Lecture 6 – LOADING SYSTEMS

Dynamic Testing – Advanced Techniques

Base excitation – Shake tables

Effective Force techniques

Pseudodynamic Excitation

Full structure

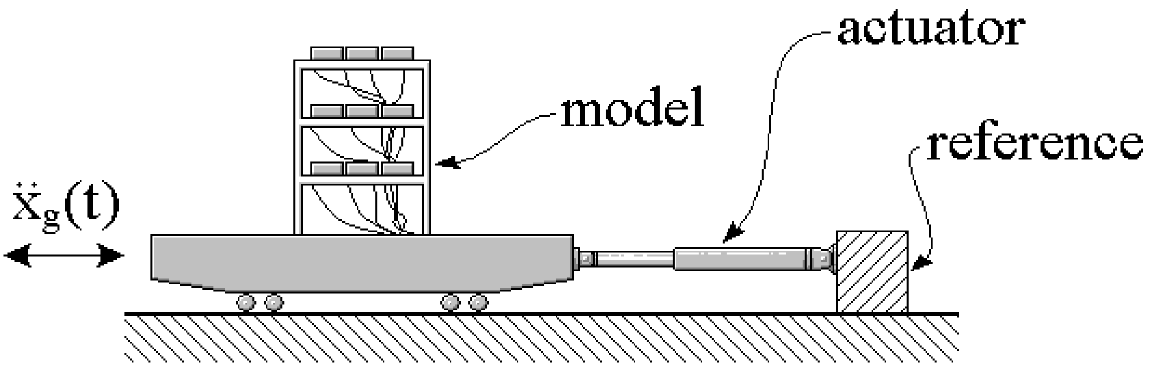
Substructure

Real Time Dynamic Hybrid Testing

Substructure

- Hydraulically driven actuators (forced vibration) – sinusoidal or random loading, and pseudo dynamic effects
- Hybrid systems

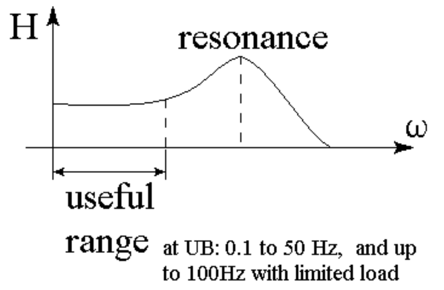
Vibrating tables



- One can use any base time history (random or harmonic).

- Limited by the force of the actuators and the frequency range of the equipment.

$$a_{max.} = \frac{F_{actuators}}{W_{model}+W_{table}}$$



- Driven by desired base acceleration or base displacement.

- The motion obtained is

$X_a = H \cdot X_d$ (with the motion not perfectly matching that desired).

X_a - Achieved motion
X_d - Desired motion
H - Shake table transfer matrix

If H is known then a correction can be applied a-priori (giving a compensated input).

- Table Compensation System:
  i.e. define:
  $\bar{X}_{drive} = H^{-1} \cdot X_d$
  apply as input history $\bar{X}_{drive}$:
  obtain:
  $X_a = H \cdot \bar{X}_{drive} = H \cdot H^{-1} \cdot X_d = X_d$
  (This is true in a linear system.)

But the system is usually non-linear, therefore: $X_D \neq X_A$

i.e. $X_D = X_A + \Delta X_D$ or $\Delta X_D = X_D - X_A$

Apply the correction again:

$$\Delta \bar{X}_{D_k} = H^{-1} \Delta X_{D_k} \quad \rightarrow \quad \bar{X}_{D_{k+1}} = \bar{X}_{D_k} + \Delta \bar{X}_{D_k}$$

And following several iterations:

$$\bar{X}_{D_{k+n}} = \bar{X}_{D_k} + \sum_{i=1}^{n-1} \Delta X_{D_{k+i}} \quad \rightarrow \quad \bar{X}_{D_0}$$

Resulting in:

$$X_A = H \cdot H^{-1} \left(\bar{X}_A + \sum_{i}^{n-1} \Delta X_{D_{k+i}} \right) \quad \rightarrow \quad X_D$$

However, compensation holds for elastic testing only. It does not work when the structure or the table changes properties.

Single Degree of Freedom Shake Tables:

1) Porto Rico Shake Table
2) UCSD Shake Table

Issues for discussion:

a) Control of displacement, or acceleration (PID ?)
b) Simultaneous control of three variables (TVC ?)
c) Overturning and lateral coupling (PID, TVC, Active)
d) Compensation inner loops and supervisory

Multiple Degrees of Freedom Shake Tables:

1) Univeristy of Naples
2) University at Buffalo SEESL

Issues for discussion:

e) Control of displacement, or acceleration single axis
f) Cross coupling of two directions (horizontals)
g) Overturning
h) Cross coupling multiple directions

Motion Simulation with Vibrating tables
(forced vibration by base movement) –
harmonic and random motion

- Harmonic (sine , etc)
- Sine Sweep (like the rotating motors)
- White noise
- Random motions
  - Natural
  - Simulated
    - Spectrum compatible
    - Empirical

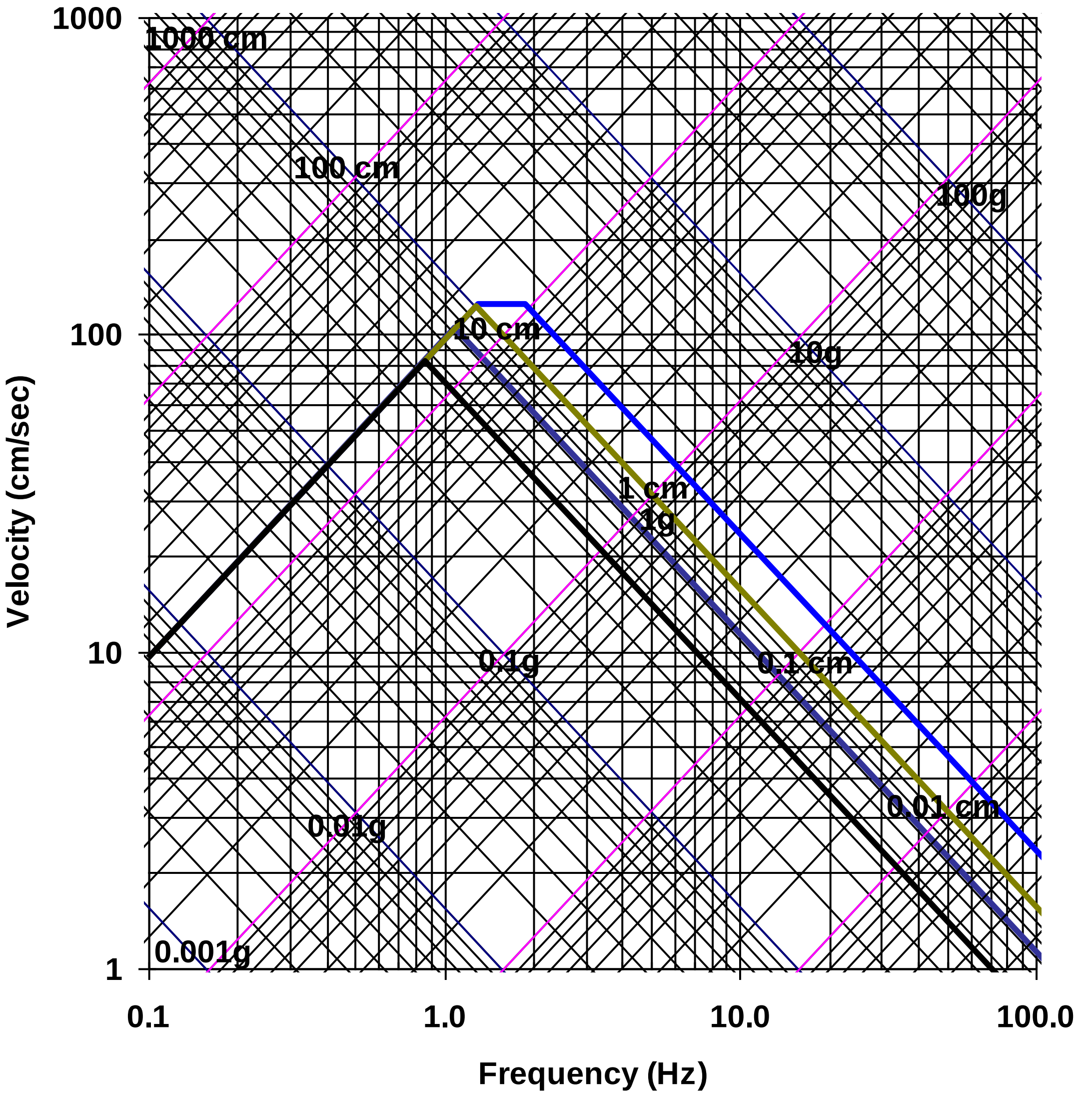
White noise: is a "random motion with a constant Power Spectrum".
Defined by:

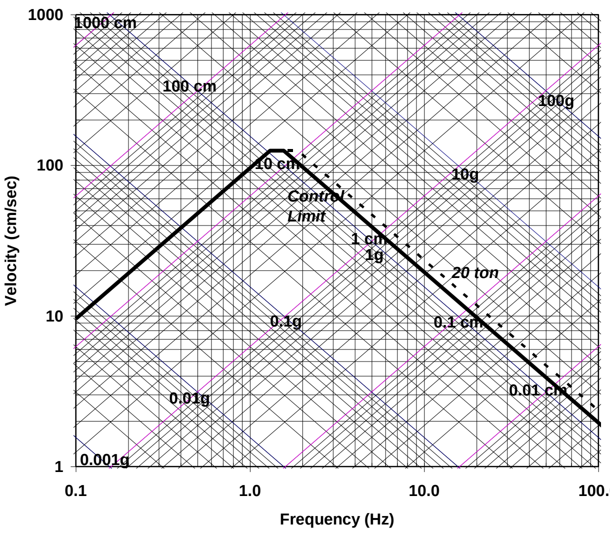
1) Frequency range (0.5-100 Hz)
2) RMS (or sq. root of the Variance)
3) Duration

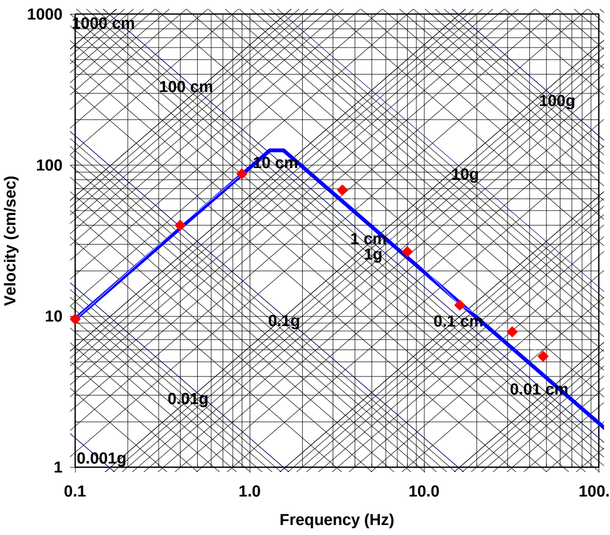
Used for identification testing

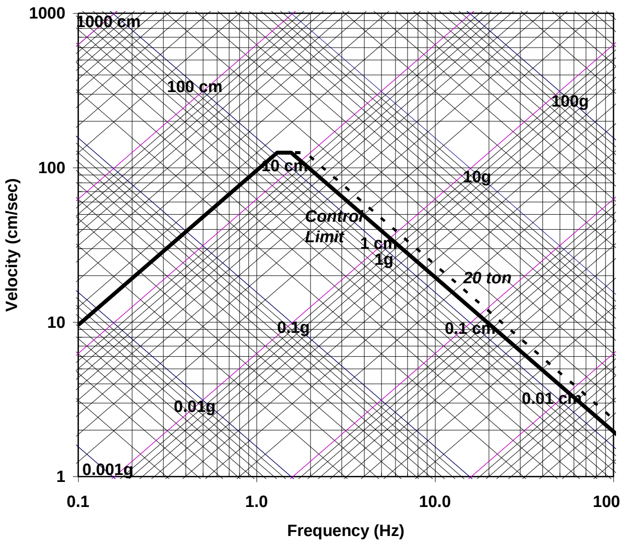
Random Motion
This includes natural earthquakes scaled properly for the models in question.

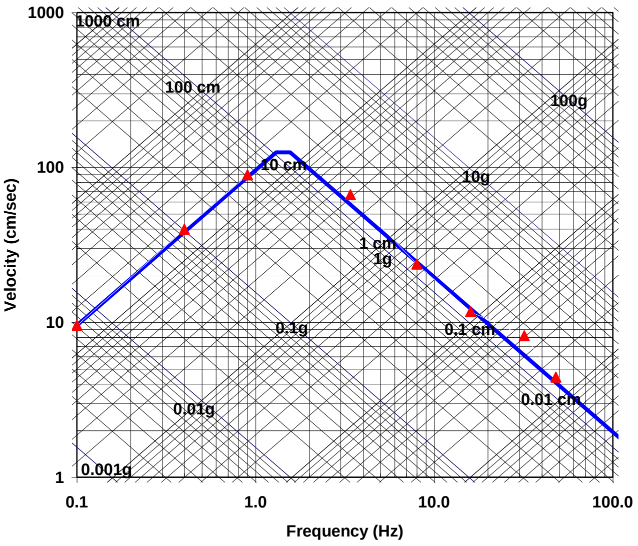
1) Libraries of Earthquakes available in lab
2) Not all earthquakes can be simulated by table.
3) Ranges are defined by performance properties of shake tables:
4) Often motion clipped to fit performance:

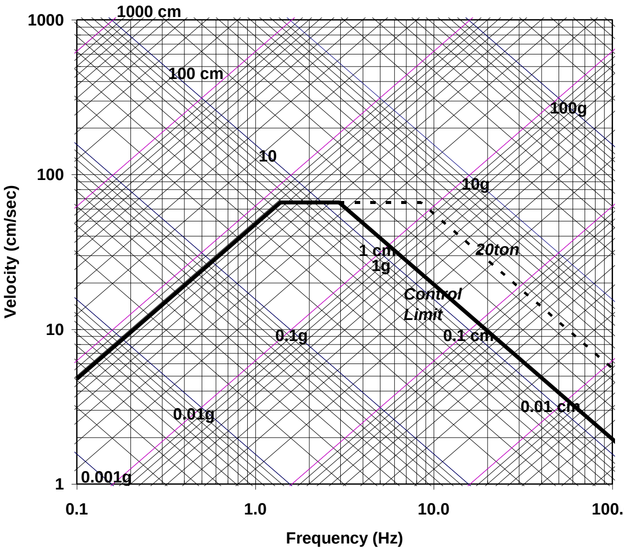

1000
100
10
1
Velocity (cm/sec)
0.1
1.0
10.0
100.0
Frequency (Hz)
1000 cm
100 cm
10 cm
1 cm
0.1 cm
0.01 cm
100g
10g
1g
0.1g
0.01g
0.001g

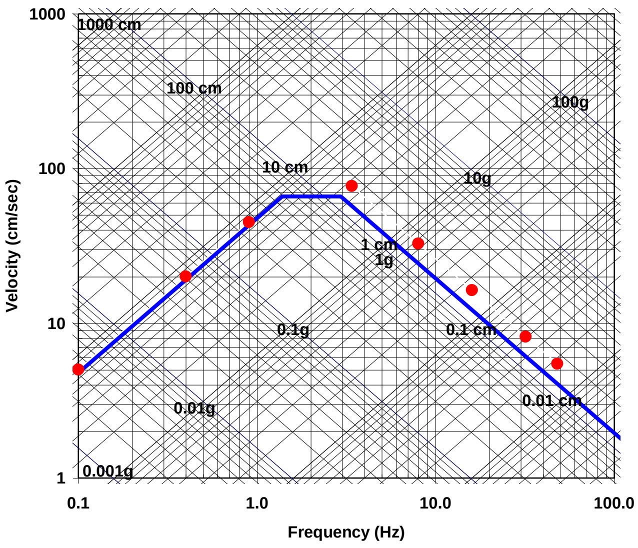

Expected Performance Curves -- Longitudinal (E-W)


Shake Table 1 (20ton) Performance Curve -- Longitudinal (E-W)


Expected Performance Curves -- Transversal (N-S)


Shake Table 1 (20ton) Performance Curve -- Transversal (N-S)


Expected Performance Curves -- Vertical


Shake Table 1 (20ton) Performance Curve -- Vertical

Ground motion simulation: (Earthquakes)

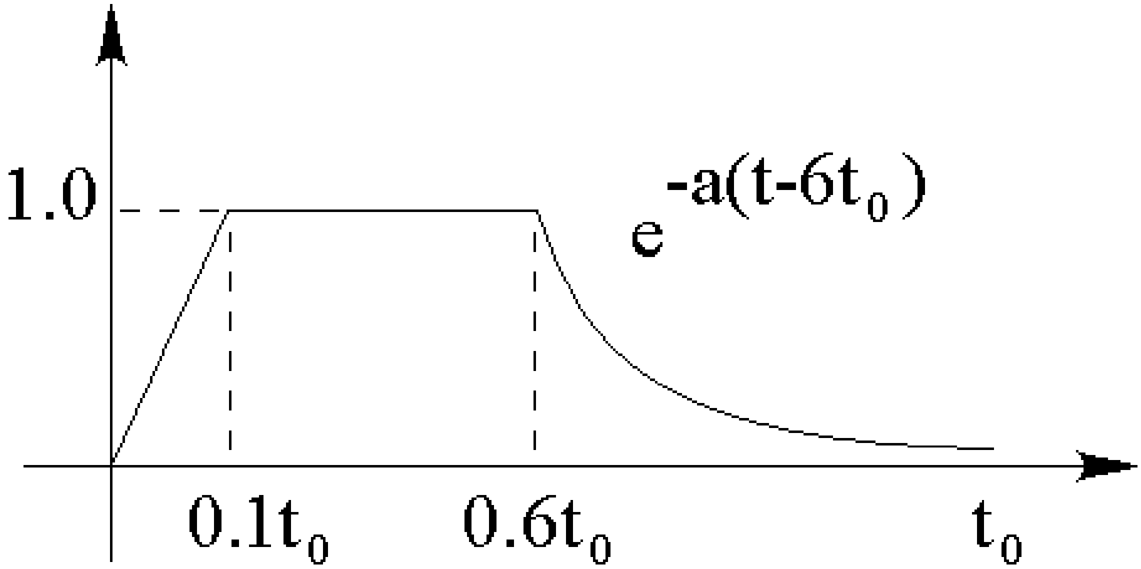
Use random vibration theory:

$$X_D(t)=\left[\sum_{i=1}^{m} A_0(\omega_i)\sin(\omega_i t+\varphi_i)\right]\cdot R(t)$$

Where ω_i is a specific frequency in the range of 0 to ω_{max}.

ϕ_i is a uniformly distributed random variable in 0 to 2π.

R(t) is an envelope function:



$$A_0(\omega)=\sqrt{2S_0(\omega_i)}$$

where S_0 is a specified power spectrum density. (This can be calculated from the power spectrum density by using SIMQKE.)

Earthquake Ground Motion Model

$$a_g(t) = I(t) \cdot a_{g0}(\phi(t))$$

where a_{g0} = zero mean, unit variance, stationary filtered white noise.

$$a_{g0}(\phi) \cong FFT^{-1}\left[H_1^2(\omega) \cdot H_2^2(\omega) \cdot S_0\right]^{1/2}$$

$$H_1^2(\omega) = \frac{1 + 4\xi_g^2\left(\omega/\omega_g\right)^2}{\left[1 - \left(\omega/\omega_g\right)^2\right]^2 + 4\xi_g^2\left(\omega/\omega_g\right)^2}$$

this is the Kanai Tajimi filter

$$H_1^2(\omega) = \frac{\left(\omega/\omega_1\right)^4}{\left[1 - \left(\omega/\omega_1\right)^2\right]^2 + 4\xi_1\left(\omega/\omega_1\right)^2}$$

where $\omega_g = 15.6\,rad/s \quad \xi_g = 0.6 \quad T_g = 0.4s$

$\omega_1 \cong 11\,rad/s \quad \xi_1 = 0.7$

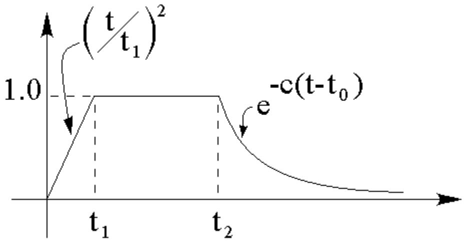
Note that $S_0 = PS_0$ = of white noise, so S_0 = 500 to 2000 cm^2/s

The above are known as the Clough and Penzien filters

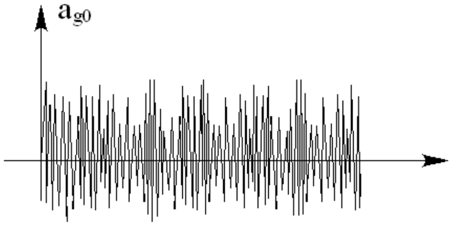
φ(t) = a frequency modulation function

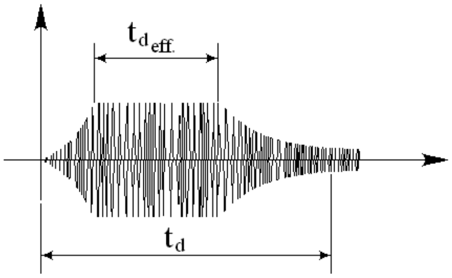
I(t) = a nonstationary envelope

= or $I^2(t) = \left(A^{tB} e^{-ct}\right) \Big/ \left(D + t^e\right)$ from Yeh and Wen, 1989



Example:





Energy Function:

$$E(t) \cong \int_0^t I^2(t)\,dt$$

Compensation holds for elastic model testing only. It does not accurately drive when model structure or shake table changes properties.

i.e. k = structural stiffness changes

Ground Motion Simulation (Earthquakes)

Use random vibration theory

$$x_D(t)=\left[\sum_{i=1}^{m}A_0(\omega_i)\sin(\omega_i t+\phi_i)\right]\cdot R(t)$$

where

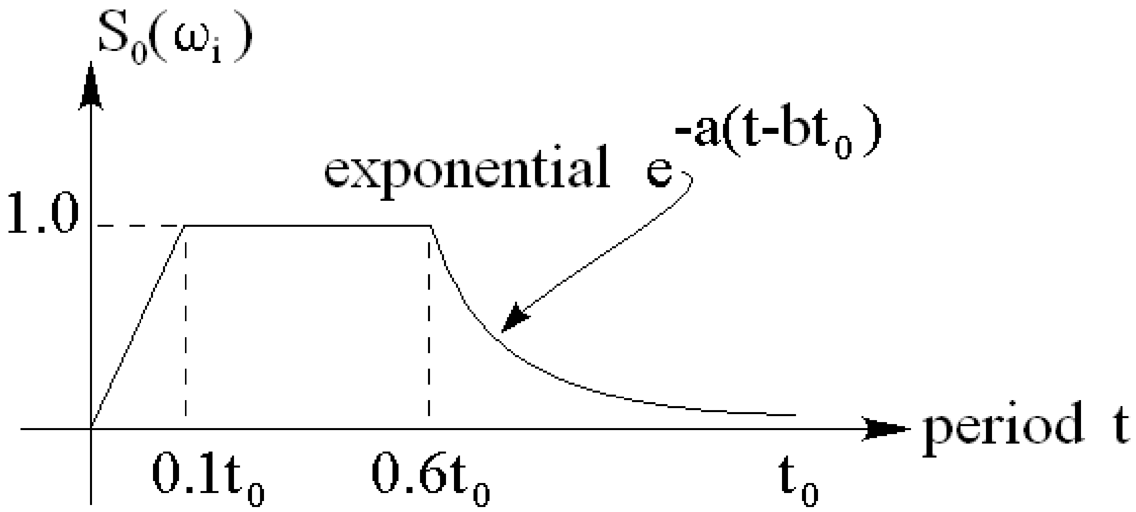
ω_i = specified frequency in range from 0 to ω_{max}

φ_i = uniformly distributed random variable ranging from 0 to 2π

R(t) = envelope function

$$A_0(\omega)=\sqrt{2S_0(\omega_i)}$$

$S_0(\omega_i)$ = specific power spectral density



Modeling of Seismic Occurrence

Most current models are probably more accurate outside the focal region in the near and intermediate far field, i.e:

1. R focal distance ≤ 350 km
2. R focal distance ≥ 20 km
3. magnitude greater than 4.0
4. D focal depth ≤ 100 km

$$\log N(M) = a - bM$$

this is the Gutenberg-Richter relation (G)
M is the magnitude of the earthquake based on an Anderson accelerograph.

$$N(M) = N(M_0)e^{-\beta M}$$

this is the Gümbel relation (G)

Note that $N(M_0) = 10^a$
$\beta = b \log_{10} e$
a & b are Gutenberg-Richter constants

correcting the Gutenberg-Richter relation for maximum earthquake:

$$\log N(M) = a + \log\left(10^{-bM} - 10^{-bM_u}\right)$$

this is the modified Gutenberg-Richter relation
M_u = the maximum recorded earthquake in the period of observation (the upper bound magnitude)
M_0 = the minimum recorded earthquake in the study
$M_0 \leq M \leq M_u$

Cumulative distribution factor $G_M(M) = F_M(m)$

Where $F_M(m) = 1 = N(m) / N(M_0)$

Attenuation Curves

Magnitude Relations $M=\dot{A}I_0+\dot{B}\log D+\dot{C}\log R+\dot{D}$

where $\dot{A}_0 \approx 0.5, \dot{B} \approx 1.0, \dot{C} \approx 0, \dot{D} \approx 1.0$

a) Intensity (I_0)
b) Focal distance and depth (R, D)

Motion Relations peak $u_p=b_1 \cdot e^{b_2 M} R^{-b_3}$

where b_1, b_2, b_3 are coefficients that vary for a, v, d

a) Focal distance (R)
b) Magnitude (M)

Duration of ground motion

a) Envelope
b) Magnitude
c) Focal distance

Example: $\log_{10} t_d=0.31M-0.774$ from Hisado and Ando (1976), for Japan

Power Spectra vs Response Spectra Relations

$$RS_{\alpha} = RS_{0} \cdot \alpha \qquad \text{or} \qquad S_{\alpha}(\omega) \cong S_{\alpha 0} \cdot \alpha^{2}$$

where α = amplification factor: (≈H(ω) from the Fourier transfer function ≈A(ω))

Note:

frequency response: $U(\omega) = FFT(\dot{\mu}(t)), \quad F(\omega) = FFT(f(t))$

$$U(\omega) = H(\omega) \cdot F(\omega)$$

power spectrum: $\frac{1}{T}\left[U^{*}(\omega) \cdot U(\omega)\right] = \frac{\|U(\omega)\|^{2}}{T} = PS_{uu}(\omega)$

$$= \|H(\omega)\|^{2} \cdot \frac{\|F(\omega)\|^{2}}{T}$$

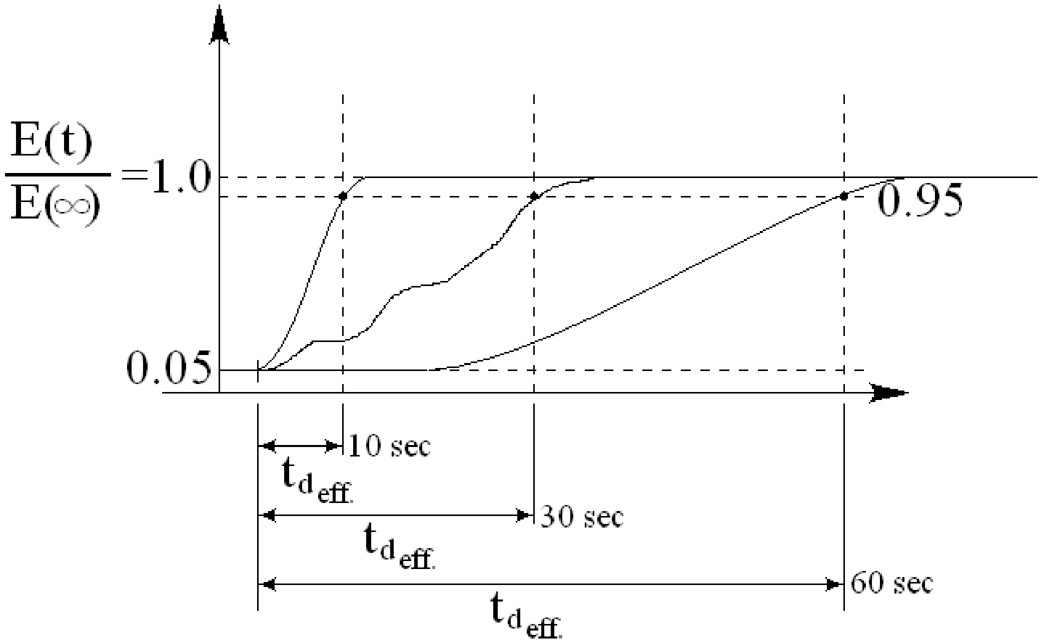
$$\boxed{PS_{uu}(\omega) = H^{2}(\omega) \cdot PS_{ff}(\omega)}$$

$\approx PS_{gg}(\omega)$ ground motion

Power spectra ratio: $\frac{PS_{uu}(\omega)}{PS_{gg}(\omega)} = H^{2}(\omega)$

Response spectra ratio: $\boxed{\sqrt{\frac{\left[RS_{u}(\omega)\right]^{2}}{\left[RS_{g}(\omega)\right]^{2}}} = H^{2}(\omega) \cong \frac{PS_{uu}(\omega)}{PS_{gg}(\omega)}}$

Effective Duration of Ground Motion



(From Trifunar & Brady, 1975)

Amplitude – power spectrum relations

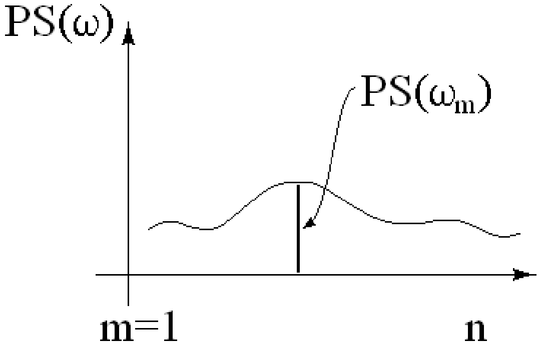
$$a_{g0}(t)=\sum_{m=1}^{n} A_0(\omega_m)\cdot\cos(\omega_m t+\theta_m)$$

$$A_0(\omega_m)=\sqrt{2\cdot PS(\omega_m)\cdot\Delta\omega} \quad \text{since} \quad A_0(\omega_m)=FFT\left(a_{g0}(t)\right)$$

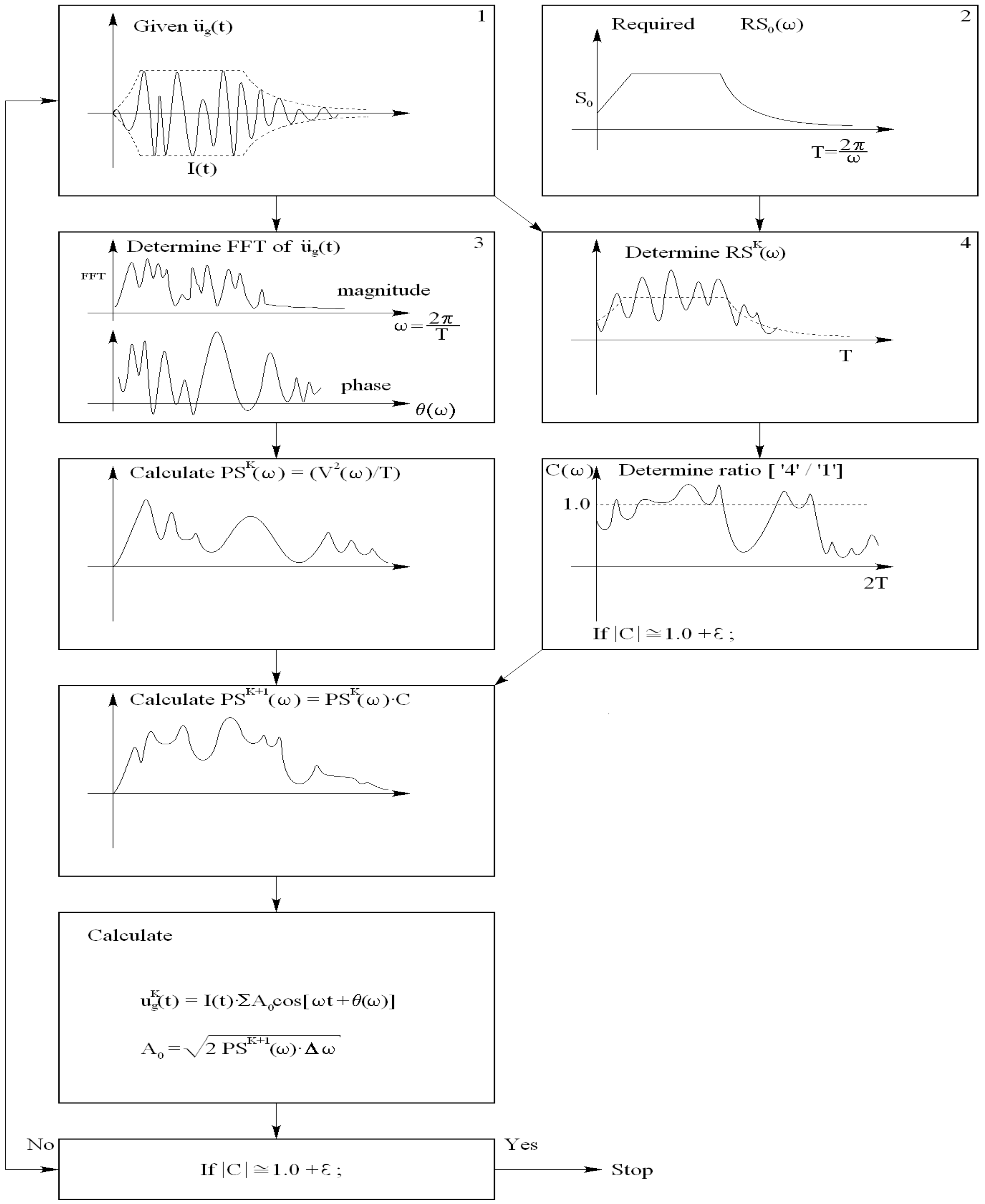
$$\Delta\omega=(\omega_u-\omega_l)/N$$ where ω_u = upper bound

and ω_l = lower bound

θ_m is a uniformly distributed random number between 0 and 2π



Response Spectrum Compatible Simulation of Earthquakes (Flow chart):



Earthquake Simulation (for a given $RS_0(\omega)$)

- Determine initial $PS_0^K(\omega)$ (where $K=1$)

- Generate $a_{g0}^K(t)$

- Determine $a_g^K(t) = I(t) \cdot a_{g0}^K(t)$

- Determine $RS^K(\omega)$

- Modify $PS^{K+1}(\omega) = PS^K(\omega) \cdot [RS_0(\omega)/ RS^K(\omega)]^2$
- If $PS^{K+1}(\omega)$ z $PS^K(\omega)$ stop the process, since you have achieved the motion. ($| PS^{K+1}(\omega) - PS^K(\omega) | \leq \varepsilon$, original Euclidian norm) If the above is not satisfied repeat from top for $K = 2,\ldots.n$ until it converges.

- Multiply by the nonstationary envelope = $a_g(t) = I(t) \cdot a_g^K(t)$

Procedures may be different for various programs:

Program SIMQKE by Gasparini and Vanmarke (1976)
Note that the original $PS_0^K(\omega)$ can be determined from:

a) $PS_0^K(\omega) = H_1^2(\omega) \cdot H_2^2(\omega) \cdot S_0(\omega)$ = Clough & Penzien

b) A given ground motion with $RS_0(\omega)$ known and $PS(\omega)$ obtained from: $FFT\,(\ddot{u}_g(t))^2/T = PS(\omega)$

Alternative techniques:

1) Various Techniques Gian Paolo Cimellaro
2) Papageorgiou A. & Halldorsson, B. – "Earthquake Simulation Package" and "Theoretical Base"

GROUND MOTION SIMULATION:

Cimellaro
Cornell&Baker
Papageorgiou&Halldorsson

Testing Procedures:

1. Perform Identification tests – white noise, sine sweep, snap-back
2. Perform testing using main motion
   a. Apply gradually low level accelerations for verification
   b. Apply the base motion desired and perform compensation
   c. Apply Incremental Dynamic Simulation to failure.
   d. Apply harmonic load usually at resonance.
3. Perform identification after each main testing in 2 above.

Test Protocols:

Example **ASME QME excerpt: QUALIFICATION OF ACTIVE MECHANICAL EQUIPMENT USED IN NUCLEAR POWER PLANTS ASME QME-05-13-2004**

QR-A7200 Qualification by Testing
QR-A7210 Introduction.
QR-A7220 Types of Tests

QR-A7221 Exploratory Tests.

- Exploratory tests consist of the measurements of active mechanical equipment dynamic characteristics by some form of modal identification procedures.
- The active mechanical equipment is mounted in a close simulation of that anticipated in the field. The active mechanical equipment is instrumented for measurement of responses at various locations anticipated to be important to interior functioning devices or at locations which provide a good indication of structural modal characteristics. It is then subjected to a suitable excitation and responses are recorded. Components which may in themselves be rigid if flexibly mounted or attached in the field shall have this flexibility represented during the test.
- In the past, sine sweep resonance tests have been widely used for these tests.
- However, random excitation or even simulated earthquake events may be used.
- Exploratory tests are not a requirement for qualification directly, not serve as the basis for even partial seismic qualification, but their results may be used in further development of procedures or in justification for qualification tests, or these results may be part of a combined analysis experience and test approach, as described in QR-A7600.

QR-A7222 Seismic Proof Tests.

- In the past, most active mechanical equipment qualification has been performed by proof test methods. This approach requires that the simulated earthquake motion at the active mechanical equipment mounting represents that anticipated from the specified SSE.
- The simulated motion usually is required to demonstrate that the test response spectrum (TRS) conservatively envelops the required response spectrum (RRS) which was generated for the active mechanical equipment mounting location as part of the test specification.
- The result of a proof test is a demonstration that the active mechanical equipment performs its specified function, during and/or after the simulated SSE event.

QR-A7223 Fragility Tests.

- Fragility tests are conducted to determine the peak amplitude level of a specified excitation waveform for which the active mechanical equipment can perform its specified function.
- A sequence of test runs is performed with increasing amplitudes of the specified waveform until malfunction is observed in the active mechanical equipment.
- When the specified motion is compared to that anticipated for the SSE at the active mechanical equipment mounting, a measure of margin is established. In addition to the response spectrum type of input loading, in-line active mechanical equipment may also be qualified by required input motion (RIM) testing as described in IEEE Standard 382.

QR-A7230 General Approach to Testing

QR-A7231 Preliminary Tests.

- Exploratory tests described in QR-A7221 are usually performed prior to conduct of the actual qualification test or qualification by a combination of testing and other methods. Other preliminary tests, such as thermal or operational aging, or any other required environmental test, shall be performed prior to the seismic test. This sequence assures that the active mechanical equipment is in the end of the qualified life state at the time of the seismic qualification.

QR-A7232 Development of Simulated Seismic Motion.

- The simulated seismic motion shall conservatively represent that which can be expected at the active mechanical equipment mounting for the SSE event.
- The general nature of earthquake motion can be represented by a nonstationary random process having broad frequency content (i.e., 1-33 Hz) at ground level, but with much narrower frequency

content near building natural frequencies, when representing filtered motion at building floor levels.

- Several characteristics of seismic motion must be noted when simulated waveforms are developed for testing purposes. These characteristics are understood to describe the motion that occurs at the equipment mounting.
  - (a) The general character of earthquake motion is a random process which builds to a relatively stationary level (called the *strong motion*), which holds at that level for some duration, and which then decays to a negligible value.
  - (b) Approximately stationary random motion occurs during the strong motion. It is this part of the excitation which causes most damage to active mechanical equipment. It must be sustained a minimum of the larger of 15 sec or the duration of strong motion during a qualification test.
  - (c) Frequency content of the required motion and actual test motion is indicated by the amplified region of a response spectrum. Thus, a test response spectrum shall closely envelop the required response spectrum to assure proper frequency content.
  - (d) Stationarity of the waveform during the simulated strong motion shall be demonstrated. This assures that all required frequencies are present to a sufficient amount during the strong motion.
  - (e) Multiaxis motions shall have an appropriate degree of statistical independence. This is determined by examining the coherence or cross correlation between the waveforms for different axes. Test waveforms which have the above characteristics may be generated by superimposing a variety of component signals, such as sine dwells, sine beats, narrow band, and broadband random signals.

QR-A7233 Conduct of Test and Functionality.

- Detailed procedures for preparing Seismic Qualification Specifications and conducting seismic qualification tests shall be obtained from IEEE Standard 344. Details for conducting functional tests for the active mechanical equipment shall be obtained from the manufacturers’ operating manuals and active mechanical equipment specifications.

QR-A7240 Acceptance Criteria.

Acceptance criteria for seismic tests shall be based on the functional requirements for the individual item of active mechanical equipment. Acceptable ranges for performance variations must further be evaluated in light of the consequences of these variations on the specified function of that equipment and any other with which it may interact. Such interactions with other active mechanical equipment which affect acceptance criteria shall be identified in the Seismic Qualification Specification. Numerical ranges for these variations shall be established and compared with observed test values. Inability of an item to function within acceptable limits during or after seismic testing shall be noted as an anomaly. Thereafter, evaluation of the consequences of the anomaly may or may not lead to a conclusion that the item has malfunctioned.

QR-A7300 Qualification by Similarity.

There are many instances of active mechanical equipment, similar to a type that was qualified, which differs only in size or in the specific qualified devices located in the assembly or structure. In such cases, it is neither practical nor necessary to test every variation of the basic qualified version. Furthermore, it may be shown that the active mechanical equipment to be qualified is similar to another that has experienced actual documented earthquake conditions. Qualification by combined test and analysis applies in these situations.

QR-A7310 Test Method.

A full test program, as described in QR-A7200 and preliminary exploratory tests (resonance search), as described in QR-A7221 are conducted on a typical piece of active mechanical equipment. Data on modal frequencies, damping, and responses throughout the active mechanical equipment must be taken and recorded.

References:

1. **Network Equipment-Building System** **(NEBS)** Requirements: Physical Protection. Generic Requirements GR-63-CORE Issue 1, October 1995. Bellcore; Bell Communications Research.

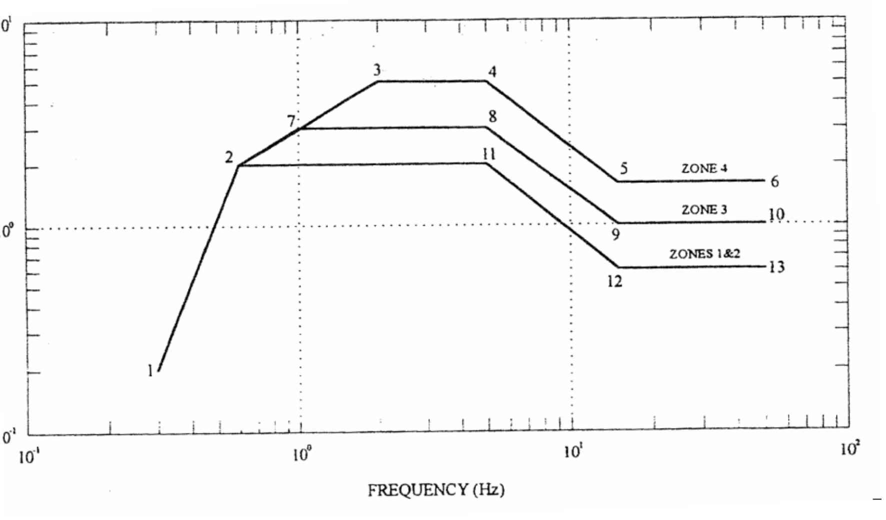
2. **ICC Evaluation Service**, Inc., "AC156 - ACCEPTANCE CRITERIA FOR SEISMIC QUALIFICATION TESTING OF NONSTRUCTURAL COMPONENTS", January 2000 (Effective February 1, 2000), Copyright W 2000, Published by ICBO Evaluation Service, Inc., A subsidiary corporation of the International Conference of Building Officials, 5360 WORKMAN MILL ROAD • WHITTIER, CALIFORNIA 90601-2299 • (562) 699-0543, FAX (562) 695-4694

3. **IEEE 693**, "Recommended Practice for Seismic Design of Substations", Draft 9, 2004, Sponsor: Substations Committee of the IEEE Power Engineering Society, Prepared by Working Group F1 of the West Coast Substation Subcommittee, Copyright 8 1998 by the Institute of Electrical and Electronics Engineers, Inc. 345 East 47th Street, New York, NY 10017, USA, All rights reserved: IEEE Standards Department Copyright and Permissions: 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA

4. **NISTIR 5800**, "Guidelines for Pre-Qualification, Prototype and Quality Control Testing of Seismic Isolation Systems", Harry W. Shenton III, Building and Fire Research Laboratory, National Institute of Standards and Technology, Gaithersburg, Maryland 20899, January 1996.

Sources available

Example of requirements:



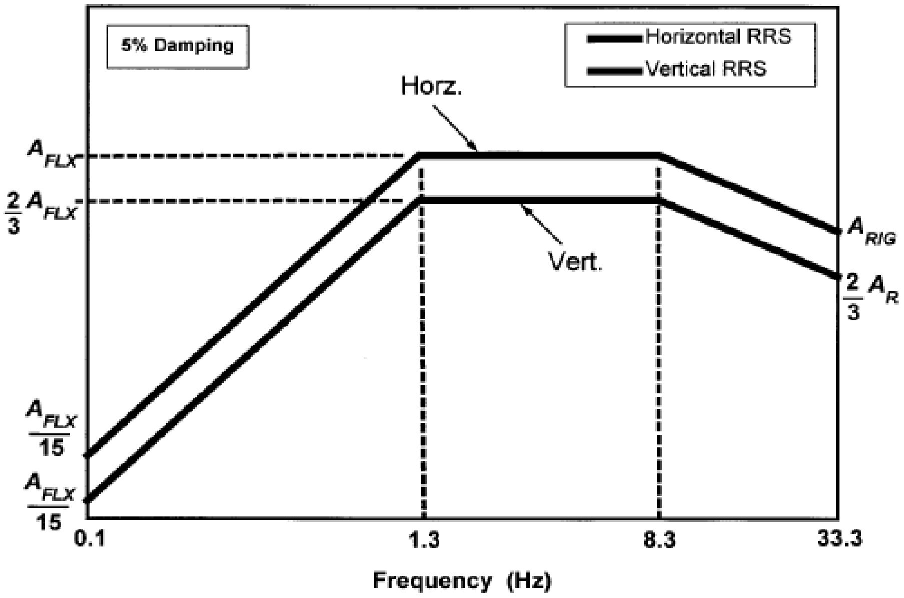


FIGURE 1—REQUIRED RESPONSE SPECTRUM, NORMALIZED FOR EQUIPMENT

$$A_{FLX} = 2.5C_a\left(1 + 3\frac{H_x}{H_r}\right) \text{ and}$$

$$A_{RIG} = C_a\left(1 + 3\frac{H_x}{H_r}\right) \text{ and}$$

where:

A_{FLX} is limited to a maximum value of 4

Advanced techniques:

1) Effective Force Method

2) Hybrid Methods
    a. Pseudo-Dynamic
    b. Real-Time Dynamic

3) Unified Approach