Transactions, SMiRT-25
Charlotte, NC, USA, August 4-9, 2019
Division V

EFFECT OF HIGH-FREQUENCY SEISMIC MOTIONS ON ELECTRICAL EQUIPMENT IN NUCLEAR POWER PLANTS

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ABSTRACT

Seismic hazard studies conducted by nuclear power plants indicate that in Central and Eastern United States, the ground motion response spectra contain high-frequency amplitudes. High-frequency spectral accelerations can exceed the safe shutdown earthquake spectra considerably. The high-frequency ground motions do not cause damage to structures. However, high-frequency accelerations can propagate through the structure into the electrical cabinets and affect safety-related sensitive equipment such as relays. Hence, it is essential to determine the amplitude and frequency content of motions that propagate through the structure into the electrical control panels and serve as input to the relays. This research is based on the hypothesis that high-frequency motion would not reach the control panels or cabinets because the displacements caused by high-frequency ground motions are relatively small. These small displacements would subsequently diminish due to the geometric nonlinearities such as gaps in a control panel's mounting arrangement. The results show that the accelerations that reaches the relays have lower spectral accelerations attained from nonlinear analysis as compared to excessively high unrealistic spectral accelerations obtained from conventional linear analysis.

INTRODUCTION

The United States Nuclear Regulatory Commission (USNRC) appointed a Near-Term Task Force (NTTF) to review the Fukushima Daiichi accident and provide recommendations for enhancing the safety of nuclear power plants (NPP) in the USA (USNRC, 2014). NTTF's Recommendation 2.1 requires the NPP licensees to reevaluate the seismic and flooding hazards at their sites with respect to current USNRC requirements. Then, update the design basis and the structures, systems and components (SSCs) to safeguard against the updated hazards if necessary. Ground motion studies (SSHAC, 1997; EPRI, 2013; PEER, 2015) indicate that in Central & Eastern United States (CEUS), the ground motion response spectra (GMRS) have high-frequency content due to the presence of hard rock soil profile as compared to low-frequency safe-shutdown earthquake spectra used as design basis in majority of nuclear power plants. The seismic hazard studies along with NTTF recommendations guided the NPPs to evaluate the vulnerability of their structures, systems and components to high-frequency ground motions.

A study conducted by EPRI (2007) notes that the high-frequency ground motions do not cause damage to the power plant structures. The high-frequency accelerations, however, may propagate through the structure and the electrical cabinets to the safety-related electrical equipment such as relays. The output signal of relays is important for safe shutdown of the plant and may be influenced by high-frequency accelerations. Usually, relays are tested on shake tables for seismic qualification (IEEE, 2013; EPRI, 2015). Historically, the relays have not been tested for seismic motions with frequencies higher than 16Hz, Electric Power Research Institute (EPRI) thus established a new testing program (EPRI, 2015) to test the vulnerability of relays when subjected to high-frequency seismic motions. Further, Vlaski et al. (2018)

conducted experimental tests on a cabinet with electrical equipment mounted on it. The cabinet was subjected to a suite of raw and filtered acceleration time histories obtained from dynamic analysis of the structure. The filtered acceleration time history is obtained by cutting off the high-frequency peaks while the raw acceleration time history shows peaks at higher frequencies. On comparison of response obtained from subjecting the cabinet to raw and filtered excitations, the high-frequency peaks of raw excitations almost vanishes and the response from raw and filtered excitations is almost similar. Thus, indicating that the high-frequency vibrations may not propagate up to equipment level and hence, may not affect equipment response during an earthquake.

Based on the testing results from EPRI (2015) report, the equipment in various NPP are qualified based on spectral acceleration of the in-cabinet response spectra obtained for different frequencies usually based on linear analysis of the building (primary system), the electrical cabinet (secondary system) and the equipment (tertiary system) mounted on the cabinet. However, the linear analysis usually yields conservative results i.e., higher spectral amplitudes even at higher frequencies. Herve et al. (2014) proposed that the high-frequency seismic motions might not be reaching the equipment because of geometric nonlinearities at the connection between the primary and secondary system. Hence, in this paper, we analyze single degree of freedom primary and secondary systems to compare the in-cabinet response spectra obtained from the linear and nonlinear analyses. In-cabinet response spectra is generated from the total acceleration of the secondary system. An uncoupled analysis of primary-secondary system subjected to a ground motion is conducted to obtain the total acceleration of secondary system. The in-cabinet response spectra, thus, gives the maximum amplitude of equipment response at different frequencies.

ELECTRICAL CABINETS BEHAVIOR

Various studies (Gupta & Rustogi, 1998; Gupta et al., 1999; Yang et al., 2002; Rustogi & Gupta, 2004) have attempted to understand the behavior of electrical cabinets subjected to seismic motion and determine the factors that influence the in-cabinet response spectra.

Gupta et al. (1999) show that in-cabinet response spectra obtained by analyzing the cabinets using all the modes is similar as that obtained by using only one or two significant modes as shown in figure 1. Hence, a cabinet can represented as a single degree of freedom system. Further, mounting arrangement of a cabinet influences the in-cabinet response spectra as much as its structural details.

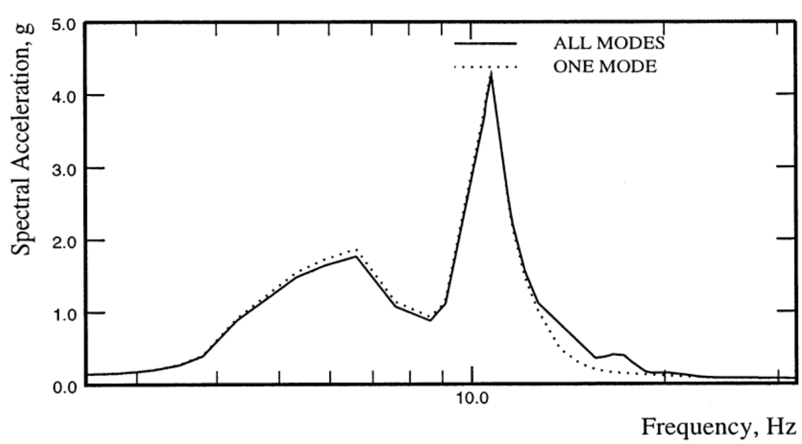
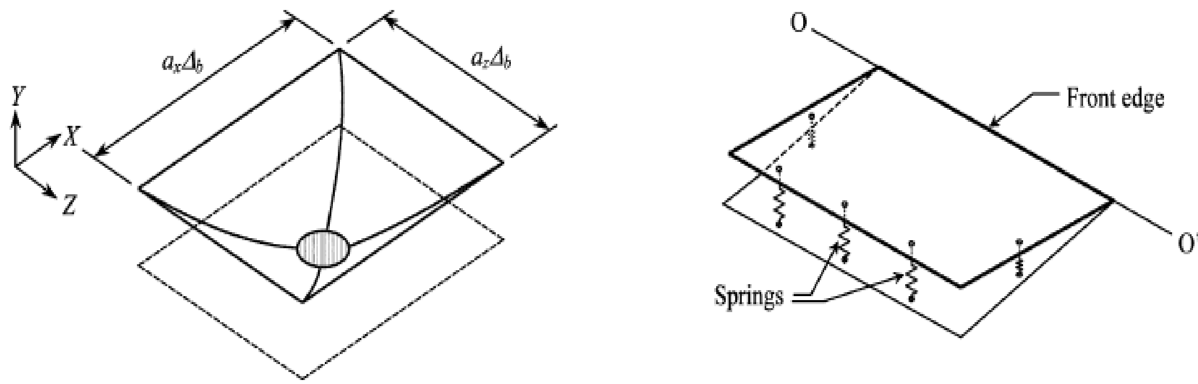


Figure 1. In-Cabinet Response Spectra for DGLSB- Frame (Gupta et al. 1999)

Mounting Arrangements

The experiments conducted on various electrical cabinets by Llambias et al. (1989) show that at low amplitudes of excitation, both experimental and analytical results predicted same natural frequencies and mode shapes but at higher amplitudes of excitation, however, the seismic testing showed that the natural frequency of cabinet decreases with increase in the level of excitation. Thus, concluding that the cabinets behave in a nonlinear manner since the first mode is a rigid body rocking mode.

Gupta et al. (1999) show that a global mode could be the significant mode of the cabinet which could either be a rocking mode if the bending of cabinet is restricted due to resistance from side plates or it could be a combination of rocking and bending. Hence, Yang et al. (2002) studied various mounting arrangements for cabinets and developed rocking stiffness formulations. A cabinet base plate rotation is restricted by the anchor bolts making the base plate to undergo localized cup-like deformation as shown in figure 2(a). The base plate curvature in the regions far from the anchor bolts is negligible and thus, the discrete springs at the location of anchor bolts represent the rotational stiffness of base plate as shown in figure 2(b).



(a) **(b)**

Figure 2. (a) Cup-like localized deformation around an anchor bolt; (b) Equivalent model with vertical springs at anchor locations (Gupta & Yang et al. 2002)

CABINET MODEL

Since the rigid-body rocking mode could be the significant mode of the cabinet, the mounting arrangement could affect the resulting in-cabinet response spectra as well as the frequency content of cabinet acceleration at the equipment level. It is anticipated that when an anchored cabinet base undergoes rocking, a gap between cabinet base plate and bolt head could hinder propagation of high-frequency vibrations to the equipment since the displacement caused by high-frequency acceleration is less as compared to low-frequency accelerations.

A model to represent the nonlinear seismic behavior of cabinets and understand its influence on the frequency content of motions that reach relays is proposed. The model represents a gap that may exist between cabinet base plate and bolt head when a cabinet rocks. Herve et al. (2014) proposed a spring-mass-damper system with a gap of 1mm in both compression and tension based on the recommendations of EPRI (2007) and International Atomic Energy Association (IAEA, 2012) as the cut-off displacement for the case of high-frequency motions due to an airplane impact.

As a modification to the Herve et al. (2014) model, we propose that there will be no gap in compression for rocking behavior of the cabinet since cabinet would not rock below the floor. Furthermore, this study also compares the differences in the in-cabinet response spectra due to different magnitudes of gaps, hence, two models of 1 mm and 5 mm gaps are analyzed. Figure 3 shows the force-displacement relationship of this model. The force-displacement relationship shows that for displacement between 0mm and a predetermined gap (Δ_{gap}), there is zero resisting force in case of tension whereas for displacements more than Δ_{gap}, the resisting force follows linear elastic relationship. Hence, it is a nonlinear elastic model that exhibits geometric nonlinearity. The model follows a simple set of equations of motion which can be written as:

$$m\ddot{u} + c\dot{u} = -m\ddot{u}_g, \quad 0 \leq u \leq \Delta_{gap} \tag{1}$$

$$m\ddot{u} + c\dot{u} + ku = -m\ddot{u}_g, \quad u < 0 \tag{2}$$

$$m\ddot{u} + c\dot{u} + k(u - \Delta_{gap}) = -m\ddot{u}_g, \quad u < \Delta_{gap} \tag{3}$$

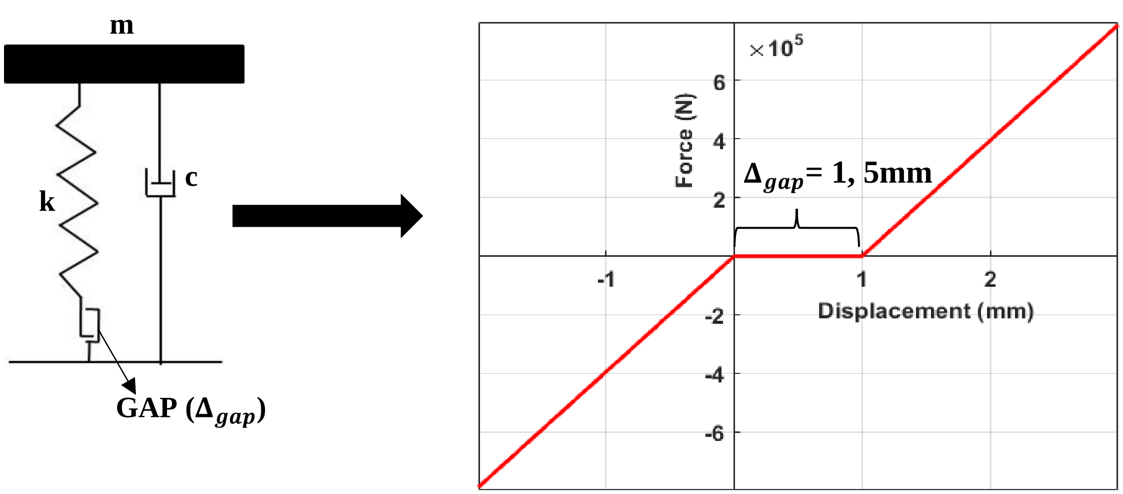


Figure 1. Force-Displacement Relationship of Gap Cabinet Model for Analysis

METHODOLOGY

The main objective of this study is to understand the difference in cabinet response obtained from linear and nonlinear behavior. A number of representative building-cabinet systems and earthquake ground motions are selected. Both the building and the cabinet are represented by a respective single degree of freedom systems to better interpret the results. The ground motions considered in this study are shown in figure 4. The ground motion response spectrum curves shown in figure 4 are normalized to a PGA of 1g, but the actual motions used in the numerical study are not normalized since the problem is a nonlinear in which the behavior is mostly dependent upon the degree of displacements. TAFT record is chosen to represent a low frequency ground motion where the peak ground acceleration is equal to 0.159g and peak occurs at 3Hz. For the high-frequency ground motion, peak ground acceleration is equal to 0.415g and the peak occurs at 35Hz.

A low-frequency building (or cabinet) is represented by a 3 Hz SDOF system and a 35 Hz SDOF system represents a high-frequency building (or cabinet). The damping ratio for the building is taken as 5% and that for the cabinet is taken as 2%. The building model is linear elastic in all cases, but the cabinet model is linear elastic as well as nonlinear elastic. A total of three models, a conventional linear-elastic or fixed-base model and two gap models with 1mm and 5mm gaps, are used to represent the cabinets. Direct integration using Newmark's average acceleration is used for analysis. The floor acceleration time history is used as an input at the base of a cabinet for analysis. The integration time step equal to 0.0001s is used to appropriately consider the effects of high-frequency ground motions.

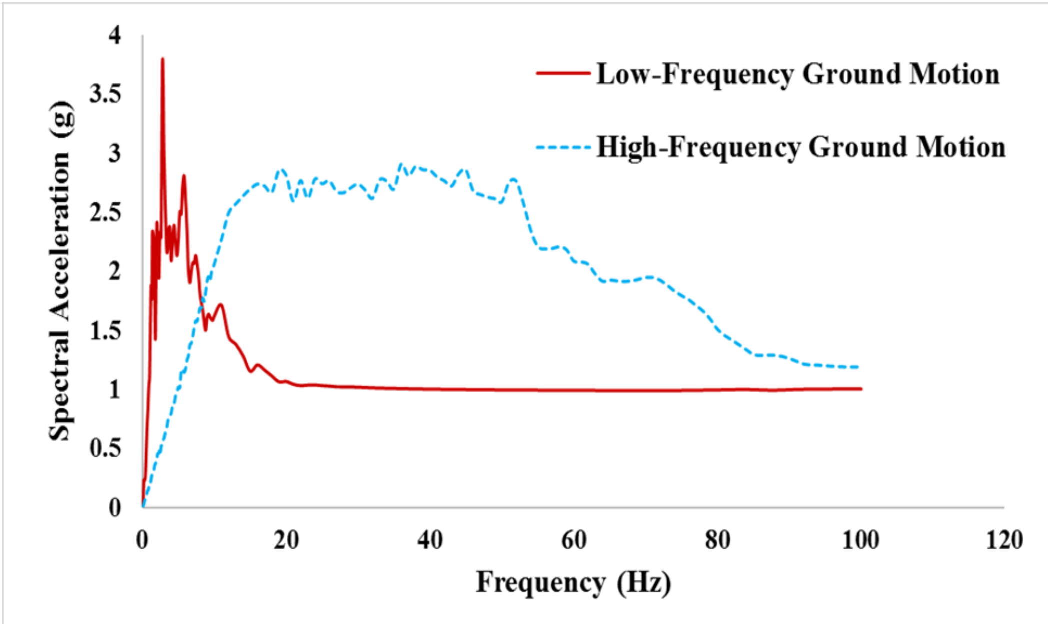


Figure 4. Low-Frequency and High-Frequency Ground Motion Response Spectra Normalized to 1g

RESULTS

About eight different combinations of building-cabinet systems are analyzed subjected to both low-frequency and high-frequency ground motions. One of the most important cases, a system of high-frequency cabinet mounted on high-frequency building subjected to high-frequency ground motion, is discussed in this paper. The in-cabinet response spectra for all the cabinet models in this case are shown in figure 5. Due to a perfect resonance between the ground motion, building and cabinet, the peak spectral amplitude for linear elastic cabinet model (about 350g) is very high as compared to that of nonlinear models. The high peak spectral amplitude may seem impractical but as the numerical derivation shown by Singh (2017), this number is what one would obtain from linear analysis.

The response obtained for nonlinear models are comparatively lower than linear model. Figure 6 shows the in-cabinet response spectra of 1mm and 5mm gap models. The peak spectral acceleration from 1mm gap model is only about 4g while that from 5mm gap model is about 1g. However, the in-cabinet response spectra shows a peculiar behavior. As discussed by Singh (2017), this behavior is attributed to the total floor displacement being more than that of the gap. Since the floor displaces more than the gap, the cabinet will hit the bolt head repeatedly. When the cabinet base hits the bolt head, the transient response of the cabinet is dominant. The interaction of transient response with the steady-state response, when the floor displacement exceeds the gap, results in higher amplitude at some frequencies and lower amplitude at other frequencies. Even though the in-cabinet response spectra shows high-frequency peaks in 1mm gap case, the peak spectral amplitude is still much lower as compared to linear model.

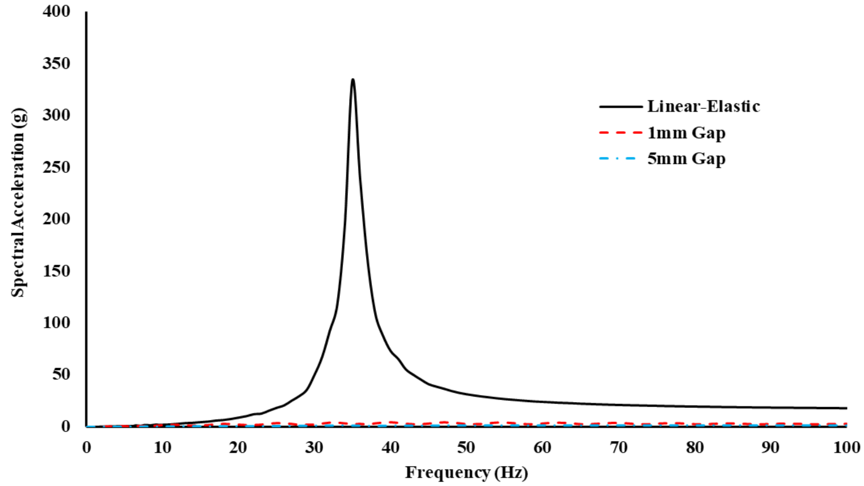


Figure 5. In-Cabinet Response Spectra for High-Frequency Cabinet Mounted on High-Frequency Building subjected to High-Frequency Ground Motion

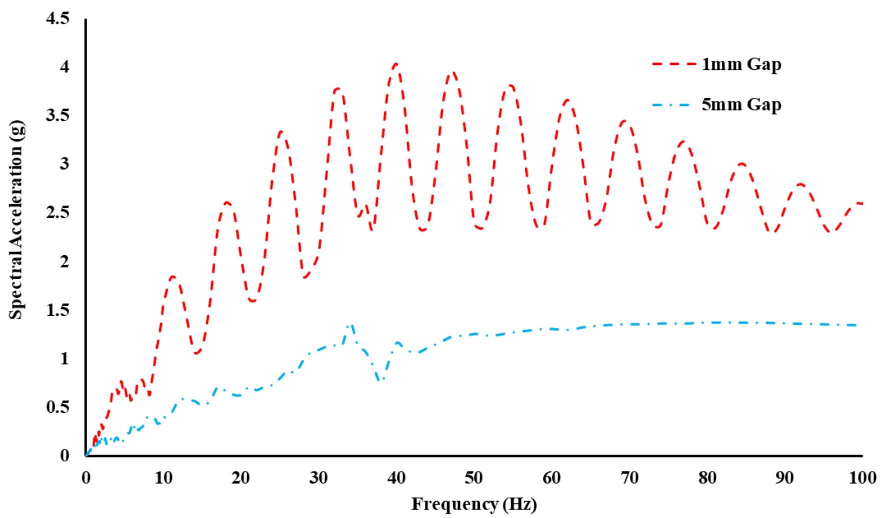


Figure 6. In-Cabinet Response Spectra for High-Frequency Nonlinear Cabinet Models Mounted on High-Frequency Building subjected to High-Frequency Ground Motion

CONCLUSIONS

In conclusion, a linear-elastic analysis can yield unrealistically high spectral accelerations in the case of a high-frequency cabinet mounted on the high-frequency building subjected to high-frequency ground motion. Currently, this situation is indeed faced by NPPs as most buildings and cabinets have higher frequency modes that are in perfect tuning with each other as well as with the frequency of ground motion. As shown in this study, however, a fixed-base or linear model is a theoretical assumption and appropriate nonlinear modeling of the system reduces such unrealistic spectral amplitudes. Most instruments may not satisfy seismic qualification requirements if the linear-elastic analysis is used as a basis of seismic qualification, thus, unrealistically increasing the cost of operating and upgrading the plant for the updated hazards.

For the nonlinear gap cases, the maximum floor displacements influences the peak spectral acceleration and peak cabinet acceleration. The in-cabinet response spectral amplitudes are significantly less if the maximum floor displacement is less than the gap. It is because the motion does not propagate through the gap. If floor displacement, on the other hand, is greater than the gap, the in-cabinet response spectra have somewhat higher spectral amplitudes in the high-frequency range for high-frequency cabinets due to repeated impulses which results in high-frequency oscillations. The acceleration-sensitive equipment such as relays must be qualified on the basis of in-cabinet spectra generated by using a nonlinear analysis which is a reality in NPPs.

ACKNOWLEDGEMENT

This research was funded by Center of Nuclear Energy Facilities & Structures, Department of Civil, Construction and Environment Engineering at North Carolina State University, Raleigh, NC.

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