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SEISMIC DEMANDS FOR INCABINET EQUIPMENT IN MOTOR CONTROL CENTERS IN TAIWAN LUNGMEN NUCLEAR POWER PLANT

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ABSTRACT

For numerical analysis or shaking table tests of in-cabinet equipment, in-cabinet response spectrum (ICRS) is commonly adopted as seismic demand. Several kinds of simplified concepts are mainly used to obtain ICRS. One of the concepts is using floor response spectrum multiplied by the in-cabinet amplification factor (AF). Other concepts generate ICRSs from FRS (floor response spectra) by frequency or time domain analysis. In this paper, a simplified numerical method to establish more realistic ICRS for motor control center (MCC) type cabinets is proposed based on the observation of shaking table test results. Global modes are simulated by a lumped-mass model, and local modes are simulated by a detailed finite element model of the plate at which in-cabinet equipment is anchored. Analysis results of the simplified model are compared with shaking table test and other analysis methods.

INTRODUCTION

For the purpose of seismic verification, Seismic Qualification Utility Group (SQUG)(2001) provided generic implementation procedure (GIP) of in-cabinet equipment (i.e. relays) at MCC type cabinets related to safe shutdown functionality. A relay is considered seismically adequate if the test response spectrum (TRS_c, relay capacity spectrum) enveloped the required response spectrum for in-cabinet equipment (RRS_c) in the frequency range from 4 Hz to 16 Hz and from 33 Hz to the zero period acceleration (ZPA). According to ANSI C37.98 standard (1984), the TRS_c were reported as one value which is the minimum value of the 5% damped TRS in the frequency range from 4 Hz to 16 Hz. Since the value of ZPA is specified to be at least 0.4 times the peak value of TRS_c, the ZPA of TRS_c is regarded as 0.4 times the reported value.

When considering the seismic demands imposed on in-cabinet equipment (i.e. RRS_c), the floor response spectrum represents the seismic inputs at the base of cabinet (RRS_B), and the in-cabinet response spectrum (ICRS) represents the seismic demand applied to the in-cabinet equipment. The most straightforward way to evaluate ICRS is to execute shaking table tests of cabinets with in-cabinet equipment. However, when a seismic re-evaluation for an existing NPP is activated, it is difficult to carry out shaking table tests of the existing cabinets in the NPP. To be compared with TRS_c, several analysis methods have been developed to estimate RRS_c. The first concept is using the RRS_B multiplied by in-cabinet amplification factors (AF). For the first concept, based on the statistical analysis results, the peak and average AF values in different frequency ranges for MCC type cabinets were reported in NUREG/CR-5203 (Bandyopadhyay, 1988). DOE/EH-0545 (DOE 1997) proposed that the RRS_c can be computed by multiplying the scaled floor response spectrum by the in-cabinet AF, which is tabulated according to the type of cabinet, and is statistically calculated from the SQUG database. According to physical testing results, Merz et al. (1990) proposed an effective AF of 3.0 for motor control center (MCC) type cabinet. Kennedy (1989) also recommended that the effective AF of 3.0 can be used to convert a High-Confidence-Low-Probability-of-Failure capacity (approximately 95% confidence of less than about a 5% failure probability) for in-cabinet equipment at the worst location in a MCC type cabinet. Based on both Merz et al. (1990) and Kennedy (1989), EPRI NP-6041-SL (1991) suggested that RRS_c, the peak spectral acceleration of the clipped required response spectrum for in-cabinet equipment at any location in a MCC type cabinet, could be obtained by multiplying the peak value of clipped FRS (RRS_B) by the effective AF. The effective AF was increased to 3.6 by the multi-axis to single-axis correction.

The above method is a simple way to obtain seismic demands on in-cabinet equipment. However, it is unreal especially in the case that the actual natural frequency of the cabinet is not in the amplified region of RRS_B. Other methods are generating rigorous ICRS from RRS_B by frequency domain analysis or time domain analysis. A frequency domain analysis (FDA) method is proposed by EPRI NP-7146-SL Report (EPRI, 1995). Based on the observations of finite element analysis results and shaking table test results, the dynamic response of a particular mounting location for in-cabinet equipment can be represented by one or two significant modes. To evaluate the ICRS by time domain analysis, Gupta et al. (1999) proposed that the ICRS can be generated by one local mode or by both local and global modes by the Rayleigh–Ritz method. Yang et al. (2001) implemented and modified the Ritz-vector approach, using a computer program that evaluated cabinet dynamic characteristics effectively and calculated the ICRS based on limited information on the properties of the cabinet.

In this paper, a simplified model is established according to the system identification results of shaking table tests. ICRS analysis results conducted by the numerical model are compared with the finite element model analysis with SAP2000 software whose global structural dynamic characteristics have been calibrated by experimental results. Analysis results of the simplified model are also compared with the frequency domain analysis results according to the method of EPRI NP-7146-SL report.

TEST CONFIGURATION

The objective of this research is to develop a reasonable design mechanism for the seismic demands of in-cabinet instruments belonging to safety-related mechanical and electrical (M/E) systems in an NPP. Referring to the Final Safety Analysis Report (FSAR, Taiwan Taipower Company 2007) for the Lungmen nuclear power plant (NPP 4), the Residual Heat Removal (RHR) system of the Advanced Boiling Water Reactor (ABWR) system was chosen due to its importance to the critical M/E system to prevent a reactor core damage accident. The associated motor control centers (MCCs) were identified as the target cabinets in this project and simulated by commercially available products (Figure 1). The cabinet without drawers is further studied in this paper (Figure 2).

Global and in-cabinet responses were obtained at *A1* and *A2* measuring points and *A4*, *A5* and *A6* measuring points, respectively. The input motions were applied simultaneously in three orthogonal directions, i.e. side-to-side (*X*), front-to-back (*Y*) and vertical (*Z*). Both the generic broad-band RRS_B (IEEE693, 2006) and the specified RRS_B of operating basis earthquake (OBE) of the Lungmen NPP (FSAR 2007) were adopted to study the elastic behavior of cabinets (Figure 3). The horizontal peak values of both inputs were approximate in the range from 500 to 600 gal. The IEEE693 TRS_B has higher amplitude below 20.0 Hz while the OBE TRS_B has higher amplitude in the range from 20.0 Hz to 30.0 Hz. Other details of test setting are reported in Lai et al. (2013).

As mentioned in Lai et al. (2013), natural frequencies of the cabinet varied depending on the mass of in-cabinet equipment and the type and amplitudes of input motions (Figure 4 and Table 1). To establish the lumped-mass model, the average natural frequencies measured at *A1* and *A2* points in strong motions were adopted, i.e. 10.16 Hz and 13.48 Hz in *X* and *Y* directions, respectively. The test results also indicate variable damping ratios of cabinets and the values are dependent on their mass, fundamental frequencies, and the vibration level. According to the white noise test results, the values 4.75 % and 5.47 % were used as the damping ratios of the target cabinet in *X* and *Y* directions respectively.

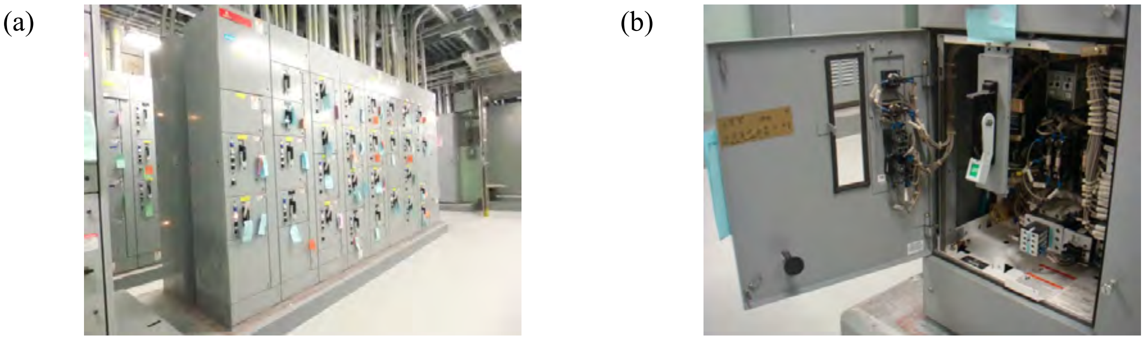

Figure 1. MCCs belonging to the RHR system in NPP 4.

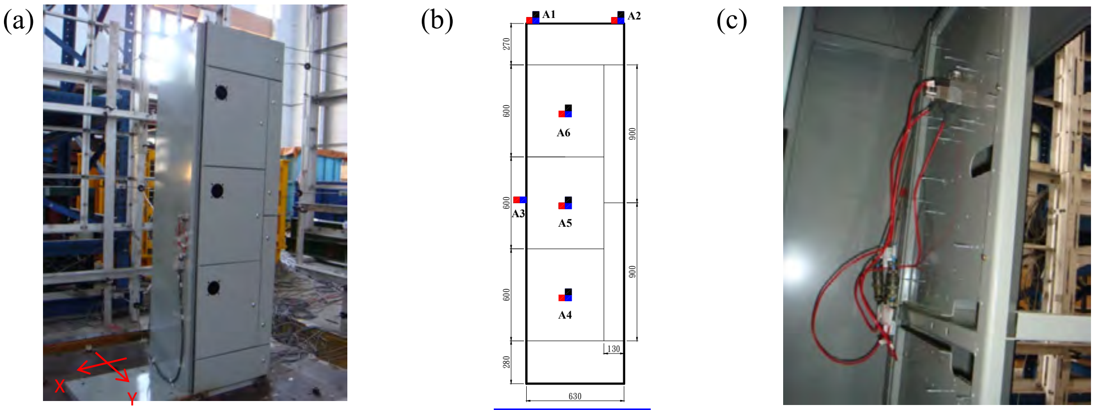

Figure 2. The test specimen to simulate MCC type cabinets (unit: mm).

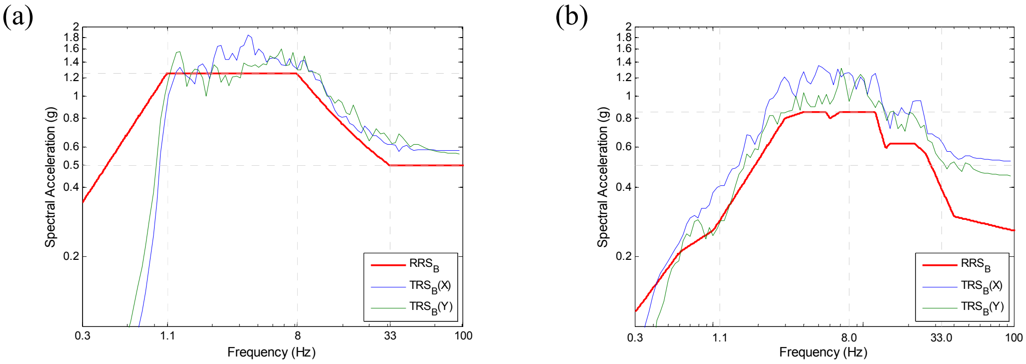

Figure 3. RRS$_B$ and TRS$_B$ in horizontal directions: (a) the IEEE693 test, (b) the OBE test.

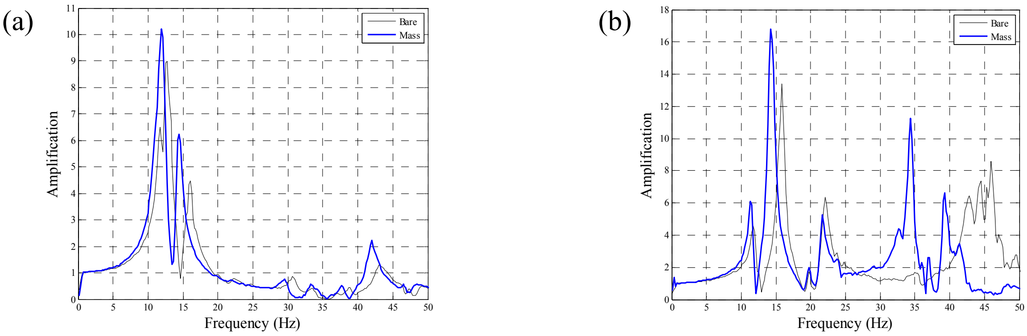

Figure 4. Transfer functions in the White Noise test: (a) in the *X* direction, (b) in the *Y* direction.

Table 1: Fundamental frequencies of the cabinet under different input motions.

Input motion		*X* direction [Hz]	*Y* direction [Hz]
IEEE693	50 %	10.16	13.67
	75 %	10.16	13.48
	100 %	10.16	13.48
OBE	50 %	10.16	14.06
	100 %	9.38	13.48
	Average	10.16	13.48
White Noise		12.50	15.82

ANALYTICAL METHODS

The frequency domain analysis (FDA) method according to the EPRI NP-7146-SL Report is adopted in seismic margin assessments for the relays in existing nuclear power plants in Taiwan. Taking the seismic event as a Gaussian process, the power spectral density function (PSD) of floor acceleration can be derived from the given RRS_B. For comparison with the ICRS obtained in tests, the TRS_B measured at the shaking table was used instead of RRS_B. The in-cabinet PSD is calculated in turn under the assumption that the cabinet is a single-degree-of-freedom (SDOF) system. Multiple in-cabinet PSD functions are obtained for specified frequencies. Finally, ICRSs are converted from in-cabinet PSD functions to result in the enveloping ICRS. Figure 5 depicts the ICRSs conducted by the FDA method and shaking table tests. The values of spectral acceleration are extremely high while the fundamental frequencies of the cabinet are in the amplified range of TRS_B. However, the values of spectral acceleration of out-of-plane ICRSs (along with the *Y* direction) are underestimated in the frequency range above 35 Hz.

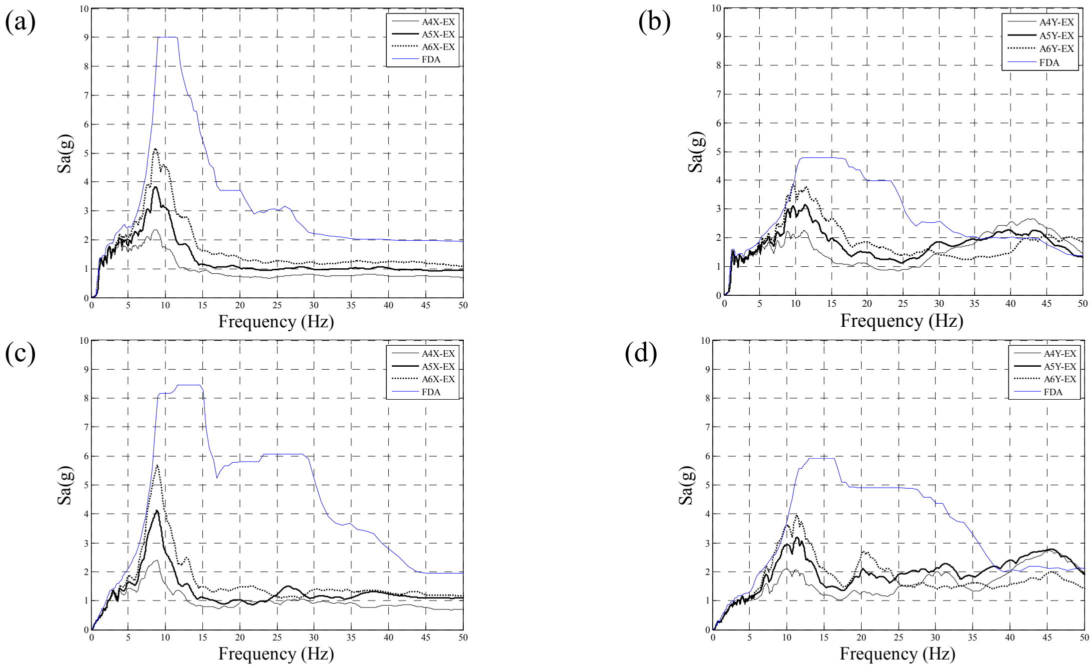

Figure 5. ICRSs in the (a) *X* direction and (b) *Y* direction in the IEEE693 test, and ICRSs in the (c) *X* direction and (d) *Y* direction in the OBE test.

To obtain more realistic ICRS for MCC type cabinets by analysis, a simplified method is proposed as below. The first step is to establish a lumped-mass model with the “link” element in SAP2000 software according to the mass distribution of the cabinet and expected positions of in-cabinet equipment. The values of stiffness of the link elements are adjusted in turn to conform to the fundamental frequency in the *X* or *Y* direction. Since the modal participating mass ratios of global dominate modes of the lumped-mass model were higher than those of the test specimen, the damping ratios of global dominate modes were adjusted to 8 % which is much larger than the experimental results. As shown in Figure 6, the lumped masses are anchored to the positions of *A1*, *A4*, *A5* and *A6* points. The *A1* point represents the position where the maximum amplitude of the global fundamental modes occurs. The *A4*, *A5* and *A6* points represent the positions of the center of mass of the in-cabinet equipment and associated mounted plates in the low, medium and high cubicles respectively. The responses of *A4*, *A5* and *A6* points are obtained by applying the input motions compatible with RRS_B at the base of the lumped-mass model.

The second step is to establish a finite element model of the plate at which the in-cabinet equipment is anchored. The reason that the finite element model of the mounted plate is recommended rather than a simplified SDOF model is to excite significantly larger spectral acceleration in the higher frequency range of ICRSs. Figure 7 depicts the real mounted plate and the simulating model established with the “shell” element in SAP2000 software. The hinge supports were simulated at six bolted positions. The mass and material properties of the plate were adjusted such that the natural frequency in the out-of-plane direction is conformable to the experimental results. Considering the phenomenon mentioned by EPRI NP-7146-SL that the local plate modes will induce lower damping, and hence, a damping ratio of 0.8 % was used corresponding to test results. With applying the vibration obtained at the *A4*, *A5* or *A6* point of the lumped-mass model to the six hinge supports, the responses at the base of in-cabinet equipment were then estimated. The responses at the central point of the plates were discussed in the following paragraphs.

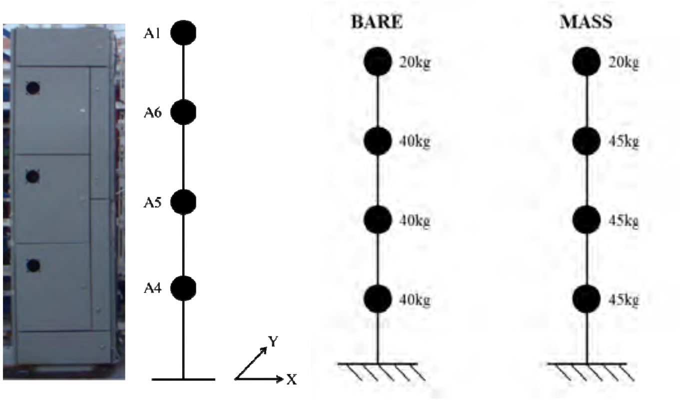

Figure 6. Lumped-mass models and measuring points of ICRS.

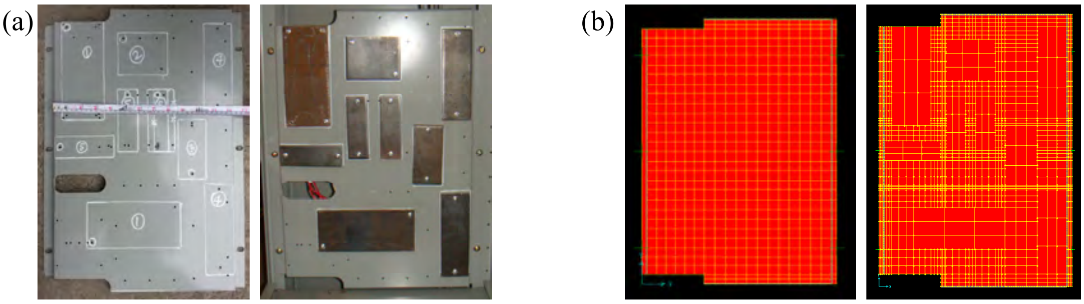

Figure 7. (a) The mounted plates of in-cabinet equipment and (b) the simulating models of the plates.

ANALYTICAL RESULTS

In order to provide more reasonable seismic demands on in-cabinet equipment, acceleration time-history responses, ICRSs and the amplification factor (AF) functions conducted by the proposed method were compared with those obtained from the shaking table test, the frequency domain analysis (FDA) based on EPRI NP-7146-SL Report, and the complete finite element model of the cabinet. Descriptions of the complete finite element model of the cabinet are reported in Lai et al.(2013).

Acceleration Time-History Responses

Figure 8 depicts the acceleration responses at the measuring point *A6Y* (i.e. in the out-of-plane direction at the highest cubicle) in the IEEE693 and the OBE tests. The acceleration responses at the supporting base of in-cabinet equipment by the proposed method were quite similar to the test results, since the dominate modes of the global and local behaviors had been captured by the lumped-mass model together with the finite element model of the plate. However, compared with IEEE 693 test, it can be seen that unexpected responses in higher frequency exist in the data of the OBE test (Figure 8b), which might be induced by rattling and bucket banging (Merz et al., 1990) and cause unstable values of spectral acceleration of ICRS in the associated frequency range.

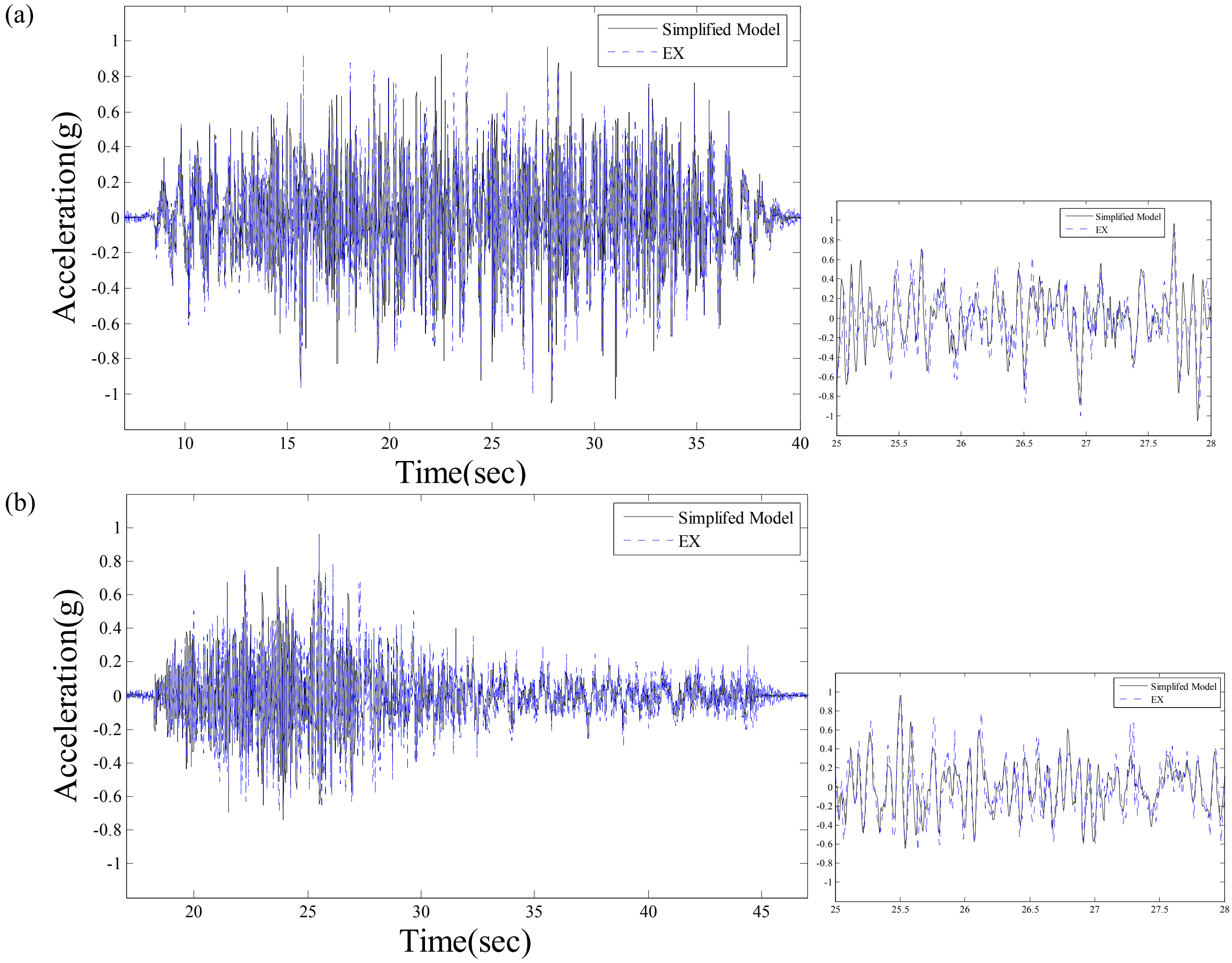

Figure 8. Acceleration responses at the measuring point *A6Y* in (a) the IEEE693 test and (b) the OBE test.

ICRS

From previous studies (NUREG/CR-5203, EPRI NP-7146-SL and Lai et al.), values of spectral acceleration of ICRSs were observed to be variable depending on the location of the accelerometer in the cabinet and input motions. Figure 9 and Figure 10 depict the ICRSs in the IEEE693 test and OBE test respectively, which were obtained at the measuring point *A*4 and *A*6 (i.e. at the lowest and highest cubicles). Figure 9 shows that the proposed model, depicted in the black line, can capture the different spectral responses between in-plane (*X*) and out-of-plane (*Y*) directions in the ICRSs larger than 30.0 Hz. Figure 9 also shows the effects of different measuring location on the peak value of the ICRSs. The peak of ICRS at the lowest cubicle as shown in Figure 9(b) is in the range larger than 30.0 Hz and it is mainly affected by the local plate behavior. On the other hand, Figure 9(d) shows the peak of ICRS at the highest cubicle is in the range less than 15.0 Hz and it is dominated by the global cabinet behavior. Figure 10 depicts the ICRSs in the out-of-plane (*Y*) direction of the mounted plate obtained in the OBE test. Comparing with the test results, the proposed model has better simulating results in the range below 15.0 Hz dominated by the global cabinet behavior. However, as mentioned above, an unexpected higher frequency response in the OBE test causes stronger amplitude above 20.0 Hz in both *A*4 and *A*6 locations.

Figure 11 compares the ICRSs conducted by FDA and the proposed method in in-plane (*X*) and out-of-plane (*Y*) directions. Compared with both the test results and the proposed analytical results, the in-plane ICRSs determined by FDA were extremely conservative in the IEEE693 test since the fundamental frequency of the cabinet is in the amplified range of IEEE693 RRS_B (Figure 5a and Figure 11a). The out-of-plane ICRSs determined by FDA were underestimated in the range larger than 35 Hz, while the proposed model can perform more precise local behavior (Figure 5b, 5d and Figure 11b, 11d).

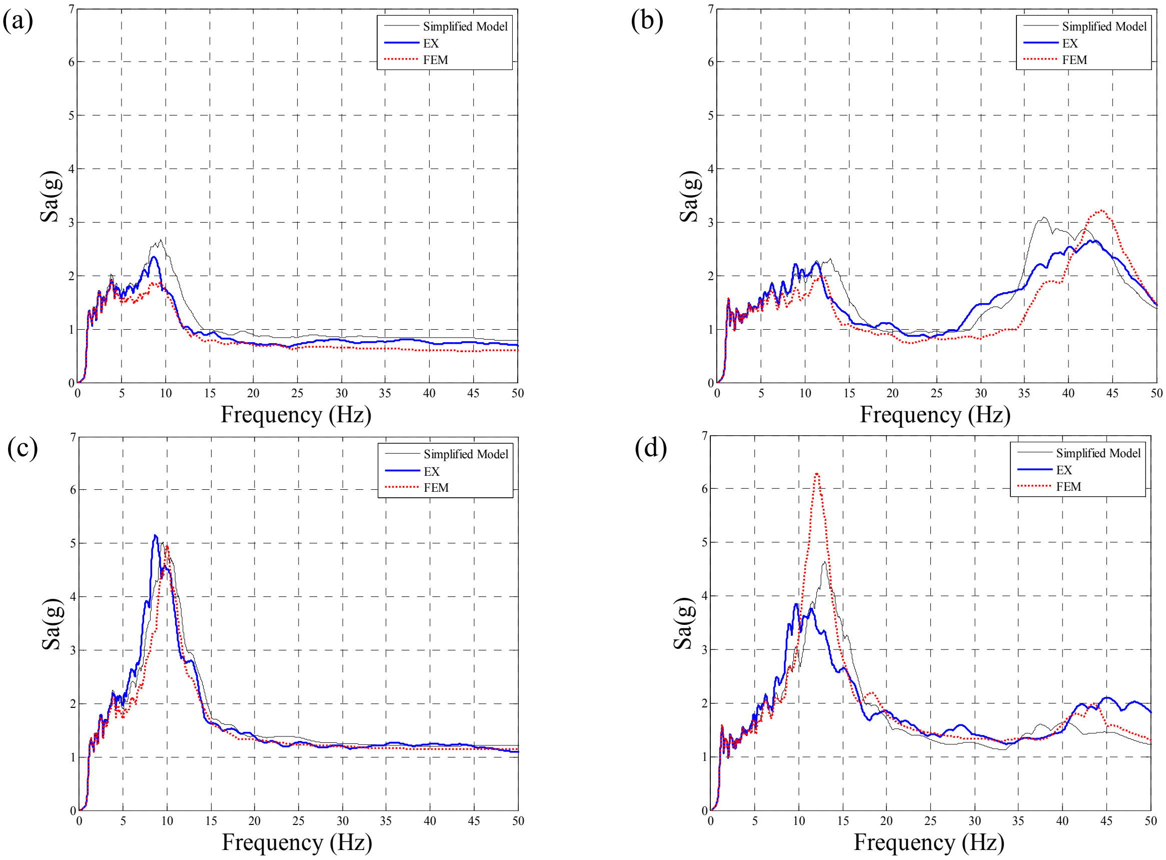

Figure 9. ICRSs of different measured positions in the IEEE693 test: (a) the ICRS at point *A*4*X*, (b) the ICRS at point *A*4*Y*, (c) the ICRS at point *A*6*X*, and (d) the ICRS at point *A*6*Y*.

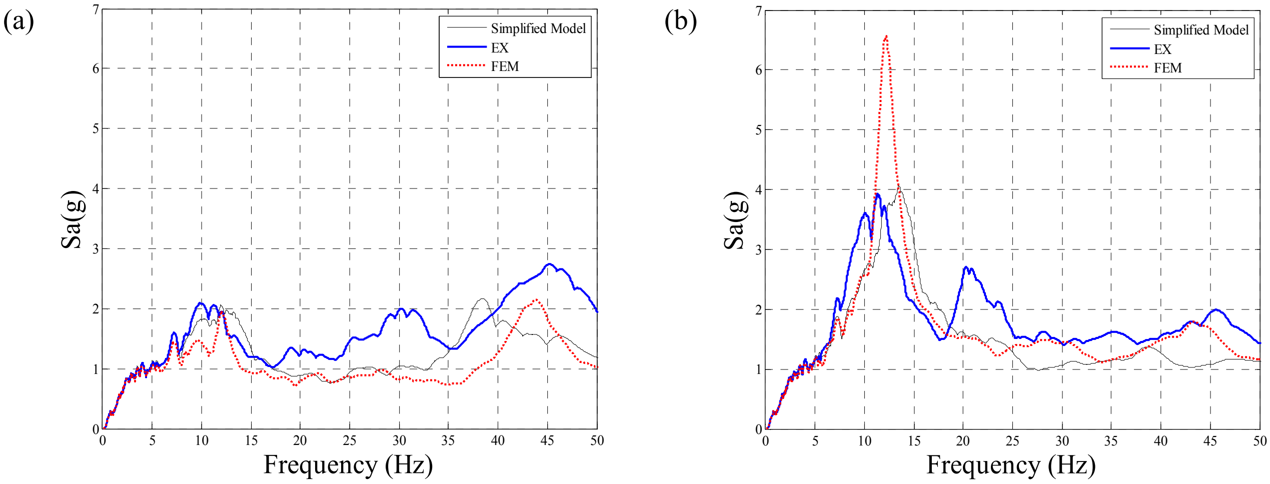

Figure 10. ICRSs of different measured positions in the OBE test: (a) ICRSs at point *A*4*Y* and (b) ICRSs at point *A*6*Y*.

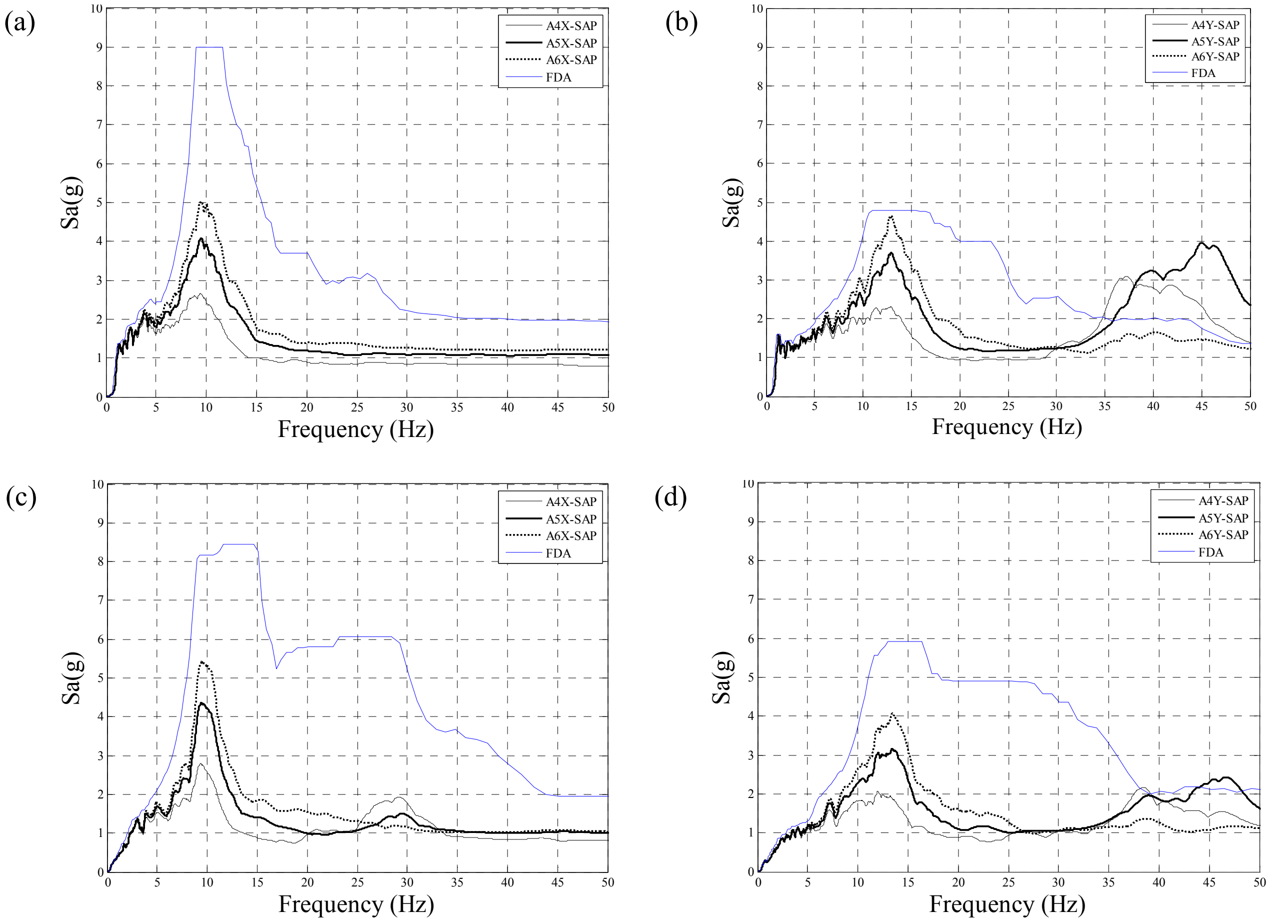

Figure 11. ICRSs conducted by FDA and the proposed method: ICRSs in the IEEE693 test (a) in the *X* direction and (b) in the *Y* direction, ICRSs in the OBE test (c) in the *X* direction and (d) in the *Y* direction.

Amplification Factor

In this paper, the in-cabinet amplification factor (AF) at any particular frequency is defined as the ratio of the corresponding spectral accelerations of the ICRS and the TRS_B. Compared with the ICRSs, the AF functions can give a better understanding of the dynamic amplification effect caused by the cabinet. As shown in Figure 12, the AF functions in the out-of-plane direction of the mounted plates were evaluated at different elevations of measuring points in IEEE693 and OBE tests. From the results of experiment and the proposed model, the enveloping AF functions approximately less than 30 Hz is controlled by the data measured at the highest cubicle (point $A6$), and by the one measured at the lower cubicle (point $A4$) in the frequency range approximately between 30 and 45 Hz for both tests. In accordance with NUREG/CR-5203, the median peak AF values in the range from 4 to 16 Hz, from 16 to 40Hz and from 40 to 100Hz are 4.8, 5.3 and 5.7 respectively. Since the influence of the in-cabinet drawers on the AF functions is excluded in this study, all the peak AF values in the both tests were smaller than the median values reported by NUREG/CR-5203, except in the range above 40 Hz measured at the lower cubicle in the OBE test (Figure 12c). Although the AF functions in the range below 16 Hz in both test results are well or conservatively fit by the proposed model, the AF function in the range above 20 Hz are underestimated especially in the OBE test. It can be seen that the proposed model cannot fit the local cabinet behavior well compared with the complete finite element model.

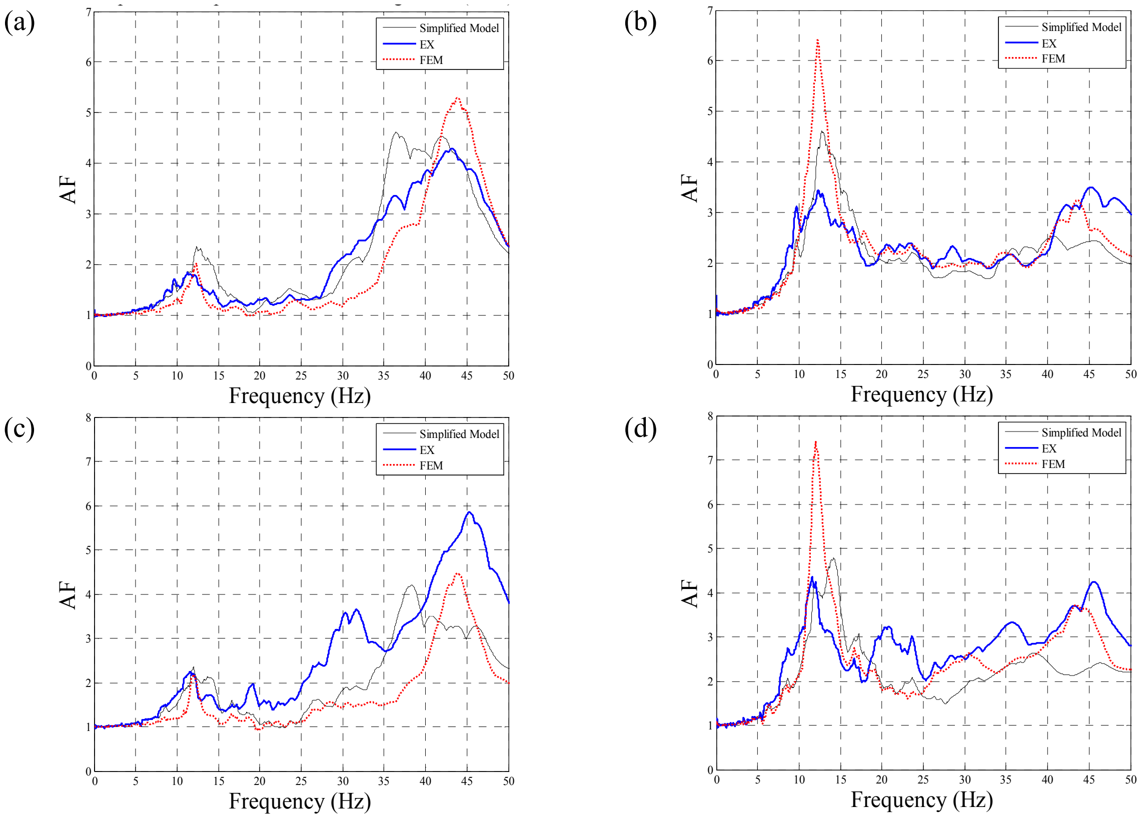

Figure 12. AF functions of different measured positions: the AF functions at (a) point $A4Y$ and (b) point $A6Y$ in the IEEE693 test, and the AF functions at (c) point $A4Y$ and (d) point $A6Y$ in the OBE test.

CONCLUSION

In order to provide more reasonable seismic demands on in-cabinet equipment for motor control center (MCC) type cabinets, a simplified method is proposed based on the observation of shaking table test results. The global modes were simulated by a lumped-mass model, and local modes are simulated by a detailed finite element model of the plate at which in-cabinet equipment is anchored. The in-cabinet response spectrum (ICRS) and in-cabinet amplification factors (AF) estimated by the proposed method are discussed by the comparison with the shaking table test results, the frequency domain analysis (FDA) based on EPRI NP-7146-SL Report, and the complete finite element model of the cabinet. From above observation, the proposed model can predict global and local cabinet behaviors better in contrast to the FDA results, but cannot fit the local cabinet behavior so well as the complete finite element model. Future research effort is to improve the proposed method to overcome the underestimate of the local behavior and other unexpected higher frequency response.

NOMENCLATURE

X, *Y*, *Z*	directions of the input motion of tests
A1, *A2*, *A4*, *A5*, *A6*	measuring points for the acceleration response of the cabinet
EX, *FEM*	results from experiment data or complete finite element model of the cabinet

REFERENCES

Bandyopadhyay, K. K., et al. (1988). “Dynamic Amplification of Electrical Cabinets,” NUREG/CR-5203, Brookhaven National laboratory (BNL), Upton, New York.

Chai, J. F. et al. (2012). “Establishment of the Technologies of Seismic Hazards Assessment and Structure Design/Analysis for Nuclear Power Plant (II),” NSC project No. NSC101-3113-P042A-004, Taipei, Taiwan (in Chinese).

Gupta A., Rustogi S. K., and Gupta A. K., 1999. Ritz vector approach for evaluating in-cabinet response spectra. *Nuclear Engineering and Design*, ENS & IASMiRT, 190 (3), 255–272.

Kassawara, R. P., et al. (1991). “A methodology for assessment of nuclear power plant seismic margin (Revision 1),” EPRI NP-6041-SL, Electric Power Research Institute (EPRI), Palo Alto, CA, USA.

Kassawara, R., et al. (2001). “Generic Implementation Procedure (GIP) for Seismic Verification of Nuclear Plant Equipment (Revision 3A),” Seismic Quality Utility Group (SQUG) , USA.

Kassawara, R. P., et al. (1995), “Guidelines for Development of In-Cabinet Demand for Devices Mounted in Electrical Cabinets,” EPRI, NP-7146-SL R1, EPRI, Palo Alto, CA, USA.

Kennedy, R. P. (1989). “Effective amplification factors for motor control centers and switchgear,” letter report to P. Y. Chen, U. S. Nuclear Regulatory Commission, USA.

Lai , Z. Y., Chai, J. F., Lin, F. R., et al. (2013). “Experimental study for MCCs in Taiwan Lungmen nuclear power plant,” 22nd SMiRT, San Francisco, USA.

Merz, K. L., Ibanez P. (1990). “Guidelines for estimation of cabinet dynamic amplification,” *Nuclear engineering and design*, 123 (2-3), 247-255.

Murray, R., et al. (1997). “Seismic evaluation procedure for equipment in U.S. Department of Energy facilities,” DOE/EH-0545, U.S. Department of Energy, USA.

IEEE Power Engineering Society (2006). “IEEE recommended practice for seismic design of substations,” IEEE Power Engineering Society, IEEE 693, USA.

Institute of Electrical and Electronic Engineers (1984). “Seismic testing of relays,” ANSI/IEEE Standard C37.98-1984, USA.

Taipower Company (2007). “FSAR of Lungmen nuclear power station units 1&2, appendix AC: seismic analysis,” Taiwan.

Yang J. F., Gupta A.(2001). “INCABS: a computer program for evaluating in-cabinet spectra,” SMiRT 16, Washington, DC, USA.