipment in Nuclear Power Plants," *Nuclear Engineering and Design*, 343 (2019) 269–275.

Gupta, A., Gupta, A.K., (1998) "Missing Mass Effect in Coupled Analysis I: Complex Modal Properties," *Journal of Structural Engineering*, 124(5): 490–495.

Gupta, A., Rustogi, S.K., Gupta, A.K., (1999) "Ritz Vector Approach for Evaluating Incabinet Response Spectra," *Nuclear Engineering and Design,* Vol. 199, pp. 255-272, March 1999. DOI: 10.1016/S0029-5493(99)00076-X.

Han, M., Cho, S.-G., Hong, K.-J., Gupta, A., (2018) "Rocking Stiffness of Electrical Cabinet Considering the Local Deformation at the Base," *In: Transactions of the Korean Nuclear Society Spring Meeting*, Jeju, Korea, May 17–18, 2018.

Herve, G., (2014) "Improvement of the evaluation of high frequency content in the calculation of impact floor response spectra," *In: 2nd Conference on Technical Innovation in Nuclear Civil Engineering TINCE 2014,* Paris.

Singh, S., Gupta, A., (2021) "Seismic Response of Electrical Equipment subjected to high–frequency ground motions," *Nuclear Engineering and Design*, Vol. 374, 111046, April 2021.

Vlaski, V., (2013) "Reduction of External Hazard (Fast Impact) Induced Vibrations," F/AB-58, *In: 1st Conference on Technical Innovation in Nuclear Civil Engineering TINCE 2013, Paris*, October 28-31, 2013.

Vlaski, V., Moersch, J., Sallmann, M., (2019) "Comparative Study for Reduction of APC Induced Vibrations," *In: Transactions of 25th Conference on Structural Mechanics in Reactor Technology (SMiRT-25), Charlotte, NC, USA,* August 4-9, 2019.

Yang, J., Rustogi, S.K., Gupta, A., (2002) "Rocking Stiffness of Mounting Arrangements in Electrical Cabinets and Control Panels," *Nuclear Engineering and Design*, 219 (2002), 127–141.

Xu, J., DeGrassi, G., Chokshi, N., (1999) "NRC-BNL Benchmark Program on Evaluation of Methods for Seismic Analysis of Coupled Systems," *USNRC,* BNL-NUREG-66409, Paper ID: K4-A6-US, 1999.

Xu, J., DeGrassi, G., Chokshi, N., (2004) "A NRC-BNL Benchmark Evaluation of Seismic Analysis Methods for Non-classically damped coupled systems," *Nuclear Engineering and Design*, 228 (2004) 345–366.