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Division V

Generation of ICRS by Frequency Domain Approach Considering Rocking Stiffness at the Base of an Electrical Cabinet

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ABSTRACT

This paper introduces a methodology to generate the in-cabinet response spectrum (ICRS) using frequency domain method. In this study, the rocking behaviour in the analytical model is represented using a rotational spring. The rocking behaviour of a cabinet is developed due to a cup-like local deformation of plates around anchors or by global bending deflection of its mounting frame. The ICRS generated using the frequency domain method is validated against the results obtained from a time domain approach. It is shown that the rocking spring at the base of the cabinet influences the seismic response of cabinets.

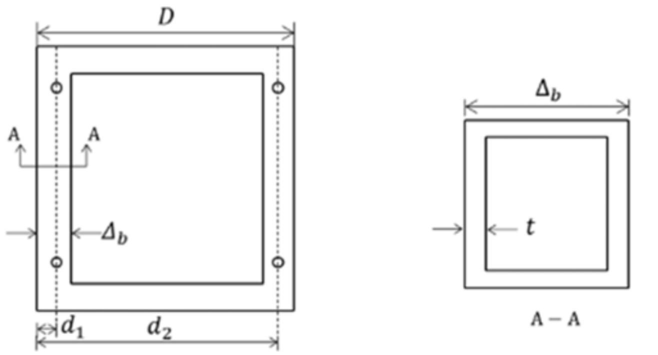
INTRODUCTION

Several studies have shown that the rocking mode of the cabinet can significantly affect the cabinet response (Yang et al., 2003; Lee et al., 1990). To demonstrate the functionality of the electrical components or instruments installed in a cabinet, a seismic test is performed using ICRS at the location where the instrument is mounted. Typically, ICRS is generated using a time domain approach (TDA) or a frequency domain approach (FDA). In TDA, a time history analysis of the cabinet is conducted by applying a ground motion at its base. The in-structure time histories are then used to generate the ICRS. In FDA, the ground motion is characterized in terms of a power spectral density (PSD) function and a frequency domain analysis is conducted to generate the PSD response at the desired location of the cabinet. The PSD response is then converted into the corresponding ICRS.

This study derives a simplified mathematical model for the rocking behaviour of a steel-box cabinet based on the results of seismic analyses and shaking table tests. ICRS for an actual cabinet considering the rocking stiffness at the base is generated using FDA.

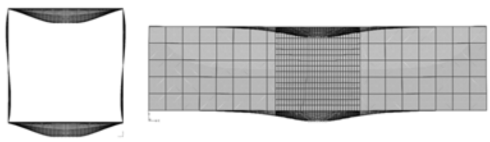
ROCKING OF CABINET

A cabinet is fixed to mounting frame by anchors at each side as shown in Fig. 1a. Fig. 1b is the section view of the tubular mounting frames. Rocking behaviour of a cabinet is developed due to a cup-like local deformation (Fig. 2) of plates around anchors and by global bending deflection of its mounting frame. In this study, we assume the spaces between the anchors are large enough so that there is no interaction between the local deformation of plates around neighbouring anchors.

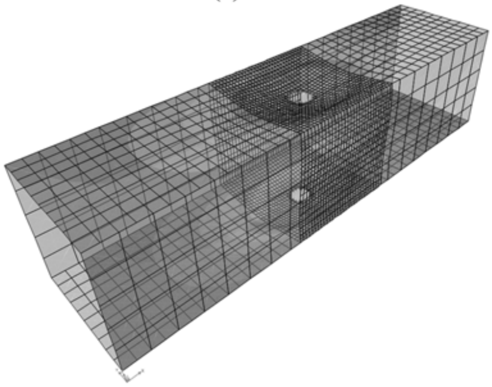


(a) Plan view of the base frame (b) Section view

Figure 1. Mounting frames and anchors of a cabinet



(a) Front elevation view (b) Side elevation view



(c) Isometric view

Figure 2. Cup-like local deformation of a plate around an anchor

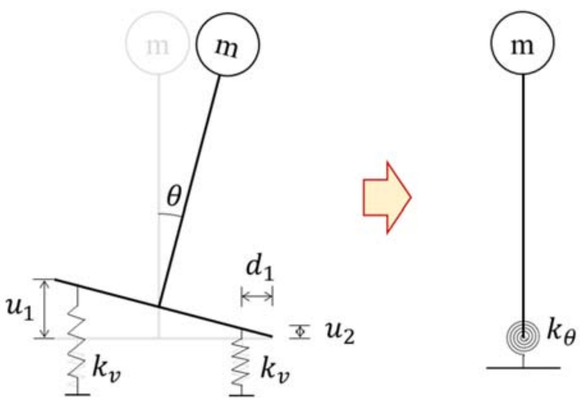


Figure 3. Rocking behaviour of simplified model

The vertical movement due to cup-like local deformation of plates around anchors can be represented by two equivalent vertical springs, $2k_v$. The rocking stiffness k_θ can be calculated considering the vertical spring by assuming that the cabinet is rocking rigidly as shown in Fig. 3. The vertical spring coefficient can be derived by using the strain energy of a local plate, U, as shown in Eq. (1).

$$U = \frac{Et^3}{24(1-\nu^2)} \times \int_0^{a_x\Delta_b} \int_0^{a_z\Delta_b} \left[\left(\frac{\partial^2 u}{\partial x^2}\right)^2 + 2\nu \frac{\partial^2 u}{\partial x^2}\frac{\partial^2 u}{\partial z^2} + 2(1-\nu)\left(\frac{\partial^2 u}{\partial x \partial z}\right)^2 + \left(\frac{\partial^2 u}{\partial z^2}\right)^2 \right] dxdz \qquad (1)$$

where u is the transverse deflection; E is the Young's modulus; ν is the Poisson's ratio; and t is the thickness of local plate. Δ_b is width of tubular mounting frame, and a_x, a_z are ratios of widths in each direction of cup-like deformation to Δ_b. The transverse deflection u can be represented by the maximum transverse deflection u_0 and shape functions in each direction, $\Phi\left(\frac{x}{a_x\Delta_b}\right)$, $\Phi\left(\frac{z}{a_z\Delta_b}\right)$ as shown below:

$$u = u_0 \Phi\left(\frac{x}{a_x\Delta_b}\right) \Phi\left(\frac{z}{a_z\Delta_b}\right) \qquad (2)$$

The derivative of U with respect to the maximum transverse deflection u_0 gives the vertical force at the anchor. Then, derivative of the vertical force with respect to the maximum transverse deflection u_0 yields the equivalent vertical spring coefficient, k_v

$$\frac{\partial U}{\partial u_0} = k_v u_0, \qquad (3a)$$

$$k_v = C \frac{Et^3}{12(1-\nu^2)} \frac{1}{\Delta_b^2} \qquad (3b)$$

where C is a constant, and itis governed by the choice of a shape function for local deflection of the plate around an anchor.

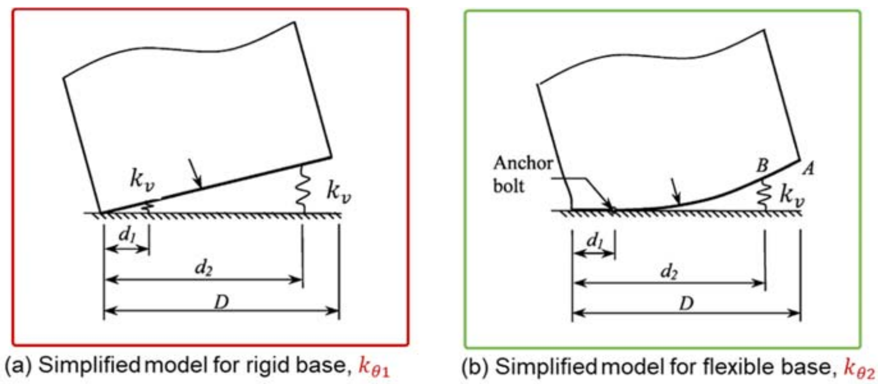


Figure 4. Simplified model for evaluating $k_{\theta 1}$ and $k_{\theta 2}$ (Yang et al., 2002)

If the bending stiffness of mounting frame is relatively high and if the anchor bolts are located only at the ends of frame member, the frame can be assumed to behave rigidly as shown in Fig. 4a and the rocking stiffness, $k_{\theta 1}$ in this case is given by Eq. (4). On the other hand, if the bending stiffness of mounting frame is relatively low, the frame can be assumed to behave flexibly as shown in Fig. 4b and the rocking stiffness, $k_{\theta 2}$ in this case is given by Eq. (5). If the mounting frames consists of frames with high and low bending stiffness, then the resultant rocking stiffness, k_{θ} is given by the sum of $k_{\theta 1}$ and $k_{\theta 2}$.

$$k_{\theta 1} = k_v \sum_{i=1}^{n} d_i^2 \tag{4}$$

$$k_{\theta 2} = 12EID^2 \left[2L^3 - \frac{k_v l^4 (3L - l)^2}{2k_v l^3 + 3EI} \right]^{-1} \tag{5}$$

CABINET

The dimensions of the cabinet selected for this study are shown in Fig. 5a. This cabinet is fixed to the mounting frames which consists of the steel tubular channels. The thickness of the side plates of cabinet is 5mm, these plates are fixed to the internal structural frames. The stiffness of the front and rear doors do not contribute for stiffness of the cabinet because there are gaps between these doors and the cabinet frames. The total weight of cabinet is 48.7kN and the weight excluding inner instruments is 28.7kN.

The cabinet is analysed as an equivalent beam-stick model with fixed base or with rocking spring as shown in Fig. 5b and 5c. The beam-stick model has horizontal and rotational degree-of-freedom (DOF) in a plane. The lumped mass and the stiffness of the beams-stick model are shown in Table 1.

The natural frequencies of the beam-stick model are shown in Table 2. The natural frequency of the beam-stick model with rocking spring is 6.75Hz, which is significantly smaller value than that with fixed base.

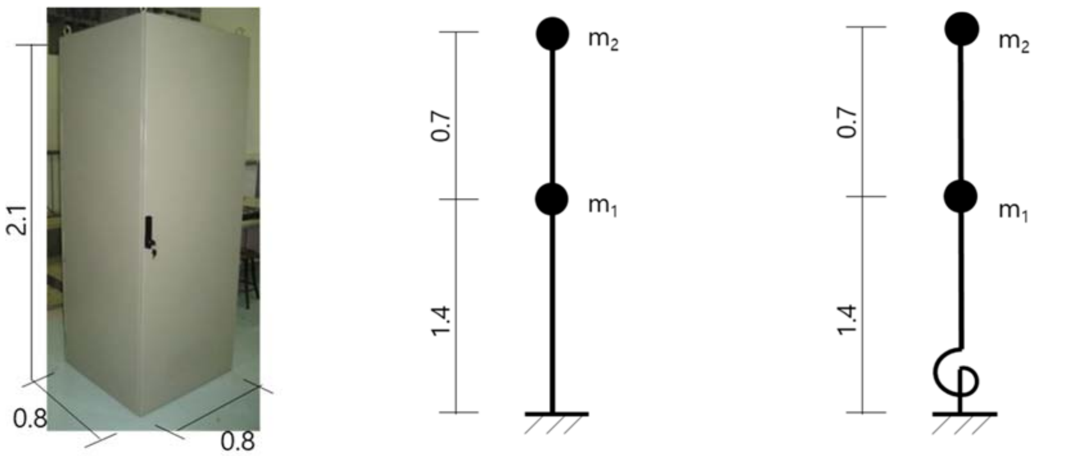
Table 1. Mass & stiffness of beam-stick model

Node	Mass	equivalent beam stiffness	rocking spring coeff.
1	24.35kN	1.73×10^5 kN/m	3.98×10^5 kN·m / rad
2	12.18kN		
base	12.18kN	-	

Table 2. Natural frequency of the beam-stick model

w/ fixed base	w/ rocking spring
9.48 Hz	6.75 Hz

To obtain the rocking stiffness based on the thickness t and the width of tubular-section Δ_b, several static finite element (FE) analyses are performed for the mounting frame shown in Fig. 1. The rocking stiffness calculated from the FE analyses is compared with those calculated from Eqs. (4) and (5) as shown in Fig. 6. Since there are no frames with high bending stiffness in the mounting frame, the rocking stiffness calculated from the FE analyses is close to the rocking stiffness of frames with low bending stiffness, $k_{\theta 2}$.



(a) dimension **(b) with fixed base** **(c) with rocking spring**

Figure 5. Beam-stick model for cabinet (unit: m)

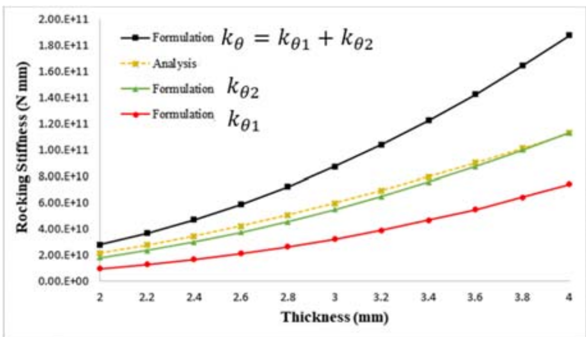


Figure 6. Comparison between analysis result, k_θ, $k_{\theta 1}$ and $k_{\theta 2}$

INPUT MOTION

The floor response at EL. 115.55m of the intermediate building in Kori 2 NPP is selected as the input motion at the base of cabinet. Fig. 7 shows the target response spectrum, and 12 artificial acceleration histories are generated in order to be matched with the target response spectrum. Fig. 8 shows that the response spectrum from the artificial acceleration histories are well matched with the target response spectrum.

TIME DOMAIN APPROACH

The 12 artificial acceleration histories are applied as input ground motion for the beam-stick model, and time history analyses are performed with a constant damping ratio of 5%. Figs. 9 & 10 show the 12 ICRS of the beam-stick model with fixed base and with rocking spring, respectively. The ICRS are compared with the response spectrum of the input motion. The solid lines in Figs. 9 & 10 are the average ICRS of the beam-stick model with fixed base and with rocking spring, respectively. The figures show that the ICRS of the beam-stick model with rocking spring is smaller than those with fixed base.

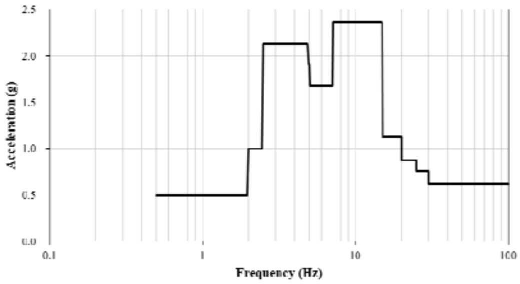


Figure 7. Target floor response spectrum

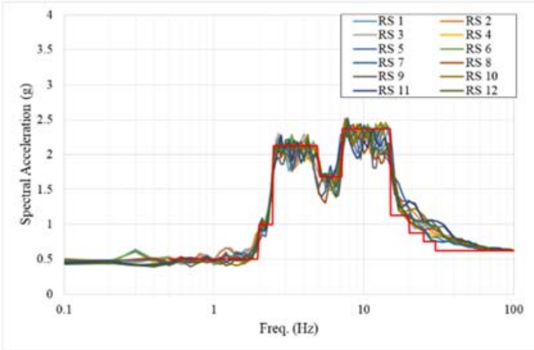


Figure 8. Response spectrum of the artificial floor response

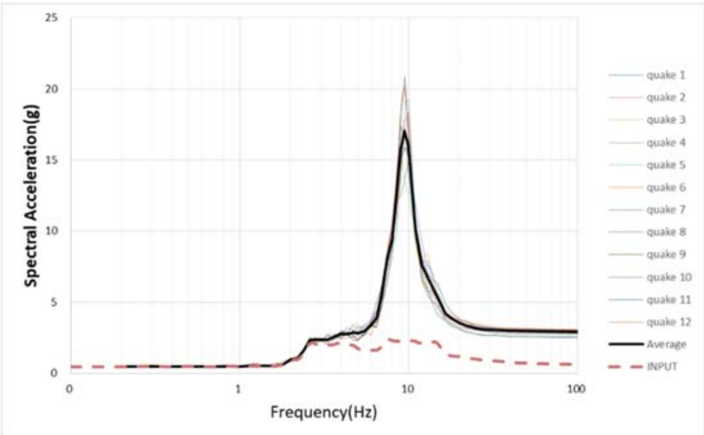


Figure 9. ICRS of the beam-stick model with fixed base

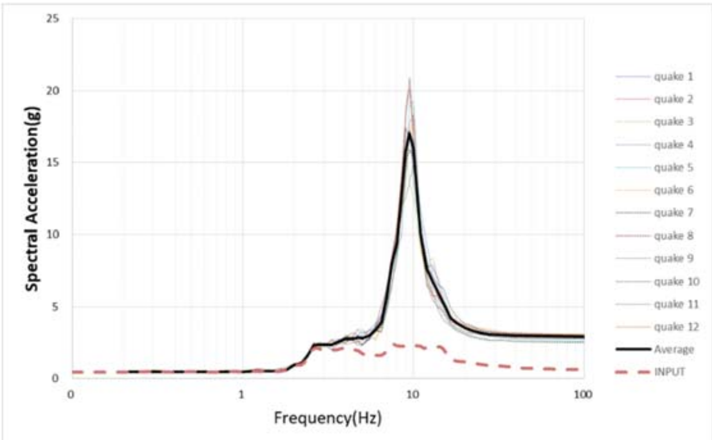


Figure 10. ICRS of the beam-stick model with rocking spring

FREQUENCY DOMAIN APPROACH

EPRI (1995) presented a frequency domain approach using the PSD function. This approach converts an input ground motion defined in terms of a response spectrum into a PSD function and it calculates the in-cabinet PSD by considering the dynamic characteristics of the cabinet. The in-cabinet PSD is then converted into the corresponding ICRS as shown in Fig. 11.

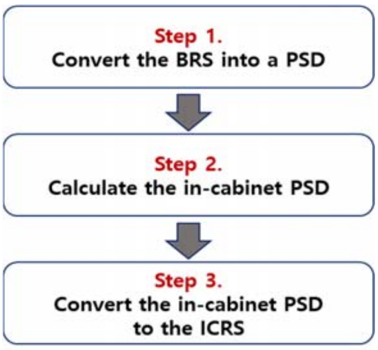


Figure 11. Procedure for calculating the ICRS using PSD

Assuming the input motion as Gaussian process, we can calculate PSD from the response spectrum. In order to calculate the in-cabinet PSD from the input motion PSD, let's assume that the relative displacement of the kth DOF in-cabinet with respect to the base is our interest.

$$u_k(t) = \sum_i \Psi_k^{(i)} q_i \tag{6}$$

where u_k is the kth DOF displacement, $\Psi_k^{(i)}$ is kth DOF component in ith vibration mode, q_i is the ith modal coordinate. By applying frequency response function, we can define relative acceleration in frequency domain as below:

$$\ddot{U}_k(\omega) = -\sum_i \Psi_k^{(i)} \ddot{H}^{(i)}(\omega)\Gamma_i \ddot{U}_b(\omega) \tag{7}$$

where $\ddot{U}_k(\omega)$ and $\ddot{U}_b(\omega)$ are Fourier transformations of the kth DOF acceleration response and the base acceleration, respectively; $\ddot{H}^{(i)}(\omega)$ is (acceleration) frequency response function; Γ_i is modal participation factor. By assuming the input motion as stationary Gaussian random process, the relationship between the input motion and the kth DOF can be represented by the acceleration PSD. Therefore, the PSD is represented by using the ensemble average, and then the equation of relative acceleration is substituted into PSD in frequency domain as below:

$$\begin{aligned} G_{\ddot{u},k}(\omega) &= 2\mathrm{E}\{\ddot{U}_k(\omega)\ddot{U}_k^*(\omega)\} \\ &= \sum_i \sum_j \Psi_k^{(i)}\Psi_k^{(j)} \ddot{H}^{(i)}(\omega)\ddot{H}^{*(j)}(\omega)\Gamma_i\Gamma_j 2E\{\ddot{U}_b(\omega)\ddot{U}_b^*(\omega)\} \\ &= \sum_i \sum_j \Psi_k^{(i)}\Psi_k^{(j)} \ddot{H}^{(i)}(\omega)\ddot{H}^{*(j)}(\omega)\Gamma_i\Gamma_j G_{\ddot{u},b}(\omega) \end{aligned} \tag{8}$$

where the superscript '*' means conjugate function. The absolute acceleration PSD is defined as below:

$$G_{\ddot{u}(abs),k}(\omega) = G_{\ddot{u},k}(\omega) + \left[1 + 2\sum_i \Gamma_i \Psi_k^{(i)} Re\{\ddot{H}^{(i)}(\omega)\}\right] G_{\ddot{u},b}(\omega) \tag{9}$$

The response spectrum is calculated from the k[th] DOF PSD by the transformation as shown below

$$S(\omega_0, \xi) = \sqrt{-2m_0 \ln\left\{-\frac{\pi}{T}\sqrt{\frac{m_0}{m_2}}\ln(1-r)\right\}} \tag{10}$$

where $m_n(\omega_0) = \int_{-\infty}^{\infty} \omega^n \, |H_0(\omega)|^2 G(\omega) d\omega,\ n = 0,2,4 \cdots$, and

$$|H_0(\omega)|^2 = \frac{\omega_0^4 + 4\omega_0^2 \xi_e^2 \omega^2}{(w_0^2 - w^2)^2 + 4\omega_0^2 \xi_e^2 \omega^2} \tag{11}$$

The ICRS at the top of cabinet is calculated based on the process explained above for the models with fixed base and with rocking spring as shown in Figs. 12 & 13, respectively. The ICRS calculated using FDA are compared with the average ICRS calculated using time history analyses (time-domain analyses, TDA). It is observed that the ICRS agree well from both the approaches (FDA and TDA). The amplification factor with respect to the input spectrum for the cabinet with fixed base is 7.09 based on TDA and 6.88 based on FDA. If the rocking spring is considered, the amplification factor is decreased to 4.78 for TDA and 4.96 for FDA.

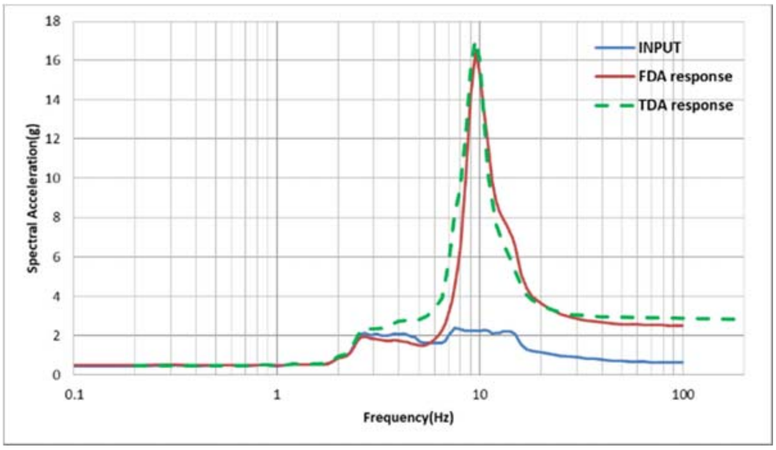


Figure 12. ICRS by PSD for the cabinet with fixed base

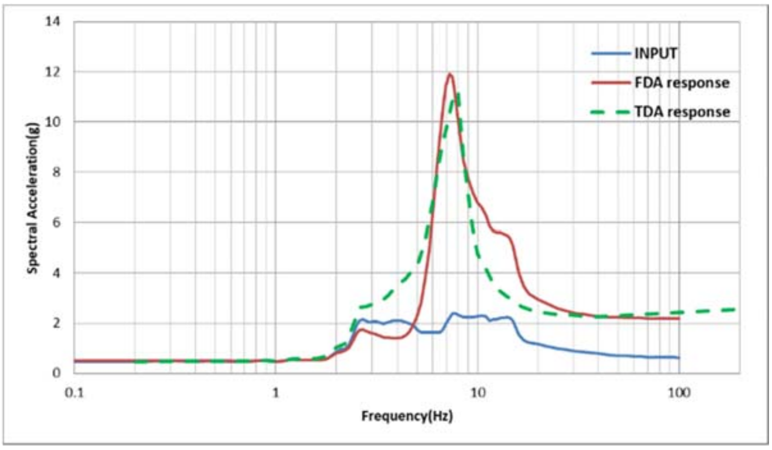


Figure 13. ICRS by PSD for the cabinet with rocking spring

CONCLUSION

The rocking behaviour of the cabinet occurs due to local deformation around anchors at the base of the electrical cabinet. In this study, the seismic response of cabinets is analysed using frequency domain approach (FDA) with PSD function. A simplified mathematical model for the rocking behaviour of cabinets has been proposed by analytical derivation and verified by numerical examples. FDA is easier to use and takes shorter time for analysis than TDA. The 12 artificial input motions are selected and applied to the base of the cabinet. The proposed FDA is verified because the ICRS calculated by FDA are quite close to that by TDA.

The rocking spring at the base of the electrical cabinet has a strong influence on the seismic response. Considering rocking behaviour of the cabinet due to the local deformation at the mounting channels decreases the natural frequency of the cabinet.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Electrical Power Research Institute (EPRI), Guidelines for Development of In-Cabinet Demand for Devices Mounted in Electrical Cabinets, EPRI, NP-7146-SL R1, 1995.

[2] Gupta A, Rustogi SK, Gupta AK. Ritz vector approach for evaluating incabinet response spectra. Nuclear engineering and design. 1999 Jun 2; 190(3):255-72.

[3] Yang J, Rustogi SK, Gupta A. Rocking stiffness of mounting arrangements in electrical cabinets and control panels. Nuclear engineering and design. 2003 Feb 1; 219(2):127-41.

[4] Lee BJ, Berak EG, Passalugo PN. Effect of base shim plates on seismic qualification of electrical control panels. In Proceedings of the 1990 Pressure Vessels and Piping Conference 1990 (pp. 301-306).

[5] Dynamics of structures, 3rd edition, Kim DK, Goominbooks, 2013(pp.476-478)