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DIRECT GENERATION OF RRS FROM FRS

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ABSTRACT

Active safety-related equipment is required to be seismically qualified by dynamic testing to demonstrate functionality. In SQ tests, an RRS (Required Response Spectrum) is often used to define the seismic input motion at the equipment mounting point. An RRS is also used in a decoupled analysis of an appendage on a floor-supported structure/component or in a device-base dynamic test of cabinet-mounted C&I equipment. An RRS is usually generated by using a time history method or empirical amplification factors. In this paper, a method for generating an RRS directly from an FRS (Floor Response Spectrum) is presented as an alternative to the time history analyses. The proposed method is derived by solving the Duhamel integral between the unit impulse response functions, and then by best estimating the response. In this way, an RRS at any point on the support can be obtained from the FRS based on the response spectrum techniques. The resulting RRS is smooth and the computational effort is much less than what is required by the time history method. For illustration of the proposed RRS generating method, numerical examples are given.

INTRODUCTION

Active safety-related equipment in an NPP is typically required to be seismically qualified per regulations such as US Nuclear Regulatory Commission R.G. 1.100, NRC (1988). SQ of such equipment is commonly performed by a shake table test to a vibration input level at its mounting location equal to or exceeding the required response spectra (RRS) under the design base earthquake (DBE). Therefore, to generate an RRS is of great practical importance.

To generate an FRS, the base input is the seismic ground excitation, whereas to generate an RRS, the support input is the seismic floor motion. For this reason, an RRS is also called a third-level response spectrum. An RRS is also used in a decoupled analysis of an appendage on a floor-supported component or in a device-base dynamic test of cabinet-mounted C&I equipment.

Currently, US NRC RG 1.122 (1978) endorses only the time history method in in-structure response spectrum generation. However, ASCE 4-98 (1999), CSA N289.3 (2010), US NRC RG 1.143 (2001), and IAEA SG-D15 (1992) all allow a non-time history method to be used to generate in-structure response spectra. As a matter of fact, several non-time history response spectrum generating methods have been published and used. While ASCE 4-98 (1999) gives detailed guidelines on direct spectra-to-spectra generation, there is no guideline specifying which method can or cannot be used to generate RRS. It is noted that presently only artificial and empirical RRS curves are given in IEEE-382 (2006) for testing valve actuators, in IEEE-C37.81 (1989) for testing switchgear assemblies, and in IEEE-C37.98 (1987) for testing relays. These RRS are considered to be conservative since they are intended to be generic to cover most of the application cases.

If recorded motions from actual earthquakes or simulated motions are used to generate an RRS, it is necessary to employ several such inputs to ensure a sufficiently broad frequency range is adequately covered. Because of uncertainties in predicting the real ground motions and large computational efforts required in the time history analysis, the use of FRS is more practical from a qualification point of view. In addition to time consuming, the time history method will produce an FRS which fluctuates from one frequency point to another, from one time history to another, and from one damping value to another. The fluctuations will accentuate more in an RRS than in an FRS.

Several researchers have proposed methods to allow engineers to generate RRS directly from FRS. These methods can be grouped into: (1) Those using the stochastic methods, such as Vanmarcke (1976), Sackman and Kelly (1980); (2) Those based on empirical amplification factors or peak factors, such as Biggs and Roesset (1970), Biggs (1971), Duff (1975), Kapur (1975), Singh (1980), Der Kiureghian et al. (1981), Yan (1983), Bandyopadhyay et al. (1988), Merz and Ibanez (1990), Djordjevic (1992), EPRI (1995), Shi (1997); and (3) Those using the simplified integration method, such as Scanlan (1977), and Yasui (1993).

This paper proposes an alternative method to generate an RRS directly from an FRS. The method is derived by solving the Duhamel integral between the unit impulse response functions in the equation for the absolute acceleration of the oscillator, and then by best estimating the response. The derivation is largely based on the response spectrum techniques.

PROPOSED METHOD

The approach is a decoupled analysis. The absolute acceleration at the point on the support where the RRS is desired is the input to a series of infinitesimal damped oscillators. The maximum response of each oscillator constitutes the RRS.

Response of the support structure

Let $x(t)$ be the relative displacement vector of the support structure. $x(t)$ is governed by the following differential equation and the at-rest initial conditions:

$$M\ddot{x} + C\dot{x} + Kx = -M\hat{I}\ddot{u}\,; \quad x(0) = \dot{x}(0) = 0 \tag{1}$$

We will use the modal superposition method to derive the absolute acceleration at a point i on the support structure, to which the oscillators are attached, as shown below:

$$x = \sum_{m=1}^{N} \xi_m(t)\varphi_m \tag{2}$$

$$\ddot{\xi}_m + 2\beta_m\omega_m\dot{\xi}_m + \omega_m^2\xi_m = -\gamma_m\ddot{u} \tag{3}$$

$$\xi_m = -\gamma_m h_m * \ddot{u} \tag{4}$$

$$h_m(t) = \begin{cases} 0\,; & t < 0 \\ \frac{1}{\omega_m} e^{-\beta_m\omega_m t} \sin\omega_m t\,; & t \geq 0 \end{cases} \tag{5}$$

For small damping $\beta_m \ll 1$,

$$\ddot{\xi}_m + \gamma_m\ddot{u} = -\omega_m^2\xi_m = \gamma_m\omega_m^2 h_m * \ddot{u} \tag{6}$$

$$\sum_{m=1}^{N} \ddot{\xi}_m\varphi_{im} + \ddot{u}\sum_{m=1}^{N} \gamma_m\varphi_{im} = \sum_{m=1}^{N} \gamma_m\varphi_{im}\omega_m^2\, h_m * \ddot{u} \tag{7}$$

$$\alpha_i = \ddot{x}_i + \ddot{u} = \gamma_1\varphi_{i1}\omega_1^2 h_1 * \ddot{u} + (1 - \gamma_1\varphi_{i1})\ddot{u} \tag{8}$$

The support structure is assumed to have only one significant mode, which is usually the case.

Response of the oscillator

$\alpha_i(t)$ is the seismic base excitation to the oscillator. Let $y(t)$ be the deflection of the oscillator relative to its base. $y(t)$ will satisfy the differential equation and the at-rest initial conditions:

$$\ddot{y} + 2\beta\omega\dot{y} + \omega^2 y = -\alpha_i \; ; \quad y(0) = \dot{y}(0) = 0 \tag{9}$$

$$y = -h * \alpha_i \tag{10}$$

$$h(t) = \begin{cases} 0 \; ; & t < 0 \\ \frac{1}{\omega} e^{-\beta\omega t} \sin\omega t \; ; & t \geq 0 \end{cases} \tag{11}$$

$$a = \ddot{y} + \alpha_i = -\omega^2 h * \alpha_i = \gamma_1 \varphi_{i1} \omega^2 \omega_1^2 h * h_1 * \ddot{u} + (1 - \gamma_1 \varphi_{i1}) \omega^2 h * \ddot{u} \tag{12}$$

The required RRS is $|a|_{max}$ estimated from the above expression.

Determination of $|a|_{max}$

Instead of assuming a $\ddot{u}$ as has usually been done, here we will solve $z = h * h_1$ and then apply the response spectrum techniques to the results. It is seen that z is from

$$\ddot{z} + 2\beta\omega\dot{z} + \omega^2 z = \frac{1}{\omega_1} e^{-\beta_1\omega_1 t} \sin\omega_1 t \; ; \quad z(0) = \dot{z}(0) = 0 \tag{13}$$

The complementary solution is:

$$z_o = C_1 e^{-\beta\omega t} \sin\omega t + C_2 e^{-\beta\omega t} \cos\omega t \tag{14}$$

The particular solution is:

$$z_p = A e^{-\beta_1\omega_1 t} \sin\omega_1 t + B e^{-\beta_1\omega_1 t} \cos\omega_1 t \tag{15}$$

With

$$\dot{z}_p = [A(-\beta_1 \sin\omega_1 t + \cos\omega_1 t) + B(-\beta_1 \cos\omega_1 t - \sin\omega_1 t)] \times \omega_1 e^{-\beta_1\omega_1 t} \tag{16}$$

$$\ddot{z}_p = [A(-\sin\omega_1 t - 2\beta_1 \cos\omega_1 t) + B(\cos\omega_1 t + 2\beta_1 \sin\omega_1 t)] \times \omega_1^2 e^{-\beta_1\omega_1 t} \tag{17}$$

$$\rho = \frac{\omega}{\omega_1} \; ; \quad \psi = (\rho^2 - 1 - 2\rho\beta\beta_1)^2 + 4(\rho\beta - \beta_1)^2 \tag{18}$$

A and B are found to be

$$A = \frac{\rho^2 - 1 - 2\rho\beta\beta_1}{\omega_1^3 \psi} \; ; \quad B = \frac{2(\beta_1 - \rho\beta)}{\omega_1^3 \psi} \tag{19}$$

The initial at-rest conditions yield:

$$C_1 = \frac{-\rho^2 + 1 - 2\rho\beta\beta_1}{\omega_1^3 \psi} \; ; \quad C_2 = -B \tag{20}$$

Consequently,

$$a = \gamma_1 \varphi_{i1} \left[\frac{(-\rho^2 + 1 - 2\rho\beta\beta_1)}{\psi} \times \omega^2 h * \ddot{u} + \frac{2\rho(\rho\beta - \beta_1)}{\psi} \times \omega \dot{h} * \ddot{u} + \frac{\rho^2(\rho^2 - 1 - 2\rho\beta\beta_1)}{\psi} \times \omega_1^2 h_1 * \ddot{u} + \frac{2\rho^2(\beta_1 - \rho\beta)}{\psi} \times \omega_1 \dot{h}_1 * \ddot{u} \right] + (1 - \gamma_1 \varphi_{i1}) \omega^2 h * \ddot{u} \tag{21}$$

The above expression is of a form to which the response spectrum method is readily applicable. For ease in the subsequent discussions, let us denote

$$R_1 = \left|\frac{\gamma_1 \varphi_{i1}(-\rho^2+1-2\rho\beta\beta_1)}{\psi} + (1-\gamma_1\varphi_{i1})\right| \times S(\beta,\omega)$$
$$R_2 = \left|\frac{2\gamma_1\varphi_{i1}\rho(\rho\beta-\beta_1)}{\psi}\right| \times S(\beta,\omega)$$
$$R_3 = \left|\frac{\gamma_1\varphi_{i1}\rho^2(\rho^2-1-2\rho\beta_1\beta)}{\psi}\right| \times S(\beta_1,\omega_1) \quad (22)$$
$$R_4 = \left|\frac{2\gamma_1\varphi_{i1}\rho^2(\beta_1-\rho\beta)}{\psi}\right| \times S(\beta_1,\omega_1)$$

Such that

$$|a|_{max} = \sqrt{R_1^2 + R_2^2} + \sqrt{R_3^2 + R_4^2} \quad (23)$$

Note R_1 and R_3 are from acceleration, whereas R_2 and R_4 are from velocity. Hence, R_1 and R_2 will be combined by SRSS as they are orthogonal. So will R_3 and R_4. The sum of the resultants will then be combined in a probabilistic sense, depending on the separation between ω and ω_1.

Observations

If the oscillator is near the base; that is, $\varphi_{i1} \approx 0$, then RRS = FRS. When the frequency of the oscillator is very high, $(\rho \gg 1) \rightarrow (\psi \approx \rho^4 \gg 1)$ yields

$$ZPA = \sqrt{[\gamma_1\varphi_{i1}S(\beta_1,\omega_1)]^2 + [(1-\gamma_1\varphi_{i1})\ddot{u}_{max}]^2} \quad (24)$$

as if the oscillator were glued to the support. The second term is a correction term.

If the oscillator has a very low frequency, $\rho \ll 1 \rightarrow \psi \approx 1$ yields

$$R_2 = R_3 = R_4 = 0 \quad (25)$$

$$RRS = R_1 = S(\beta,\omega) \quad (26)$$

as if the oscillator were sitting directly on the floor.

When ρ is substantially different than 1,

$$RRS = \sqrt{R_1^2 + R_2^2 + R_3^2 + R_4^2} \quad (27)$$

When $\rho = 1$ but $\beta \neq \beta_1$, we have

$$\psi = 4\beta^2\beta_1^2 + 4(\beta-\beta_1)^2 \approx 4(\beta-\beta_1)^2 \quad (28)$$

$$a = \gamma_1\varphi_{i1}\left[-\frac{\beta\beta_1}{2(\beta-\beta_1)^2} \times \omega_1^2 h * \ddot{u} + \frac{1}{2(\beta+\beta_1)} \times \omega_1 \dot{h} * \ddot{u} - \frac{\beta\beta_1}{2(\beta-\beta_1)^2} \times \omega_1 h_1 * \ddot{u} - \frac{1}{2(\beta_1+\beta)} \times \omega_1 \dot{h}_1 * \ddot{u}\right] + (1-\gamma_1\varphi_{i1})\omega_1^2 h * \ddot{u} \quad (29)$$

$$RRS(\beta,\omega_1) = |\gamma_1\varphi_{i1}| \times \frac{\sqrt{[S(\beta,\omega_1)]^2 + [S(\beta_1,\omega_1)]^2}}{2(\beta+\beta_1)} + |1-\gamma_1\varphi_{i1}| \times S(\beta,\omega_1) \quad (30)$$

The sum is by SRSS, for the contributions are from velocity and acceleration, respectively.

When $\omega = \omega_1$ and $\beta = \beta_1$, it can be shown that $z = h_1 * h_1$ is equal to

$$z = \frac{e^{-\beta_1\omega_1 t}\sin\omega_1 t}{2\omega_1^3} - \frac{te^{-\beta_1\omega_1 t}\cos\omega_1 t}{2\omega^2} \quad (31)$$

For $0 < \epsilon \ll \beta_1$, we have

$$(1-\epsilon\omega_1 t)e^{-\beta_1\omega_1 t}\cos\omega_1 t = e^{-(\beta_1+\epsilon)\omega_1 t}\cos\omega_1 t \quad (32)$$

$$-te^{-\beta_1\omega_1 t}\cos\omega_1 t = \lim_{\epsilon\to 0}\left[\frac{e^{-(\beta_1+\epsilon)\omega_1 t}-e^{-\beta_1\omega_1 t}}{\epsilon}\right]\times\frac{\cos\omega_1 t}{\omega_1} \quad (33)$$

$$a = (1-\gamma_1\varphi_{i1})\omega_1^2 h_1 * \ddot{u} + \frac{\gamma_1\varphi_{i1}}{2}\lim_{\epsilon\to 0}\left[\frac{\omega_1\dot{h}(\beta_1+\epsilon,\omega_1)*\ddot{u}-\omega_1\dot{h}(\beta_1,\omega_1)*\ddot{u}}{\epsilon}\right] \quad (34)$$

$$RRS = max.|a| = |1-\gamma_1\varphi_{i1}|\times S(\beta_1,\omega_1) + \left|\frac{\gamma_1\varphi_{i1}}{2}\right|\times\left|\lim_{\epsilon\to 0}\frac{S(\beta_1+\epsilon,\omega_1)-S(\beta_1,\omega_1)}{\epsilon}\right| \quad (35)$$

$$RRS = |1-\gamma_1\varphi_{i1}|\times S(\beta_1,\omega_1) + \left|\frac{\gamma_1\varphi_{i1}}{2}\right|\times\left|\frac{\partial S(\beta,\omega_1)}{\partial\beta}\right|_{\beta=\beta_1} \quad (36)$$

By letting $\beta = \beta_1$ in the previous result, we obtain

$$\left|\frac{\partial S(\beta,\omega_1)}{\partial\beta}\right|_{\beta=\beta_1} = \frac{S(\beta_1,\omega_1)}{\sqrt{2}\beta_1} \quad (37)$$

$$\therefore\quad RRS = |1-\gamma_1\varphi_{i1}|\times S(\beta_1,\omega_1) + |\gamma_1\varphi_{i1}|\times\frac{S(\beta_1,\omega_1)}{2\sqrt{2}\beta_1} \quad (38)$$

The sum is by SRSS, for the first term is from acceleration and the second term is from velocity. The same result was reported in Ref. [1], which follows a different approach.

Estimate of resonant RRS by peak factor

Let $\zeta(t)$ be a bounded, transient random process. The peak factor κ_ζ for $\zeta(t)$ is defined as

$$\kappa_\zeta = \frac{\max.|\zeta|}{\sigma_\zeta} \quad (39)$$

The Fourier integral transform of $\zeta(t)$ exists; that is, $|\mathcal{F}_\zeta(\upsilon)| < \infty$. Let $s_\zeta(\upsilon)$ be the temporal spectral density function of $\zeta(t)$; that is,

$$s_\zeta(\upsilon) = \frac{1}{T}\left|\mathcal{F}_\zeta(\upsilon)\right|^2 \quad (40)$$

The following well-known relationship follows:

$$\frac{1}{2\pi}\int_\upsilon s_\zeta(\upsilon)d\upsilon = \frac{1}{T}\int_T \zeta^2(t)dt = \langle\zeta^2\rangle = \sigma_\zeta^2 \quad (41)$$

Let us return to the expression for the total acceleration of the oscillator and denote

$$a_1 = \gamma_1\varphi_{i1}\omega^2\omega_1^2 h * h_1 * \ddot{u} \quad (42)$$

$$a_2 = (1-\gamma_1\varphi_{i1})\omega^2 h * \ddot{u} \quad (43)$$

Then,

$$RRS = \max.|a| = \max.|a_1| + |1-\gamma_1\varphi_{i1}|\times S(\beta_1,\omega_1) \quad (44)$$

Here, we will use peak factors to estimate the RRS, as shown below.

$$\left|\mathcal{F}_{a_1}(\upsilon)\right|^2 = \gamma_1^2\varphi_{i1}^2\omega^4\omega_1^4\,|\mathcal{H}|^2\,|\mathcal{H}_1|^2\,|\mathcal{F}_{\ddot{u}}(\upsilon)|^2 \quad (45)$$

$$\sigma_{a_1}^2 < \gamma_1^2\varphi_{i1}^2\,\omega^4|\mathcal{H}|^2_{\max}\,\frac{1}{T}\int_\upsilon \frac{\omega_1^4}{2\pi}\,|\mathcal{H}_1|^2\,|\mathcal{F}_{\ddot{u}}(\upsilon)|^2 d\upsilon \quad (46)$$

With

$$\omega^4|\mathcal{H}|^2_{max} = \frac{1}{4\beta^2} \; ; \quad \frac{1}{T}\int_\upsilon \frac{\omega_1^4}{2\pi} |\mathcal{H}_1|^2 |\mathcal{F}_{\ddot{u}}|^2 d\upsilon = \sigma_s^2 = \frac{S^2(\beta_1,\omega_1)}{\kappa_s^2} \tag{47}$$

$$\therefore \quad \max.|a_1| = \kappa_o\sigma_{a_1} < |\gamma_1\varphi_{i1}| \times \frac{S(\beta_1,\omega_1)}{2\beta_1 \times \frac{\kappa_s}{\kappa_o}} \tag{48}$$

The peak factor of a broad band process is larger than the peak factor of a narrow band process. That is to say, $\kappa_s > \kappa_o$ It is reasonable to treat the transient response of the support as sine beats and the strong motion of the oscillator as sinusoidal. Then, the theoretical value is:

$$\frac{\kappa_s}{\kappa_o} = \frac{2}{\sqrt{2}} = \sqrt{2} \tag{49}$$

Consequently, a good estimate of the RRS for the resonant case is given by:

$$RRS = |1 - \gamma_1\varphi_{i1}| \times S(\beta_1, \omega_1) + |\gamma_1\varphi_{i1}| \times \frac{S(\beta_1,\omega_1)}{2\sqrt{2}\,\beta_1} \tag{50}$$

The expression is the same as obtained earlier.

Determination of RRS for Design Evaluation

Once the raw RRS is generated from above procedure, the techniques, such as peak broadening and peak reduction, recommended in NRC R.G. 1.122 (1978) and ASCE 4-98 (1999) can be applied to finalize the design RRS for seismic qualification of equipment in order to account for the uncertainties in responses due to the uncertainties in supporting structure frequencies and soil-structure interaction analysis. As per ASCE 4-98 (1999), the minimum broadening shall be ±15% at each frequency in the amplified response region for generation of FRS. Since RRS is directly generated from FRS in the proposed method, more uncertainties may be embedded and shall be taken into account during the finalization of the design RRS. Therefore, the peak broadening of ±20% for RRS is recommended. In addition, in conjunction with response spectrum peak broadening, a 15% reduction in peak amplitude is permissible provided the subsystem damping is less than 10% according to ASCE 4-98 (1999). Therefore, to determine the design RRS, the same technique of peak reduction may be adopted for the proposed method.

EXAMPLE

We derived the direct generation formula for RRS in above sections. This method permits a designer to generate a RRS directly from FRS using only the mode characteristics of a structure without having to creating artificial seismic waves and performing costly time history analysis. We give an example to illustrate the method and compare its results with the real in-cabinet response of a 480V MCC reported in the study by Kim et al., (2012).

In this example, an electrical cabinet (480V MCC) is considered and has the fundamental frequency of 12 Hz, which has been thoroughly studied by shaker table testing in Kim et al., (2012). An RRS with 5% damping is subjected to be generated for seismic qualification of in-cabinet electrical equipment. The seismic input motions (2% and 5% damping) based on the US NRC RG 1.60 (1973) design spectrum with PGA of 0.8g are used as the FRS applied at the base of the cabinet, shown in Figure 1. In order to compare with the recorded in-cabinet responses reported in Kim et al., (2012), two locations inside the MCC are chosen to generate the RRS by the proposed method, namely, the upper position (E1) and lower position (A2) in Figure 2. The raw RRS generated by the proposed method for the two locations are presented in Figure 3. Then, the design RRS for the two locations in the MCC together with the comparison to corresponding real in-cabinet response are shown in Figure 4 and Figure 5, respectively. It’s noted that both peak broadening and reduction techniques are used to finalize the design RRS as well as the amplification factor of 3 is conservatively taken for determining the ZPA of the RRS curves.

It's observed from the comparisons of proposed RRS and real responses that the design RRS obtained by the proposed method cover most of frequency content with comfortable margins in the frequency range of interest as far as seismic qualification of in-cabinet equipment is the concern. It demonstrates that the proposed direct generation method of RRS from FRS is capable of predicting the behavior of equipment mounting on/in the support structures subjected to seismic loads efficiently.

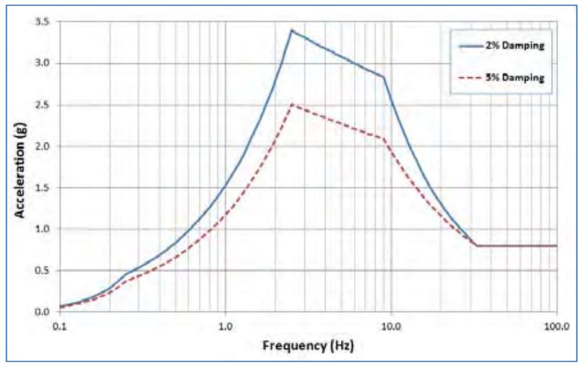

Figure 1. Seismic Input Motions Based on US NRC R.G. 1.60 Design Spectrum (PGA=0.8g).

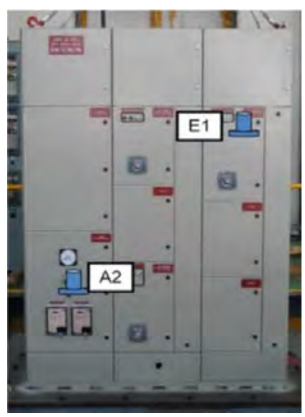

Figure 2. Locations of Upper and Lower Accelerometers for In-cabinet Responses in Kim et. al., (2012).

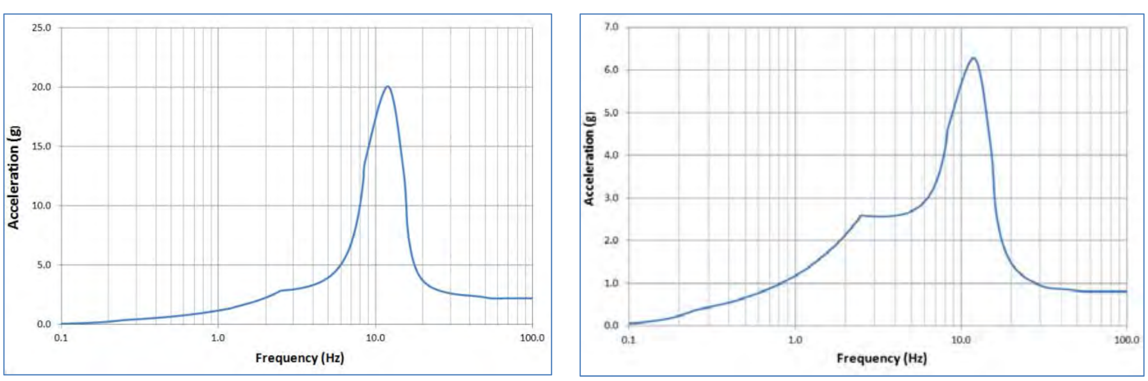

Figure 3. Raw RRS Generated for Upper Position of MCC (Left), Raw RRS Generated for Lower Position of MCC (Right)

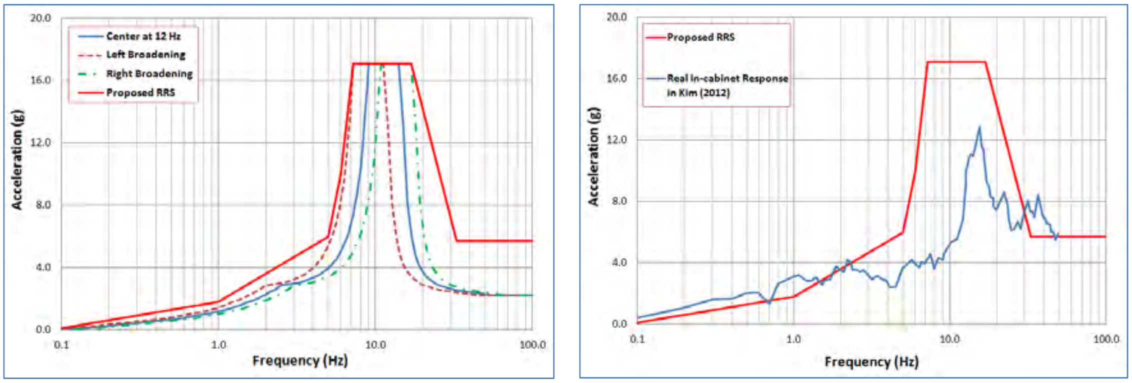

Figure 4. Proposed RRS with Peak Broadening and Reduction at Upper Position of MCC (Left), Comparison of Proposed RRS with Real In-cabinet Response at Upper Position of MCC (Right)

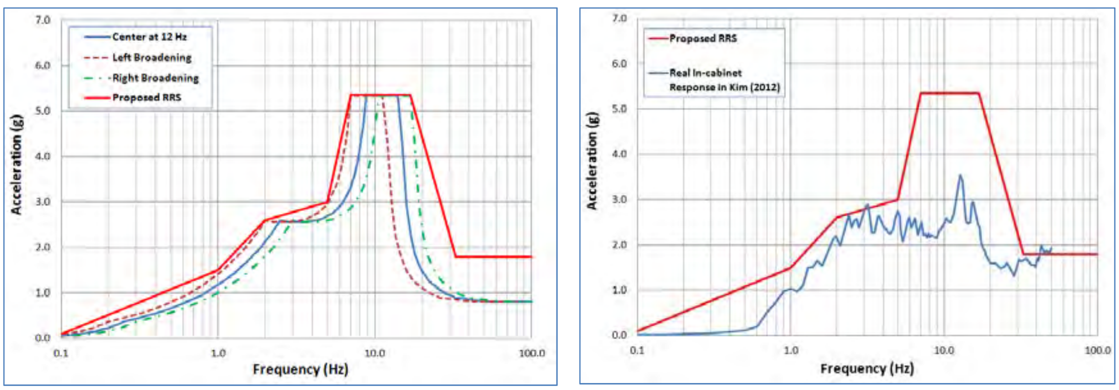

Figure 5. Proposed RRS with Peak Broadening and Reduction at Lower Position of MCC (Left), Comparison of Proposed RRS with Real In-cabinet Response at Lower Position of MCC (Right)

CONCLUSIONS

The present method is a viable alternative to the time history method for generating an RRS from an FRS. It is efficient, easy to use, and within the realm of the response spectrum method. Its derivation is straightforward and does not rely on assumptions such as empirical amplification factors or peak factors, and unrealistic ergodicity or stationarity for a transient random process.

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