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DESIGN EARTHQUAKE GROUND MOTIONS FOR NUCLEAR POWER PLANTS

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SUMMARY

In order to apply the time-history method of seismic analysis to the design of nuclear power plants it is necessary to generate an artificial time history to use in the design. This problem is further complicated since a true representation of the earthquake ground motion should involve different component time-histories (three transactional and three rotational). In this paper, a state-of-the-art review of the different options and methods available to solve the problem is presented. A review of the recent nuclear regulatory requirements related to statistical independence, three-dimensional effects and power spectrum requirements is presented. Examples are drawn from the seismic analysis of nuclear power plants structures to demonstrate the compliance with these requirements. It is concluded that properly generated three- dimensional design time histories can be achieved. Extreme care and control should be exercised to maintain realistic results.

INTRODUCTION

Current practice for seismic design of Nuclear Power Plants (NPP) structures and components is to utilize a design basis response spectrum [1,2]. This response spectrum represents an envelope of possible ground motions or floor motions on a series of one degree of freedom oscillators. In order to apply the time-history method of seismic analysis to the design of NPP structures and components, it is necessary to generate a spectrum-compatible time-history from a given design response spectrum. Acceptance criteria have evolved over the years. Early acceptance criteria were based on the concept that the time-history spectrum must envelope the design response spectrum. When it is required to excite the mathematical models with three-dimensional seismic motions, an additional criterion has emerged which is the statistical independence between the different ground motion components.
In this paper, a state-of-the-art review of the different methods available to develop spectrum-compatible time-histories is presented. The current regulatory requirements are reviewed. Example three-dimensional time-histories are generated and tested against the current requirements.

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METHODS AVAILABLE FOR SPECTRUM-COMPATIBLE TIME-HISTORIES

Nuclear Power Plants have been seismically designed utilizing both spectrum methods as well as time-history methods where real or adjusted earthquake records have been used. These real and adjusted earthquake records are limited in the sense that they are conditional on the occurrence of a set of random parameters (e.g., magnitude, focal depth, attenuation, frequency content, duration etc). It is very unlikely that such a set of random parameters will ever be the same for a new site under consideration.
Recognizing this difficulty, numerous mathematical models to predict the nature of the ground shaking in the vicinity of the causative fault have been proposed and used since the 1960s [3,4,5 and 6]. The success and the comfort with such theoretical approaches are still lacking.

The methods currently available for the generation of design time-histories can be classified into two basic approaches. The first one is the deterministic approach and the second one is the random vibration approach.

In the deterministic approach, a time-history of an actual earthquake is modified at selected frequency points to achieve the desired spectrum compatibility.

In the random vibration approach, waves having random amplitudes and phase angles are generated. In both of these approaches, adjustments are made in order to achieve spectrum compatibility. The number and the extent of the adjustments are not unique. Spectrum compatible motions can be obtained by widely different adjustments.

The current available time-history generation technique involve the following basic steps:

1. Establishing an "initial guess" time-history. This step may involve the selection of a real time-history that is believed to exhibit some unique features to be expected in future earthquakes at the site. Alternatively this step may involve the superposition of a large number of sinusoids as modulated by an envelope deterministic function. It may involve theoretical calculations of the expected time-history from seismological models.
2. Manipulation of the "initial guess" time-history in the time-domain or in the frequency-domain, and generation of successive time-histories that have response spectra converging to the target design spectrum.
3. Testing the resulting time-history to establish its adequacy as a representation for the seismic threat at the site as well as its adequacy to meet criteria established by the codes and the regulatory authorities.
4. For three-dimensional seismic environment, the other components of motion are extracted and some cross testing is performed among the components to establish adequacy.

In general the following features of the resulting time-histories should be evaluated for adequacy:

1. The response spectrum of the resulting motion.
2. The resulting motion parameters (acceleration, velocity and displacement).
3. The rising characteristics, the duration of the significant shaking, and the decay characteristics of the motion.
4. The Fourier Amplitude and phase spectra.
5. The apparent frequency and the Power Spectral Density (PSD).
6. The correlation between the different components of motion.

Historically, the only two criteria to evaluate these features were the resulting response spectrum which is required to envelope the design or target response spectrum and the different components of motion are required to be statistically independent with small correlation coefficients (typically less than or equal to a value between 0.16 and 0.30). Recently criteria related to the Fourier and the PSD have been introduced.

The second feature is partially covered, as far as the ground acceleration, by the closeness of the resulting response spectrum to the design response spectrum at the high frequency end, although velocity and displacement values are rarely looked at to ensure their reasonableness.

The third feature should be defined based on the seismo-tectonic behavior governing the site seismcity. From the engineering point of view, acceptable and conservative parameters are implemented.

The fourth feature is related somehow to the first one by the well-known relationship between Fourier Amplitude and the zero-damping response spectrum. This simply means that the Fourier amplitude spectrum should be reasonable if a close agreement between the resulting response spectrum and the design response spectrum is achieved. Two interesting comments should be pointed out in this regard. The first is that artificial time-histories for NPP seismic design are generated and tested in a certain frequency range (typically 1 to 33 Hz). The frequency content of real earthquakes is not known above 33 Hz (actually closer to 25 Hz which represent the limit of conventional instrument accuracy). Thus the resulting time-histories should not contain any frequency component beyond 33 Hz. This is crucial considering the fact that time-histories are sometimes used in analyzing NPP systems and components exhibiting nonlinear behaviour under impact loads where the presence of these fictitious frequencies may result in erroneous response calculations (unless suitable high-pass and low-pass filters are implemented in the calculations).

The second comment is that phase spectra of actual earthquakes are random in nature. Thus the resulting artificial time histories should have random phase spectra. The author is familiar with one method for time-history generation that intentionally uses the phase difference for actual earthquakes and does not change this during the generation process. There are several other methods that attempt to test for the phase angles randomness.

The fifth feature represents the apparent frequency of a time-history and is an indication of the number of zero-crossings that affects the cyclic seismic response of equipment and structures. The number of zero crossings present in a seismic accelerogram has implications on phenomena such as low-cycle fatigue and liquefaction potential evaluations.

As far as the sixth feature, it is noted that cross-correlation coefficients at zero time delay have been used as a measure of the statistical independence between motion components. Cross-correlation coefficients at zero time delay cannot form a sound basis for determining completely the time phase relationships between the input components. It can be shown that by shifting one input component slightly along the time axis, the cross-correlation coefficients at zero time delay for the shifted and the original component can be very small. Above the zero time delay, however, the correlation coefficients may become large values and may achieve unity (e.g., if one time-history is tested against its shifted one). Consequently, in order that the time-histories will posses the same characteristics of real earthquakes, it may be necessary to compare the auto-correlation and cross-correlation coefficient functions for the component motions with real earthquake records.

The following is a brief review of the methods currently available for the generation of spectrum-compatible time-histories:

Deterministic Methods

These methods typically utilize recorded earthquake motion whose spectrum resembles as close as possible the design spectrum (for some appropriate damping value) and perform modifications. Typically this involves linear scaling of the entire motion record to raise or lower the response spectrum, modifying the digitization interval to shift the location of the spectral peaks and valleys and lastly a one-degree of freedom system is utilized to decrease the power of the motion at desired frequencies. There are different varieties of these “spectrum raising” and “spectrum suppression” techniques. Raising the spectrum can be achieved by superposing on the selected ground motion sinusoidal components of suitable amplitudes, frequencies and phase angles. The suppression of the spectrum can be achieved by passing the selected motion through a set of frequency suppressing filters which controls the bandwidth of significant suppression (2-DOF mechanical system). These manipulations can be performed in the time or frequency domain. Of particular interest is the idea of scaling the Fourier amplitude only since the original phase angle spectrum can be maintained. Physically this means that the phasing, as represented by the phase spectrum, of the original starting time-history and the final time-history are the same. This feature is different from other generation methods, which either filter the original time-history, thereby changing the phasing, or use a random number generator to select the phase of each element of the Fourier Transform at each stage of the iteration process.

While this unique feature may not be important for the generation of a single time- history, it appears to offer some advantages by preserving the phasing relationships between various directional components of a real life seismic event. The retention of the original phasing assures the retention of the same coherence functions. These functions are a measure of statistical independence present between components of the original seismic event. This overcomes the well-known problem that small correlation coefficients are necessary but not sufficient condition for two stochastic processes to be statistically independent. Thus the preservation of the phase relationships of the initial recorded directional components constitute a valid treatment of the degree of correlation between artificial time histories used for multi-directional seismic response analysis.

The richness of the time-history is achieved by choosing a large number of closely spaced frequency points such that their half power points overlap. This leads to:

$$\Delta f_i \leq 2\beta f_i \tag{1}$$

Where:

Δf_i = Increment in frequency f_i

β = Percentage of critical damping utilized.

The specific minimum requirements for frequencies are given in References 1 and 2.

Random Vibration Methods

Briefly these methods are based on the concept that an artificial earthquake consists of a random oscillatory function of time multiplied by an "envelope function" which defines the general or overall character. This leads to the following equation:

$$a(t) = I(t) \sum A_i \operatorname{Sin}(2 \pi f_i t + \phi_i) \tag{2}$$

The envelope function, I (t) can be chosen to define the overall duration of the earthquake as well as the rise, duration of the strong motion, and decay.

The number of frequencies is chosen such that all frequencies of interest are included. The phase "ϕ_I " is chosen as a set of N independent random numbers on the interval $(0, 2\pi)$. The form of equation 2 for the ground motion has the characteristics that, whatever the choices of A_i and Φi may be, the earthquake envelope maintains the overall desired general shape in time.

The relationship between the response spectrum value "S_a " for a particular damping and the spectral density function (s.d.f.) was established in the early pioneering work by Vanmarke [8,9]. Vanmarke assumed the ground motion to be a suddenly applied stationary acceleration with s.d.f. G (ω) and an equivalent duration "S". The pesudo-velocity response spectrum $S_v(\omega, \beta)$ for a linear one-degree of freedom system with natural frequency ω_n and damping ratio β take the following form:

$$S_v(\omega, \beta) = r\,\sigma_v \tag{3}$$

Where:

σ_v = pesudo-velocity standard deviation at time S

r = dimensional peak factor.

The standard deviation of relative displacement (σ_d), pesudo velocity (σ_v), and pseudo acceleration (σ_a) response are related as follows:

$$\sigma_a = \omega_n \sigma_v = \omega_n^2 \sigma_d \tag{4}$$

$$\sigma_a \cong 1/\omega_n \left[G(\omega_n)\, \omega_n \left[\pi/4\beta_s - 1\right] + \int_0^{\omega_n} G(\omega)\, d\omega\right]^{1/2} \tag{5}$$

$$\beta_s = \beta / \left[1 - e^{-2\beta\omega s}\right] \tag{6}$$

Note that β_s tends to β when ω_n S is large compared to β^{-1} which is the case of when the steady state response has been developed, and that β_s is a finite value "$1/(2\omega_n S)$" even when β tends to zero.
The peak factor "r" of equation 3 can be expressed as a function of n; where n is dependent on the average number of cycles of response motion ($S.f_n$), and the desired non-exceedence probability "P". For example the median peak factor r (P=0.5) can be expressed as a function of n=1.4 ($S.f_n$) for different damping values β. An approximate upper bound value for r which is approached when the damping is high is given by the expression $r = \sqrt{2 \ln(2n)}$.
The equations given define the relationship between the response spectrum (for a specified damping value) and the power spectrum density of ground motion. Conversion from S_v to G (ω) can therefore be made and used for the generation of response spectrum-compatible motions.

BACKGROUND TO ACHIEVE SPECTRUM-COMPATIBILITY

Based on the above discussions, artificial time-histories that are similar to real earthquakes can be generated with no problem. These time-histories should exhibit great similarities to real earthquakes in terms of the number of cycles in the strong motion segment and the number of maximum peaks. Similar distribution of energy with frequency as well as smooth distribution of energy with time is achieved and finally a close matching with the target spectrum. It is practically impossible to achieve perfect match with the target response spectra at all damping ratios. It is also practically impossible to achieve perfect match at Zero-Period Acceleration (ZPA) and the broadened peak segment of the spectrum at all frequencies. As a result some requirements to judge the degree of matching are needed.
The PSD function of the artificial time-history must adequately match a target PSD function compatible with the design spectra.
The Power Spectral Density (PSD) of an acceleration time-history is defined by

$$PSD(\omega) = 2\,|F(\omega)|^2 / 2\pi S \tag{7}$$

Where $|F(\omega)|^2$ is the square of the Fourier spectrum amplitude and S is the equivalent strong ground motion duration.

$$F(\omega) = \int_0^T a(t)\, e^{-i\omega t}\, dt \tag{8}$$

Where T is the total duration of the acceleration time-history.
Whenever earthquakes are specified in the three directions, statistical independence should be maintained. This can be achieved by calculating the correlation coefficient ρ_{ij}; where this is given by the expression

$$\rho_{ij} = E\left[x(t) - m_x\right] E\left[y(t) - m_y\right] / \sigma_x \sigma_y \tag{9}$$

Where:

E	=	Mathematical Expectation
m_x, m_y	=	mean values for x and y respectively
σ_x, σ_y	=	Standard Deviation of x and y respectively

The correlation coefficients are calculated for a time delay equal to zero. Suggested correlation coefficients limits are given by Chen [9] and ASCE [10].
To get a good quantitative measure for the strong motion duration, the duration can be estimated based on the time between achieving the 90% and 5% of the energy from the temporal variation of energy plots. This is based on Arias Intensity defined by:

$$\text{Arias' Intensity AI (t)} = \int_0^T a^2(\tau)\, d\tau \qquad (10)$$

Calculation of the Arias Intensity provides a further verification to ensure a smooth energy build-up. CSA N-289.3 requirements and those of U.S. NRC are reviewed in the following as they apply to NPP seismic design.

CSA N-289.3 REQUIREMENTS

CSA N289.3 considers it acceptable to modify the amplitudes and frequency of an artificial or actual accelerogram. A minimum set of frequencies to calculate the response spectrum is given for the frequency range of interest. No more than 6 % of the points are allowed to fall below the target Spectrum. When this occurs the point should not fall by more than 10 % below the target response spectrum. The duration of the seismic motion shall be a minimum of 15 s.

US NRC REQUIREMENTS

The U.S. requirements per Standard Review Plan are very similar to CSA requirements. The overall duration is stipulated between 10 and 25 s with a strong motion duration between 6 and 15 s, unless site-specific analysis indicates otherwise. U.S. requirements allow no than 5 points to fall below the target spectrum and by no more than 10%. The 5 points requirement are independent of the number of frequency points used in the analysis
Recently as part of the Standard Review plan revisions, Power Spectral Density (PSD) requirements were introduced by U.S. NRC [2,11,12]. The average PSD should be more than 0.8 of the target PSD as given in Reference 2.

EXAMPLE

Figure 1 shows the CSA DBE GRS for a nuclear power plant rock site. The peak horizontal ground acceleration is 0.2g. The peak ground velocity of 142.2 mm/s and the peak ground displacement of 62 mm are implemented following the Canadian National Standard N289.3. Figure 2 shows the CSA GRS for a soil site. The corner frequencies are different from those of a rock site.
An example is drawn from recent design of a nuclear power plant. The shape of the Ground Response Spectrum (GRS) follows CSA N289.3 [1]. In the Canadian seismic design practice, the vertical ground motion parameters are 2/3 of the horizontal ground motion parameters. It has been long recognized that the 2/3 ratio between the vertical and the horizontal motion parameters is very reasonable and somewhat conservative for the far/intermediate, as well as deep seismic events. The amplification factors used to obtain the GRS in CSA N289.3 are based on the 90-percentile level per the Canadian practice.
A set of synthetic design time histories is generated which is compatible with the DBE GRS.
The initial time histories were chosen with characteristics similar to those of the target spectra. The amplitude and frequency were modified by suppression and raising techniques to achieve spectrum compatibility. The damping value for the target response spectrum was chosen as 2 %. This is the same as the damping for equipment applications being analyzed. The time step of 0.01 seconds was chosen which is adequate for seismic applications. The total duration is selected as 20 seconds with the strong motion

duration of 15 seconds. This satisfies the nuclear design requirements. The acceptance criteria, per Clause 3.4.3 of CSA N289.3 [1], for meeting the spectrum enveloping requirements is that no more than 6% of the total number of points used to generate the spectrum from the time-history shall fall below the design ground response spectrum, but by no more than 10% at any frequency point. The calculated response spectrum and the target GRS were compared at a large number of points per CSA N289.3 requirements (typically 83 frequency points) to ensure meeting this acceptance criteria for each component of the acceleration time-history. This point-by-point comparison is considered the only reliable way to ensure spectrum compatibility. The three components of the time-histories are given in Figures 3, 4 and 5. The response spectrum of the acceleration time-history at 2% damping is overlaid on the target GRS for each component of acceleration time-history as shown in Figures 6, 7 and 8.

In order to satisfy the Power requirements for these acceleration time-histories, the Power Spectral Densities were calculated. The results are shown in Figure 9,10 and 11 in units of in^2 /s^3. Typical point-by-point spectrum compatibility plot for acceleration are given in Figures 12,13 and 14 where the ratio of the calculated spectral acceleration to the target design spectrum is shown. This demonstrates that none of the points fall below 0.90 of the target. In this particular case the minimum observed ratio was 0.947 with an overall average ratio over all frequencies of 1.084 (i.e., on the average a 8% conservatism exists). Table 1 gives for each time history the number of points below the target spectrum.

Table 1 Number of points for Spectrum Compatibility Requirements (Clause 3.4.3 – CSA N289.3)

Time-History	Number of Points below the Target GRS	%	Minimum Ratio	Average Ratio
TH-1	3	3.6	0.921	1.100
TH-2	5	6.0	0.947	1.066
TH-3	3	3.6	0.956	1.087
Average	3.3	4.4	0.941	1.084

The target design spectrum itself represents a one plus sigma (or more) standard deviation and as a result the 6 % criteria of CSA is therefore a conservative measure of enveloping. Continuous enrichment of the time history to meet these criteria typically leads to further conservatisms.

The target PSD shown in Figures 9, 10 and 11 is that of USNRC Standard review plan. Therefore these time-histories are rich in the frequency range of interest and meet the target PSD requirements such as those of USNRC. The power spectral density was calculated with a frequency window of 20%. This is in agreement with the USNRC recommendations.

It is worthwhile mentioning that there is no explicit requirement for meeting a target PSD function per Canadian Standards. However it has been well recognized that PSD calculations are useful to detect any deficiency of power over the frequency range of interest. PSD calculations are therefore performed to demonstrate the lack of deficiency of power and the richness of the frequency content of the time-histories. The same objective can be achieved by reviewing the Fourier amplitudes. A time-history that produces a response spectrum, which closely matches the design response spectrum at relatively, low damping (e.g. 2%) over the entire frequency range from 0.4 to 33 Hz must contain power throughout this frequency range consistent with the Design Response Spectrum.

In order to perform an analysis by applying the three components of the motion simultaneously, the three components must be statistically independent. Therefore the correlation coefficients between any of the two acceleration components must be less than a specified small value. The correlation coefficients were calculated and the results are displayed in the form of a correlation matrix as follows:

$$\begin{pmatrix} \rho_{11} & \rho_{121} & \rho_{13} \\ \rho_{21} & \rho_{22} & \rho_{23} \\ \rho_{31} & \rho_{32} & \rho_{33} \end{pmatrix} = \begin{pmatrix} 1.000 & 0.085 & -0.012 \\ 0.085 & 1.000 & 0.176 \\ -0.012 & 0.176 & 1.000 \end{pmatrix} \tag{11}$$

Thus it is concluded that the three components are statistically independent. Since the three components are statistically independent, a single analysis where these earthquakes time-histories are applied simultaneously is acceptable and sufficient to obtain the seismic response of nuclear structures and systems.

CONCLUDING REMARKS

Methods for synthetic time-history generation, to use in the seismic analysis of Nuclear Power Plants design, have been reviewed. Current practices in Canada and U.S. regulatory requirements are discussed. An example drawn from recent nuclear power plant design application is used to demonstrate some of the challenges in arriving at reliable three-dimensional synthetic time-histories.

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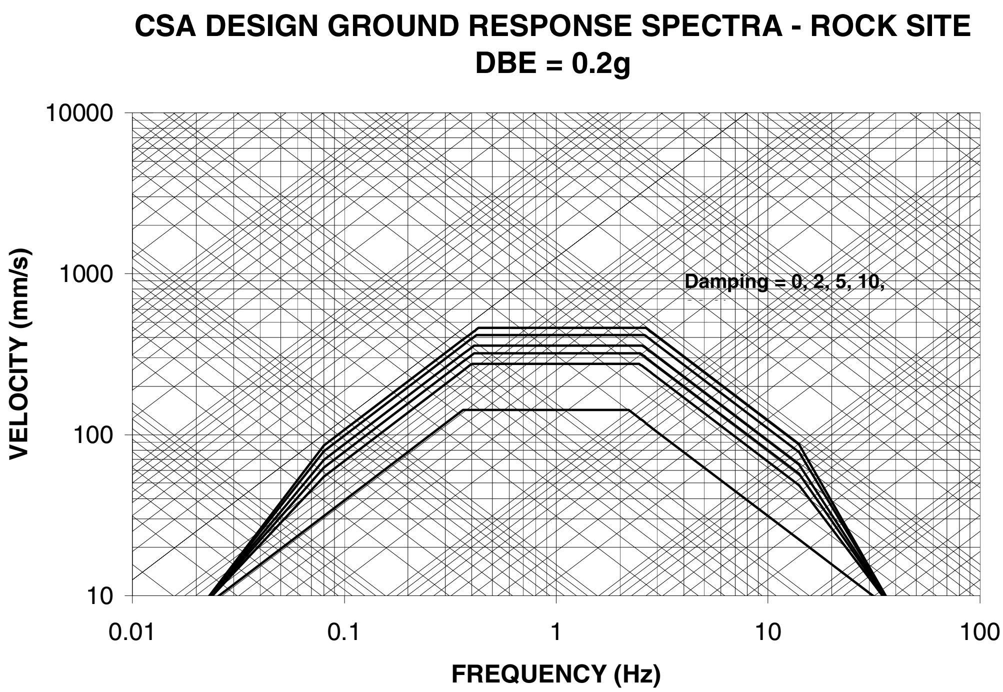

Figure 1 CSA N289.3 Design Basis Earthquake (DBE) Ground Response Spectrum (GRS) - Rock

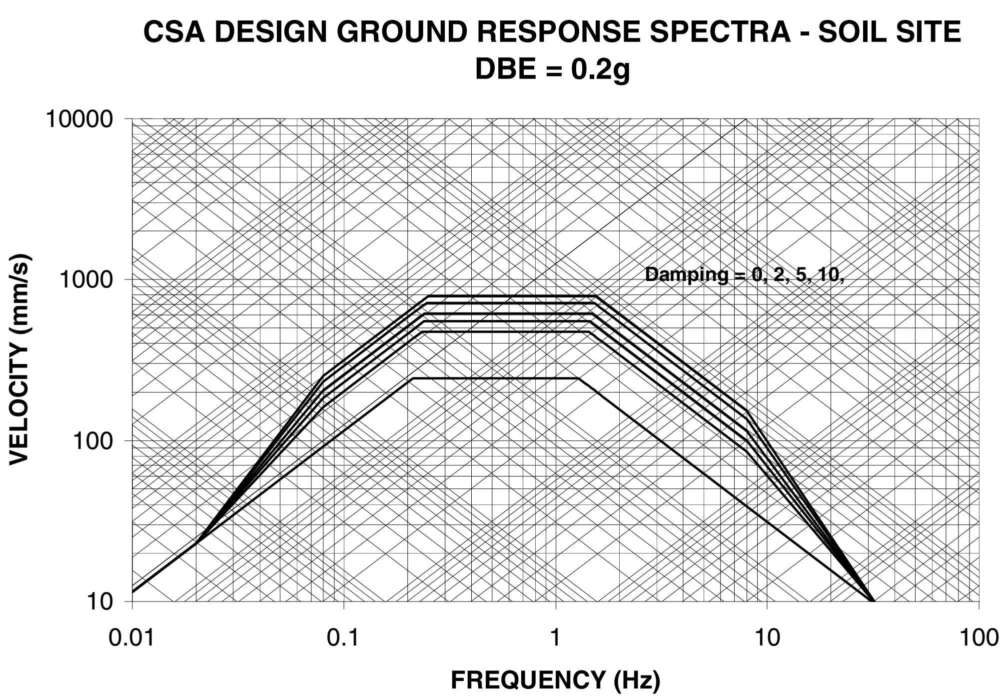

Figure 2 CSA N289.3 Design Basis Earthquake (DBE) Ground Response Spectrum (GRS) - Soil

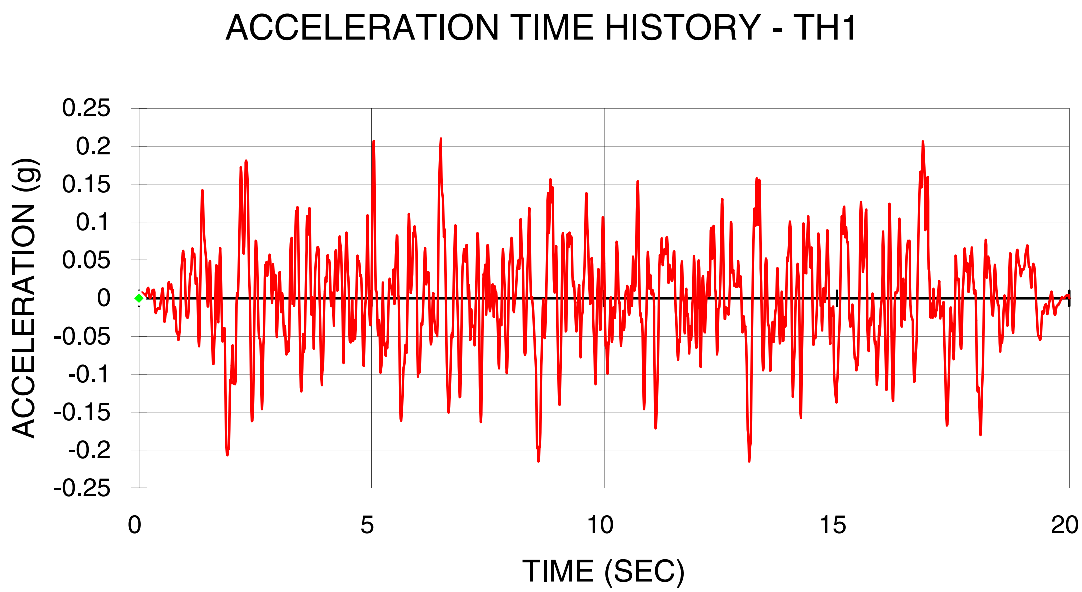

Figure 3 Acceleration Time-History (TH-1)

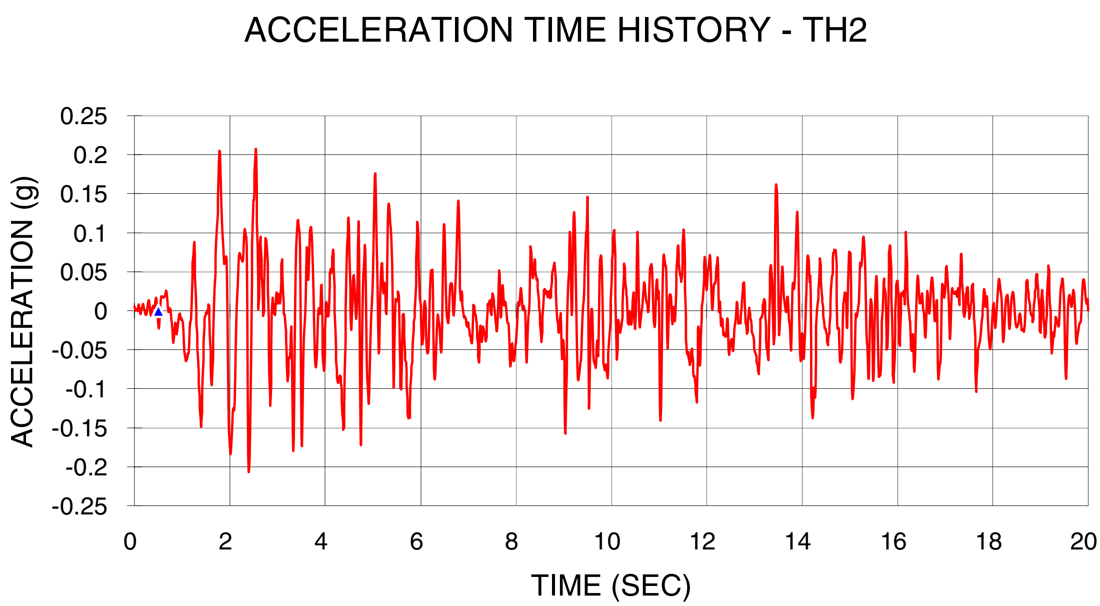

Figure 4 Acceleration Time-History (TH-2)

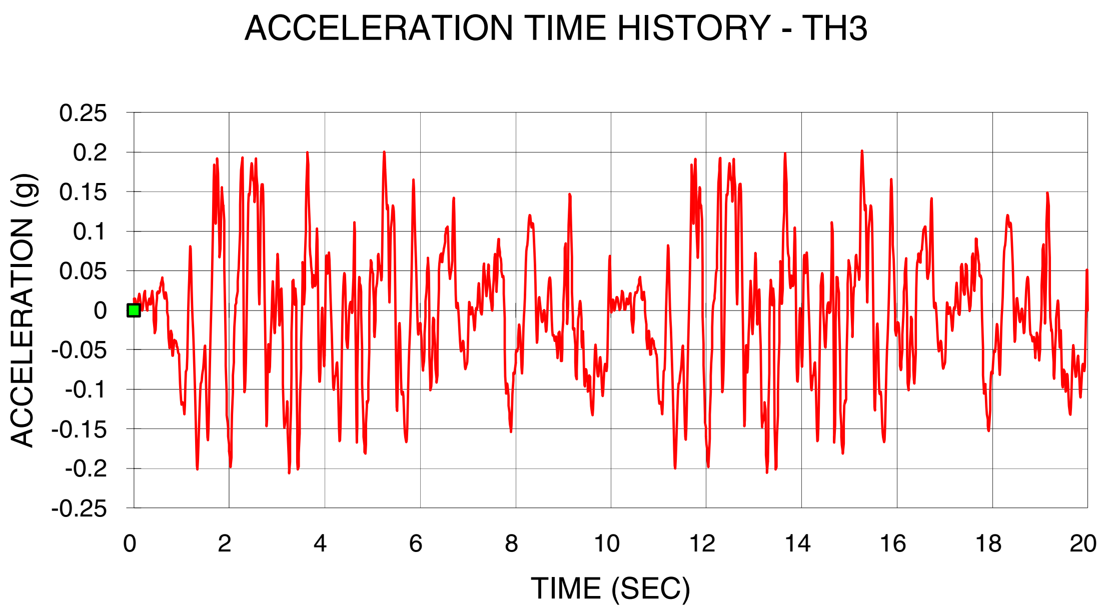

Figure 5 Acceleration Time-History (TH-3)

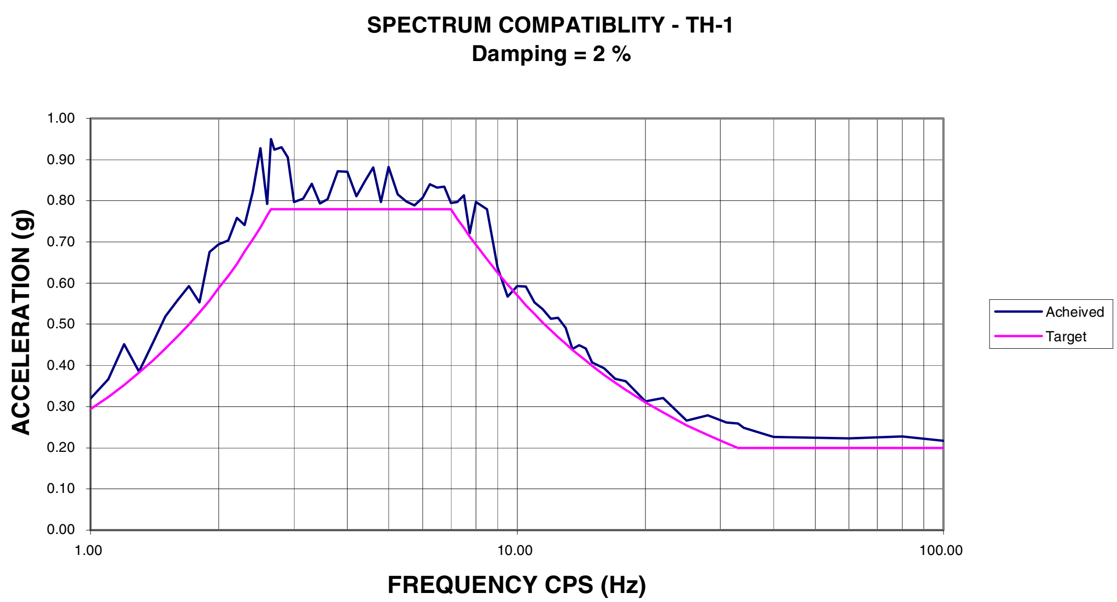

Figure 6 Response Spectrum Compatibility for TH-1 at 2 % Damping

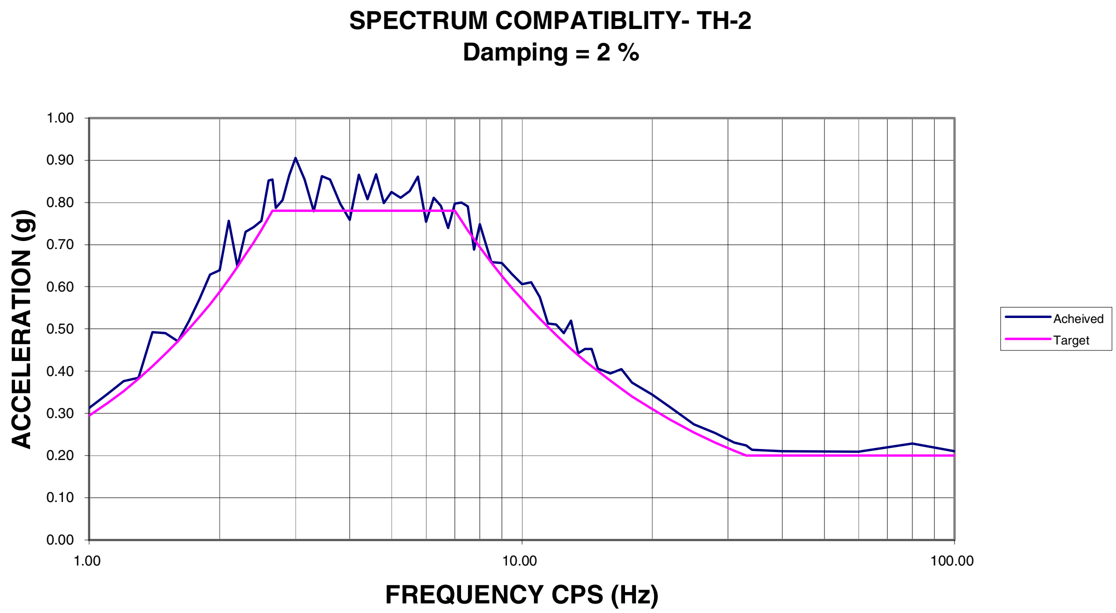

Figure 7 Response Spectrum Compatibility for TH-2 at 2 % Damping

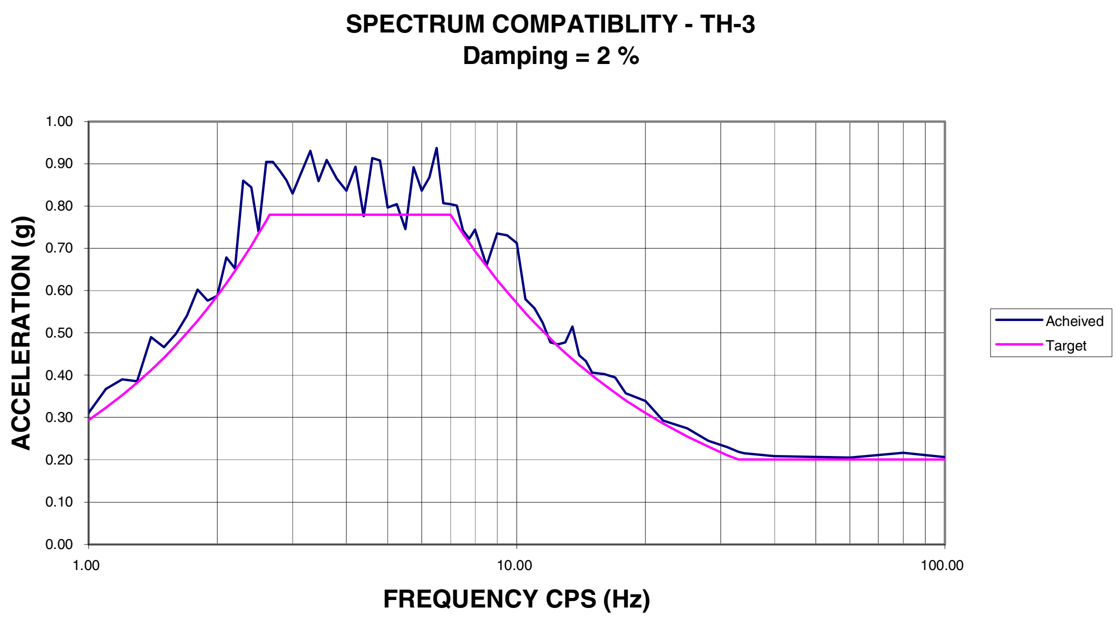

Figure 8 Response Spectrum Compatibility for TH-3 at 2 % Damping

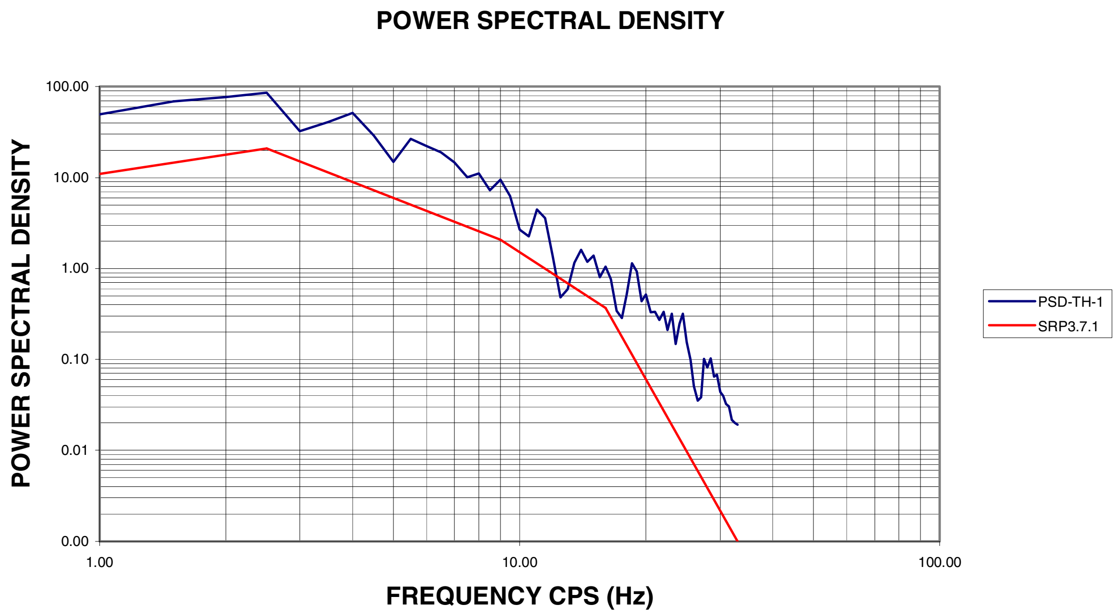

Figure 9 Power Spectral Density for TH-1

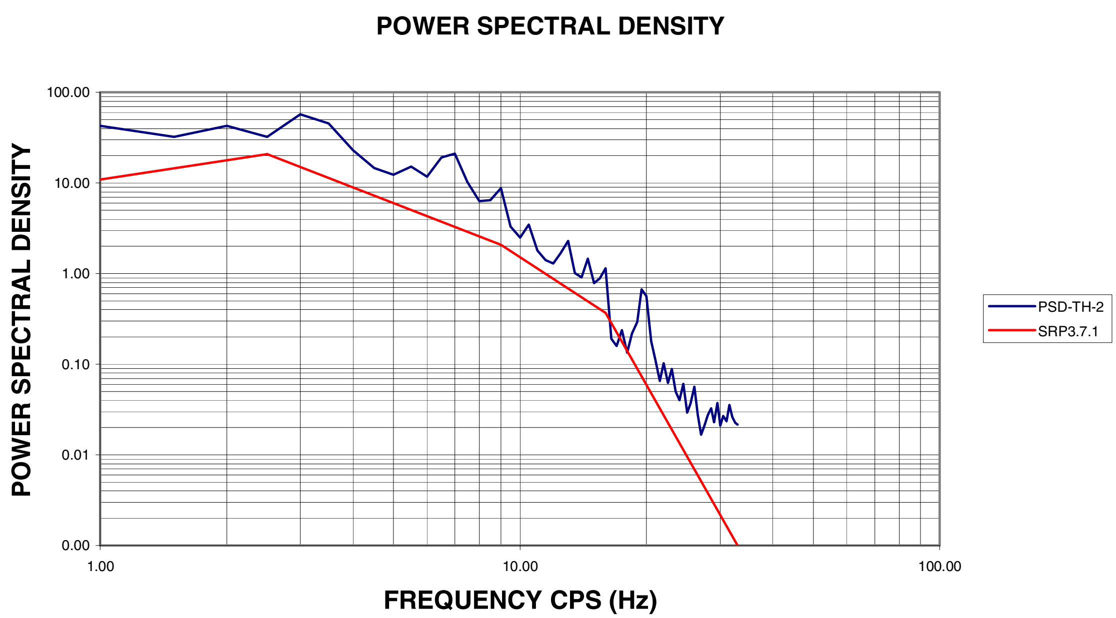

Figure 10 Power Spectral Density for TH-2

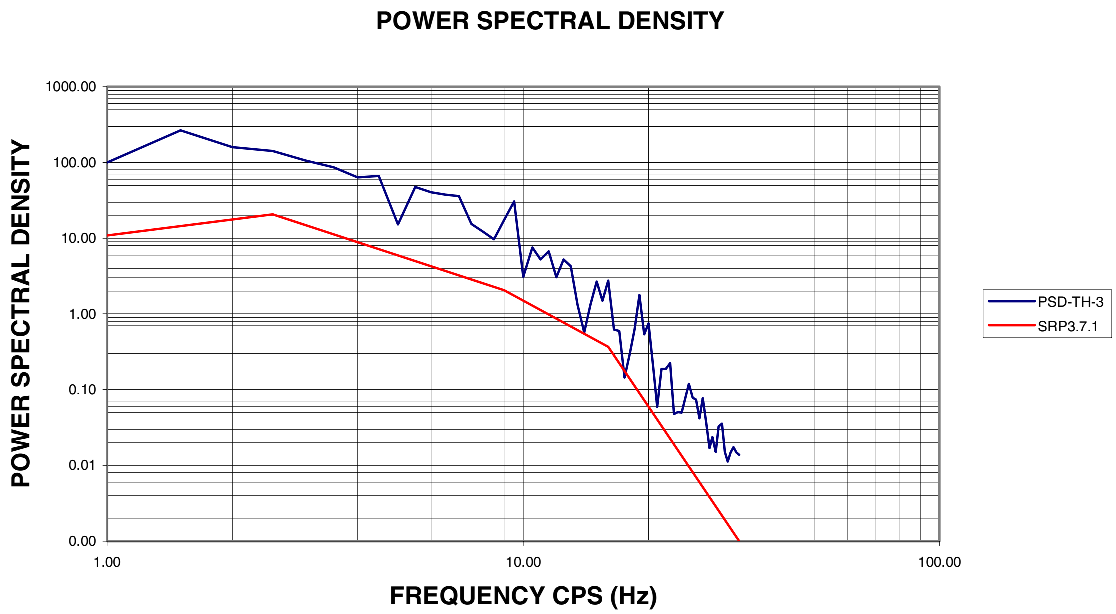

Figure 11 Power Spectral Density for TH-3

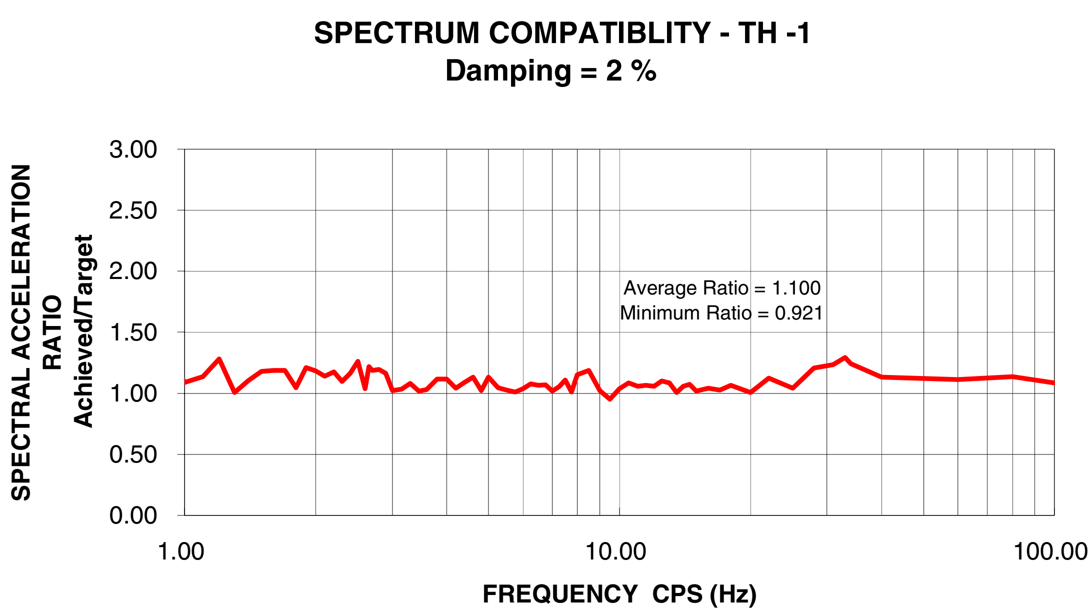

Figure 12 Spectrum Compatibility Point-by-Point Comparison

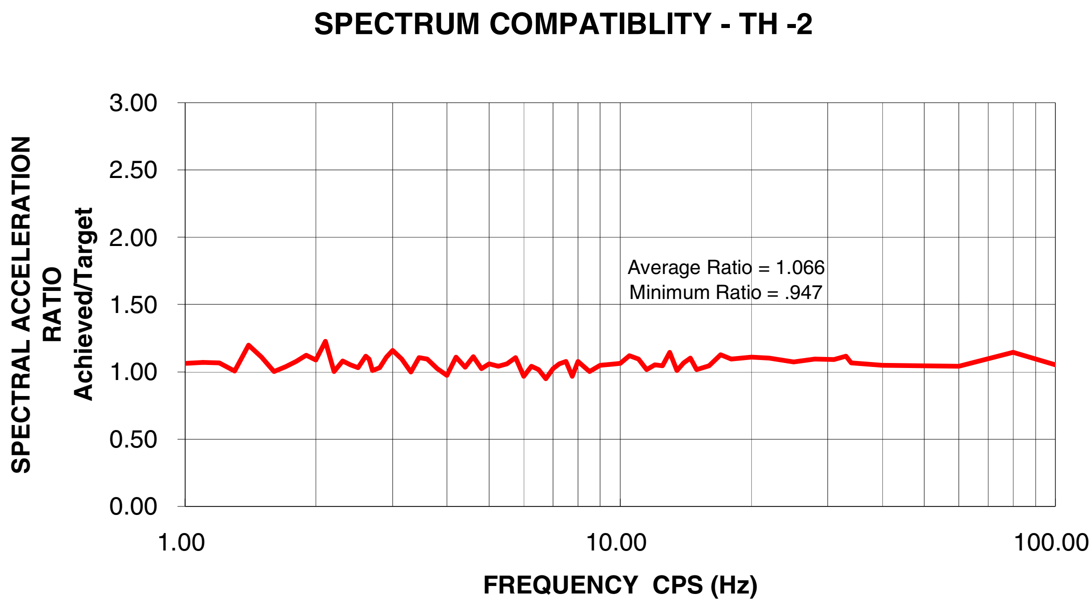

Figure 13 Spectrum Compatibility Point-by-Point Comparison

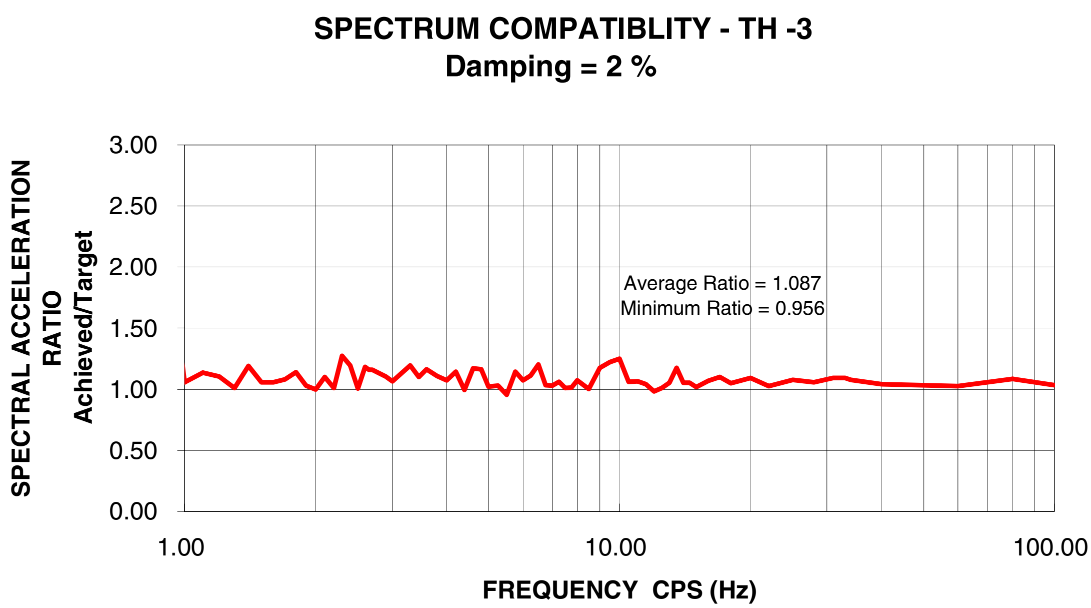

Figure 14 Spectrum Compatibility Point-by-Point Comparison