SEISMIC INPUT FOR DESIGN OF LONG PERIOD STRUCTURES

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ABSTRACT

The seismic response of long period systems, either with low damping (highway bridges) or high damping (e.g., base isolated structures) is based on ground velocities and/or ground displacements rather than on ground accelerations. As a result, a number of factors which lead to low-frequency errors in the processing of strong motion accelerograms become very significant, and must be carefully analyzed for design purposes.

Among these factors are: 1) source effects; 2) type of earthquake; 3) local site geology; 4) digitization errors; 5) initial conditions of motion; and 6) computational algorithm.

The different stages in the recording and processing of the signal operate in various ways that sometimes counteract each other. For instance, the integration scheme of acceleration values acts as a recursive digital filter that distorts unevenly the frequency content of the signal, and may result in misleadings velocity, displacement or response spectrum records.

In this paper the aforementioned effects are investigated in the frequency domain, focusing on the spectral analysis of the response of flexible structures. After reviewing carefully the influence of source and site factors, digitization and correction procedures, as well as integration methods, on the reliability of long period spectral ordinates, a parametric study of the sensitivity of response spectra to system initial conditions is presented. Along this path, two approximate methods are developed to correct standard response spectra of optical records for the effect of non-zero initial conditions. Finally, the extent to which these findings may affect the proposed design requirements of seismic isolation structures (SEAOC, 1990) is discussed.

INTRODUCTION

Response spectrum plots either in natural scales or tripartite log-log form have become a routine design tool to represent the frequency content of the time histories of the earthquake ground motion. Such plots are obtained by maximizing the solution, u(t), of the equation of motion of the 1 d.o.f. system:

$$u'' + 2\,\omega\zeta\,u' + \omega_2\,u = -y''(t) \qquad (1)$$

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as well as the related magnitudes, u'(t) and x"(t) = u" + y"(t), in the following manner:

$SD = |u(t)|_{max}$ = relative displacement response spectrum

$SV = |u'(t)|_{max}$ = relative velocity response spectrum

$SA = |x''(t)|_{max}$ = absolute acceleration response spectrum

$PSV = \omega.SD = (2\pi/T)\,SD$ = pseudo-relative velocity spectrum

$PSA = \omega^2.SD = (2\pi/T)^2\,SD$ = pseudo-relative acceleration spectrum.

In eq. (1), $\omega = 2\pi/T$ is the circular frequency of the oscillator whose spectral ordinate is being computed for the damping ratio ζ and the motion y"(t).

Figure 1 depicts the results of some response spectra computations (PSV) in the log-log tripartite graph. The main advantage of this type of analysis (frequency domain) is the possibility of showing in only one diagram several response calculations in the time domain, each one being a function of the characteristics of the excitation, y"(t), and the properties of the system (ω, ζ). Furthermore, the use of pseudospectra -as defined above- instead of true response spectra, eases the cost and complexity of the calculations by assuming a quasi- linear response of the oscillator, which works then as an undamped elastic spring.

From the aspect of the spectral curves of the accelerogram in the trilogarithmic diagram, it becomes obvious that the real irregular contours of the response espectra can be "linearized" for design purposes (fig. 2). Thus some "geometrical shapes" for the design response spectra, that may or may not depend from the geotechnical characteristics of the site, are obtained. Such spectra consist of three regions clearly differentiated: high- frequency region (acceleration zone, A), intermediate-frequency region (velocity zone, V) and low-frequency region (displacement zone, D). In the following, only the latest two regions of the spectrum are dealt with.

2.- Spectral analysis of the ground motion in the long period range. Governing factors

The engineering characterization of the ground motion in the long period range is important for structures with high natural period (bridges, base-isolated structures, flexible high-rise buildings, etc.).

The design of all these structures varies with respect to the conventional design in two fundamental aspects:

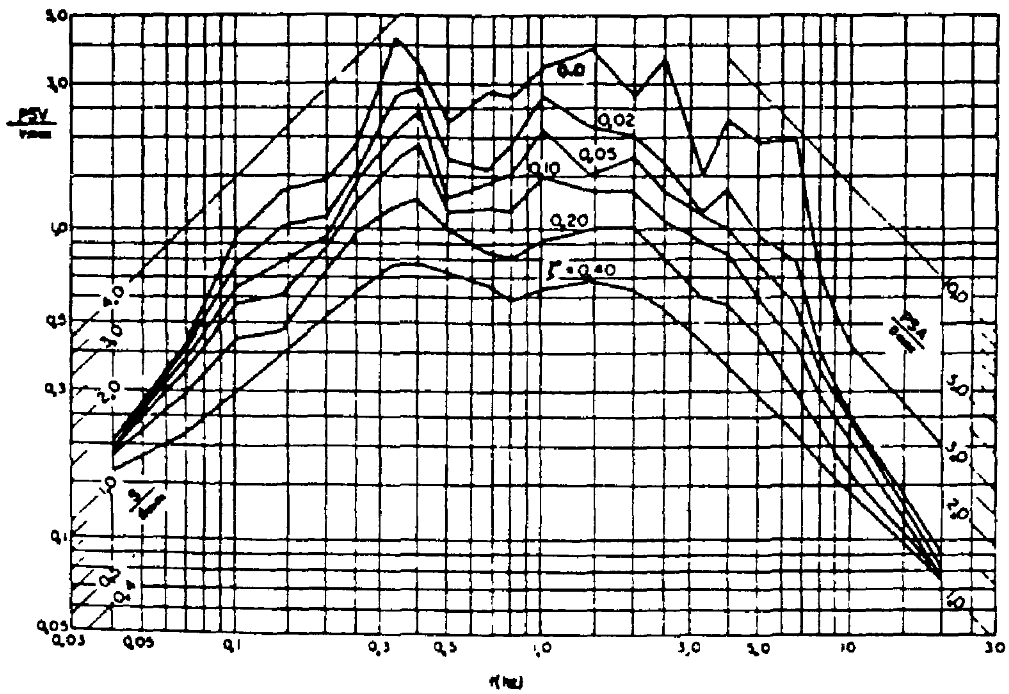


Fig. 1.- Response spectra plotted on the tripartite log-log diagram.

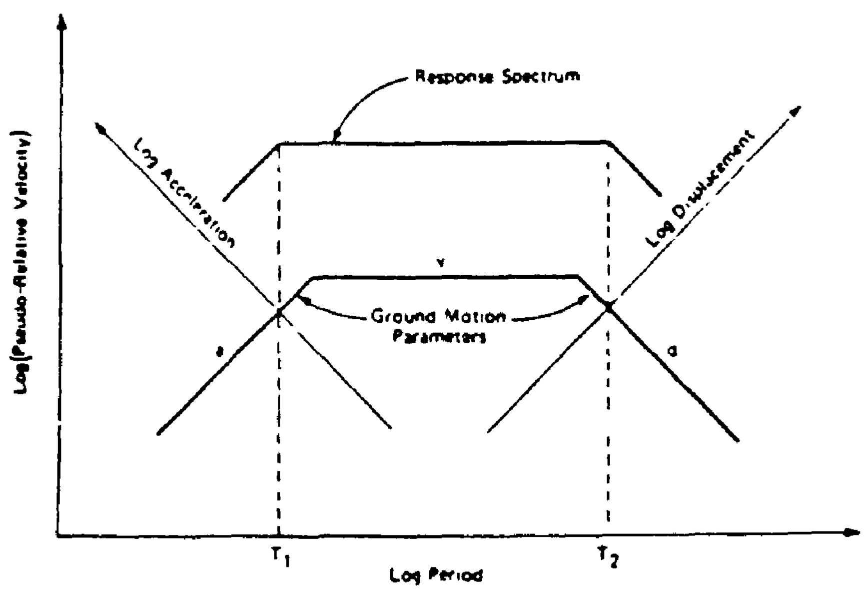


Fig. 2.- Derivation of design response spectra from peak ground motions.

a) the uncertainties inherent to the recording and correcting processes of accelerograms are greater in the region of high periods.

b) strictly speaking, the definition of the seismic actions for the long period range must be based on the velocity and displacement regions of the design response spectrum.

The above considerations lead to the conclusion that, for long period motions and/or structures, the velocity (or the displacement in the case of very long periods) is the correct reference parameter to be used. If the system is linear, the response spectrum approach is applicable and allows us to make a quick estimation of the seismic behavior of the structure. Nevertheless, such a behavior is affected by several factors, namely:

* Source-and-path-dependent factors:
    - magnitude
    - epicentral distance
    - type of earthquake

* Site-dependent factors:
    - local geology
    - geotechnical properties of soil profile

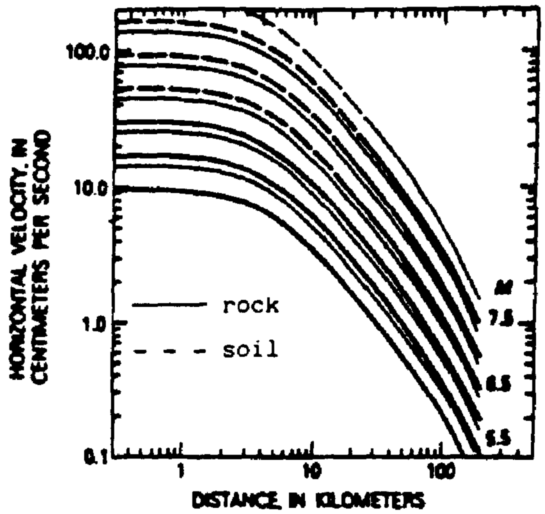
* Computation-dependent factors:
    - digitization of record
    - initial conditions of motion
    - integration algorithm

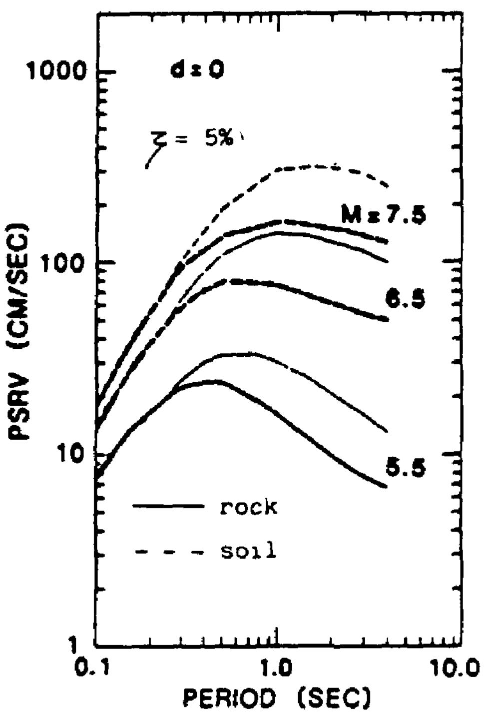
Next, all these items are briefly analyzed and their relative influence on the seismic response spectra is evaluated.

3.- Influence of magnitude and epicentral distance

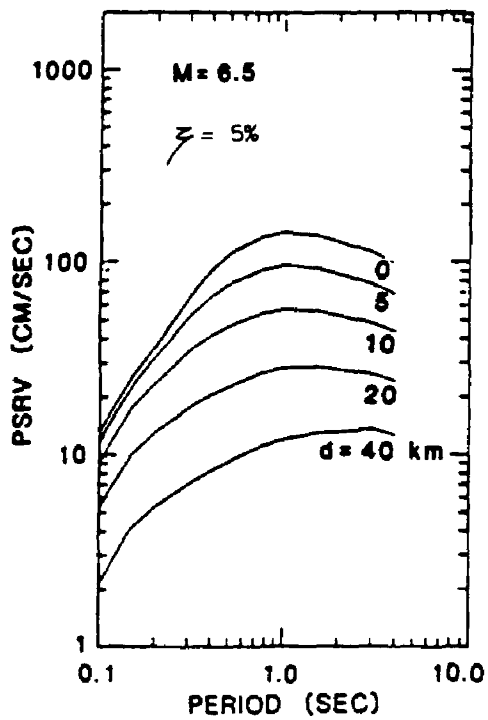
The magnitude and epicentral distance have a dual effect on the ground motion. First, the attenuation curves for the peak velocity clearly depend on the magnitude both for soil and rock layers (Fig. 3). Second, for a given site geology, the spectral ordinates depend on the magnitude and the distance to the source. Figure 4 exemplifies these points with regard to the relative pseudovelocity spectrum.

Fig. 3.- Attenuation relationship for peak horizontal velocity at rock and soil sites (Joyner and Boore, 1982)





(a)



(b)

Fig. 4.- a) Predicted pseudovelocity response spectra of horizontal motion for zero distance and various values of moment magnitude.

b) Predicted pseudovelocity response spectra of horizontal motion at soil sites for a moment magnitude of 6.5 and various distances (Joyner and Boore, 1982)

In addition, the following considerations can be taken into account:

a) As far as velocity is concerned, the influence of the magnitude on the attenuation laws in stronger than for the acceleration.

b) Response spectra in the long period range are very sensitive to variations in the magnitude and/or epicentral distance of the earthquake.

c) For near-field records and long rupture zones within the fault, the epicentral distance is a rather inadequate parameter, and the relationships shown in Figures 3 and 4 must be used with caution.

Therefore, it can be concluded that the shape of the spectra depends strongly on magnitude, epicentral distance and site conditions, indicating that the common practice of scalıng a fixed spectral shape by a peak motion parameter is fundamentally incorrect, and may cause serious error in the long period region of the spectrum.

4.- Influence of the type of earthquake

Al' the facts stated in the previous paragraph are strictly valid only for shallow earthquakes, since they are derived basically using the data set of Californian earthquakes. Deep-focus earthquakes (subduction-zone earthquakes) require a specific study. In general these earthquakes exhibit a poorer content on surface waves, which results in lower spectral ordinates for high periods. As a consequence, the mean spectra and attenuation laws for subduction-zone earthquakes must be derived independently, including the focal depth as an additional parameter (Ref. 4).

In the vicinity of the source other effects, such as the directivity of the fault (Doppler effect), become increasingly important and give way to low-frequency velocity pulses (fling), more damaging than the acceleration pulses (Fig. 5). All that leads to a spatial variation of the response spectrum of the earthquake, as a function of the relative positions of the epicenter and the recording station.

5.- Influence of the local geology

This effect is very significant for earthquakes recorded far away from the source on soft soil sites. In that case the low- frequency region of the spectrum becomes greatly amplified and pseudo-resonance phenomena take place between the input predominant frequency and the natural frequency of the layer. In situ performance of soil deposits corroborate this statement, as has been repeatedly observed, particulary in the recent catastrophic events of Michoacán (1985) and Loma Prieta (1989).

Under these conditions, the phenomenon of "progresive collapse" of yielding structures founded on soft soils becomes particularly important. As Figure 6 illustrates, this phenomenon is entirely due to the variation in shape of the spectrum with soil conditions. When the excitation goes on, the natural period of the cracked structure becomes progressively coupled with the predominant period of the input. As a result, the spectral amplification increases with the duration of shaking (normally high in these situations), and so does the damage to the structure.

6.- Influence of the digitization errors

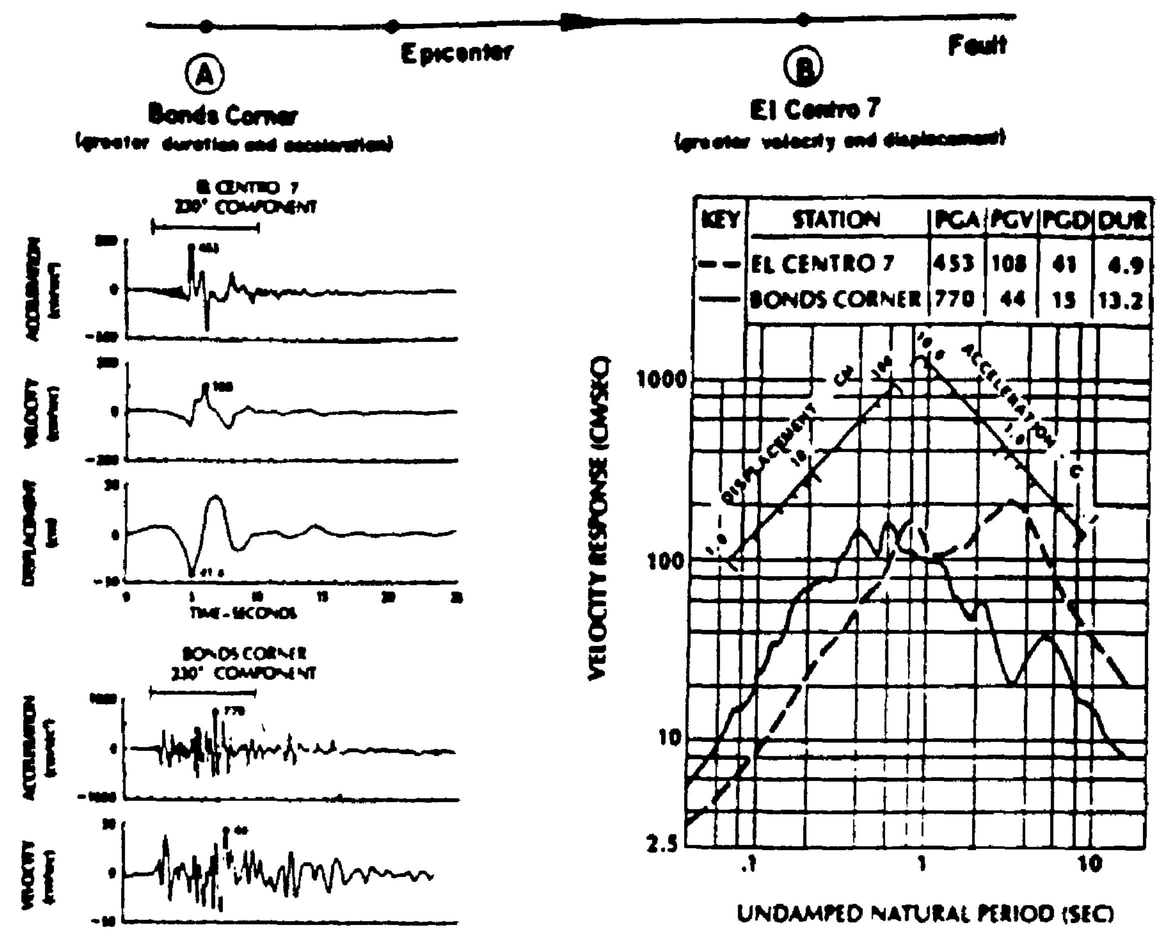
The main source of long-period errors due to the processing of the accelerograms is the digitization step of the records. Figure 7 shows schematically the effects of the digitization procedure in the manual case. The human error of digitization comes in the form of a high-frequency random error (operator- dependent) superimposed to the curved trace resulting from averaging the baselines of the digitization samples. Precisely this false baseline (should be a straight line), constitutes a low-frequency systematic error (Fig. 8) introduced by the digitizing machine itself. Furthermore, the noise associated to this error is magnified by repeated integration of the accelerogram in order to obtain velocities and displacements of the ground.

To correct the digitization error, a high-pass filter (rectangular or Ormsby filter; Fig. 9) is applied to the signal. The characteristics of the filter (f_R, f_c) depend on the signal-noise relationship and the level of noise associated to the digitization system itself.

Since in the region of high periods signal and noise levels have similar amplitudes, one must be careful because filtering in excess may eliminate valid information, uncontaminated by the digitization process. For this reason, the calibration data of the digitization system constitutes the basic factor for determining the range of reliable frequencies of the record.

As an example, Figure 10 shows, in the tripartite diagram, the mean noise spectrum of the automatic digitization system used in CSMIP (Ref. 8). Such an spectrum was derived after digitizing the two fixed traces of analog acceleration records (straight lines), and considering one of them as a signal.

The curve of Figure 10 is very useful for interpreting of accelerograms, simply because beyond the cross-point of the signal and noise spectra the ground accelerations are not recoverable from the record, as they are undistinguishable from the noise of the system.



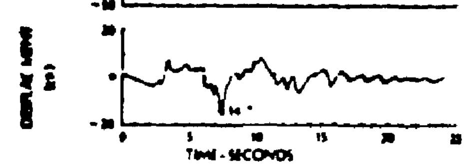


Fig. 5.- Directivity effects in near-field strong ground motion (Singh, 1981).

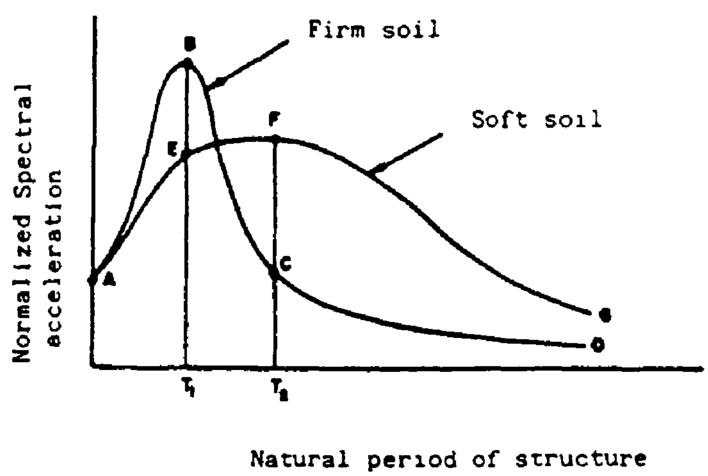
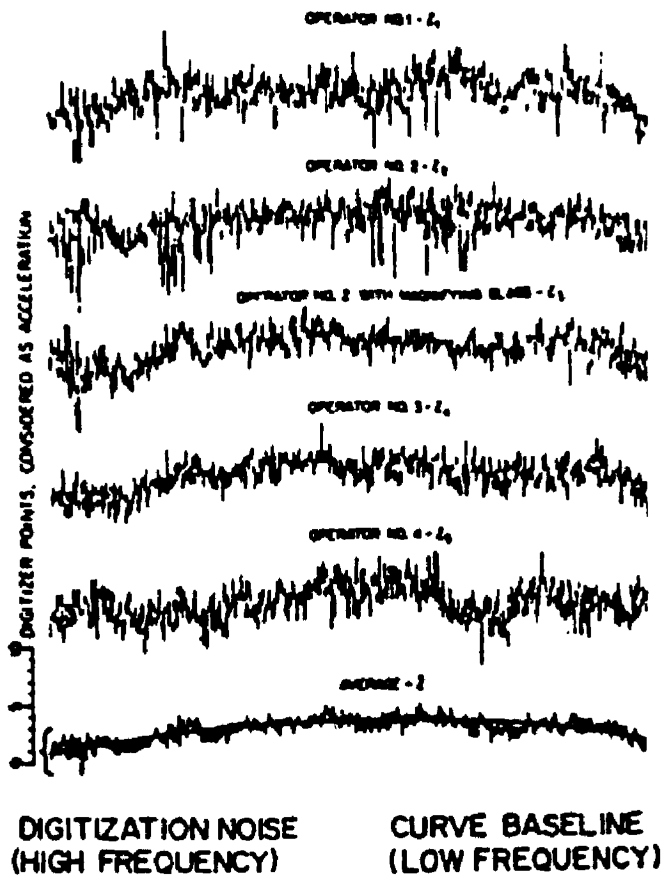


Fig. 6.- Mechanics of the "progressive collapse"phenomenon (Ohsaki, 1969).



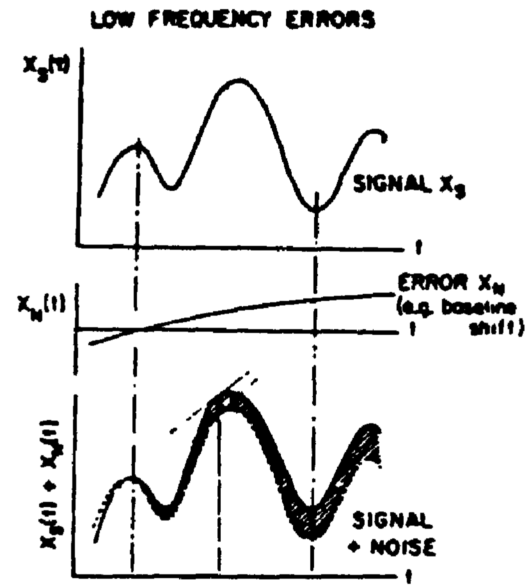


Fig. 8.- Baseline error in accelerogram digitization (Hudson, 1979).

Fig. 7.- Digitization of a straight line showing operator random errors (Trifunac, Udwadia and Brady, 1973).

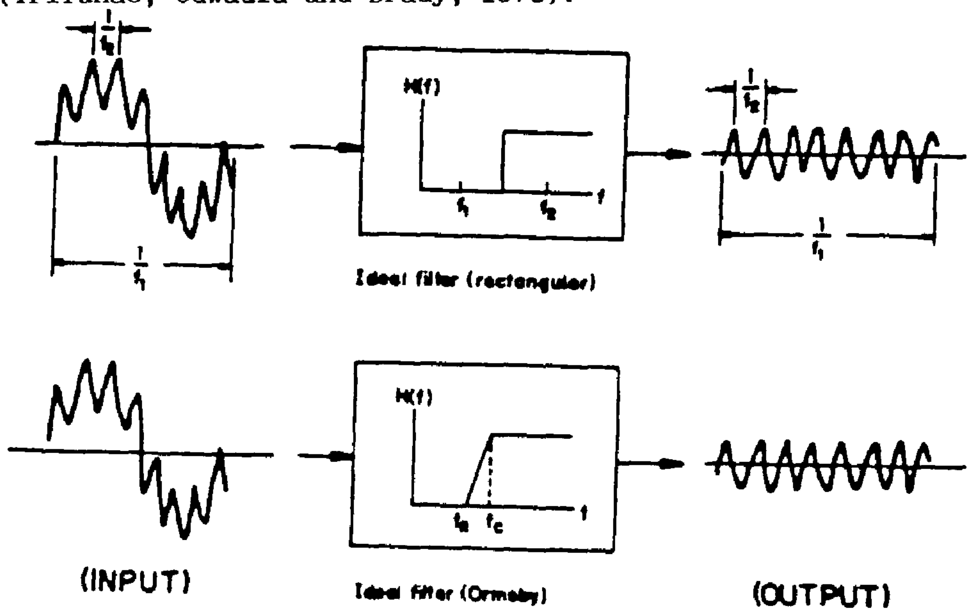


Fig. 9.- Some ideal high-pass filter types (Hudson, 1979).

7.- Influence of initial motion conditions

By integrating the differential equation (1) the following expression for the relative displacement time history is obtained:

$$u(t)=u_t+u_f=\left(\frac{1}{\omega_D}\int_0^t a(t)e^{-\omega\zeta(t-\tau)}\sin\omega_D(t-\tau)d\tau\right)+\left(\frac{u(0)+u'(0)\zeta\omega}{\omega_D}\sin\omega_D t+u(0)\cos\omega_D t\right) \quad (2)$$

where $\omega_D = \omega\sqrt{1-\xi^2}$ stands for the damped natural frequency of the oscillator and u(0), u'(0) are the initial conditions for the motion of mass m. The physical existence of such conditions in optical accelerographs can be explained by analyzing the way of functioning of these instruments. As for levels of signal which fall below the prefixed thereshold level the instrument is not triggered, unavoidably that portion of the accelerogram remains unrecorded, originating some (unknown) values of the ground and the mass motion for zero time. The relationship between the input motion and the motion of the oscillator at t = 0 depends on the mechanical properties of the latter, and can be expressed as follows:

$$U_0 = u(0) = f(d_0, v_0 ; T, \zeta) \quad (3\text{-}1)$$

$$U'_0= u'(0)= g(d_0, v_0; T, \zeta) \quad (3\text{-}2)$$

in which V_0, d_0 are, respectively, the initial velocity and the initial displacement of the ground (for t_0 = triggering time of the apparatus).

Equations (3) are plotted on Figure 11 for the case of sine-wave excitation (Ref. 1). As can be seen, for long periods (T_g/T 0) the asymptotic relations:

$$u(0) = -d_0 \quad (4\text{-}1)$$

$$u'(0) = -v_0 \quad (4\text{-}2)$$

are satisfied, regardless of the damping level. These findings agree with previous data reported by other researchers (Ref. 6).

The standard method for calculating response spectra assumes "at rest" initial conditions:

$$u(0) = u'(0) = 0 \quad (5)$$

Comparing with equations (4) it is concluded that such a procedure applies only to high-frequency systems (rigid structures), for which the free vibration phase of the motion can be neglected. For other types of systems (flexible structures) the initial conditions for base motion -which in turn

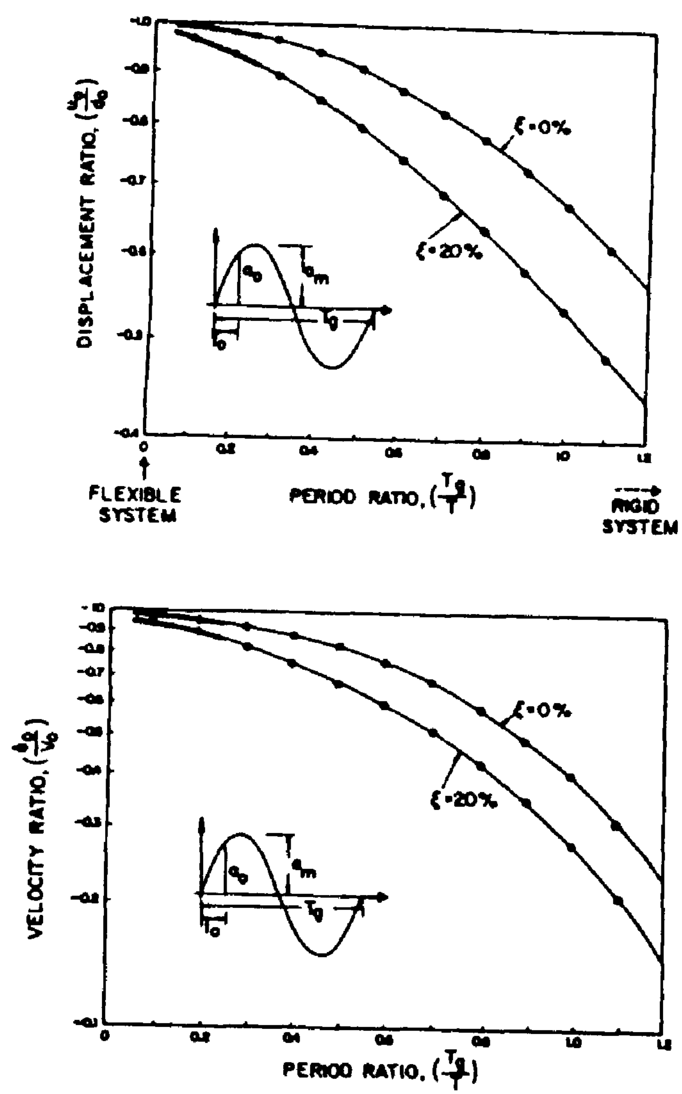


Fig. 11.- Ratio of initial motions of the oscillator to initial motions of the ground for sinusoidal acceleration wave (Blázquez and Kelly, 1988).

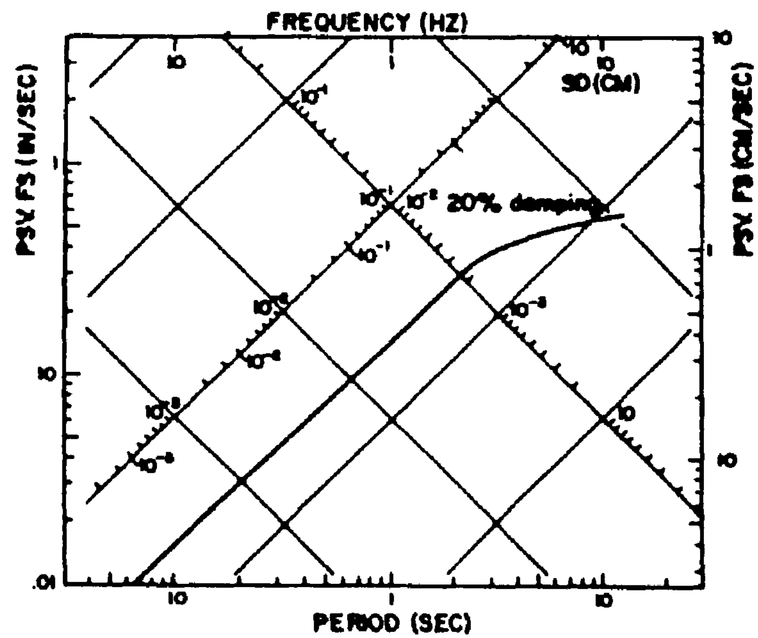


Fig. 10.- Digitization noise spectrum at CSMIP automatic system (Shakal and Ragsdale, 1984).

depend on the characteristics of the accelerograph and the trigger level- should be taken into account.

Ventura and Blázquez have reported recently (Ref. 11) a rather comprehensive study on the sensivity of the true response spectra (SD, SV and SA) to the initial conditions of the motion, for the case of sinusoidal excitation. Figures 12 and 13 show some results. The response spectra are plotted in a non dimensional form, employing the peak velocity (Y') and peak displacement (Y) of the ground as normalizing factors. On the other hand, the initial conditions of the oscillator are introduced by means of the non-dimensional parameters:

$$\alpha = -\frac{\omega^2 U_0}{Y''} \qquad (6\text{-}1)$$

$$\beta = -\frac{\omega U_0'}{Y''} \qquad (6\text{-}2)$$

where Y" is the maximum acceleration of the ground. It is observed that non-zero initial conditions greatly distort the spectral ordinates within the long period range.

In the same work cited above (Ref. 11) the authors have proposed two approximate methods to correct standard response spectra ($U_0=U'_0=0$) for the effect of non-zero initial conditions in the oscillator, assumed to be known ($U_0 > 0$; $U'_0 > 0$).

These two approaches, denominated SAV and SRSS methods, can be summarized as follows (u_t = forced vibration part of displacement time history u(t), u_f = id. id. free vibration part; see eq. 2)

SAV Method (Fig. 14):

$$SD = |u(t)|_{max} \approx |u_t| + |u_f| \qquad (7\text{-}1)$$

SRSS Method (Fig. 15):

$$SD = |u(t)|_{max} \approx (|U_t|^2 + |u_f|^2_{max})^{1/2} \qquad (7\text{-}2)$$

whereas the conventional method is:

$$SD = |u(t)|_{max} = |u_t|_{max} \qquad (7\text{-}3)$$

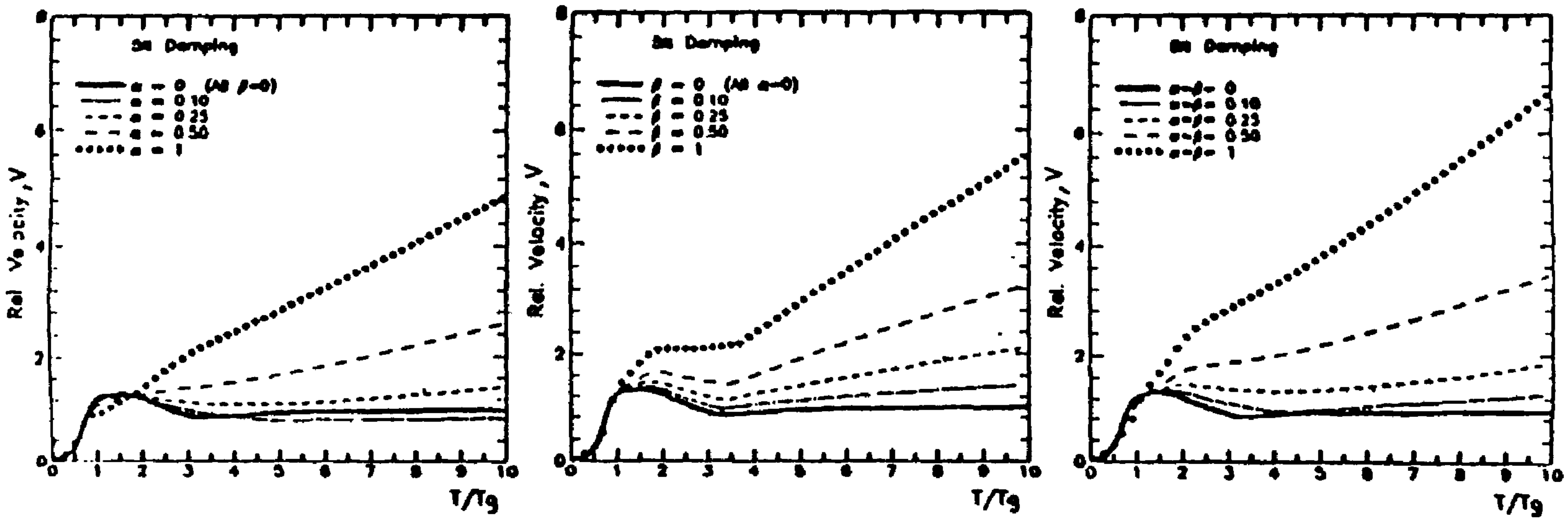


Fig. 12.- Sensivity analysis of velocity response spectra to initial base motion of oscillator. Sinusoidal input. (Ventura and Blázquez, 1990).

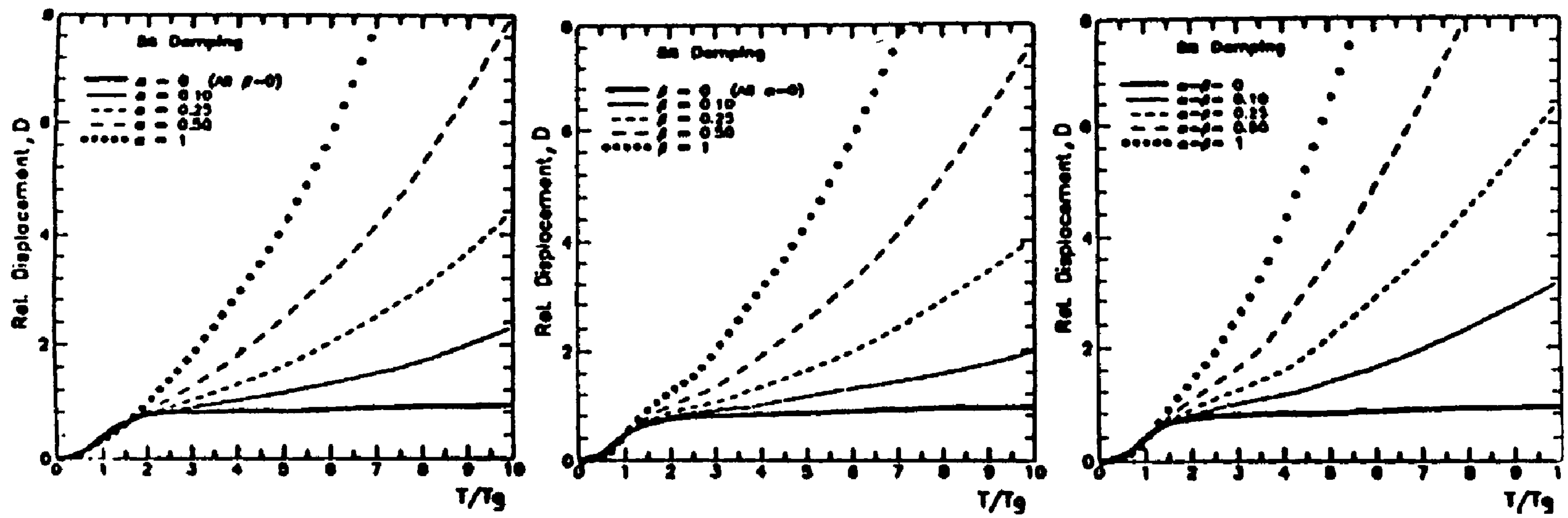


Fig. 13.- Sensivity analysis of displacement response spectra to initial base motion of oscillator. Sinusoidal input. (Ventura and Blázquez, 1990).

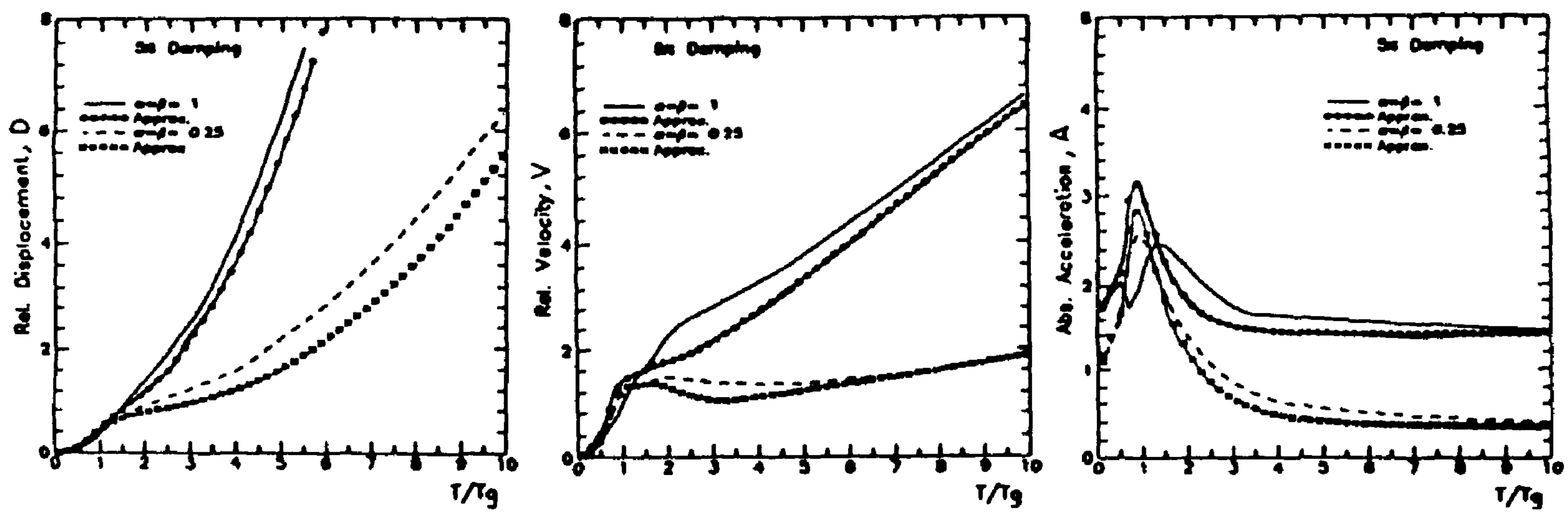


Fig. 14.- SAV Method for correctin response spectra for initial base motion of oscillator.
(Ventura and Blázquez, 1990).

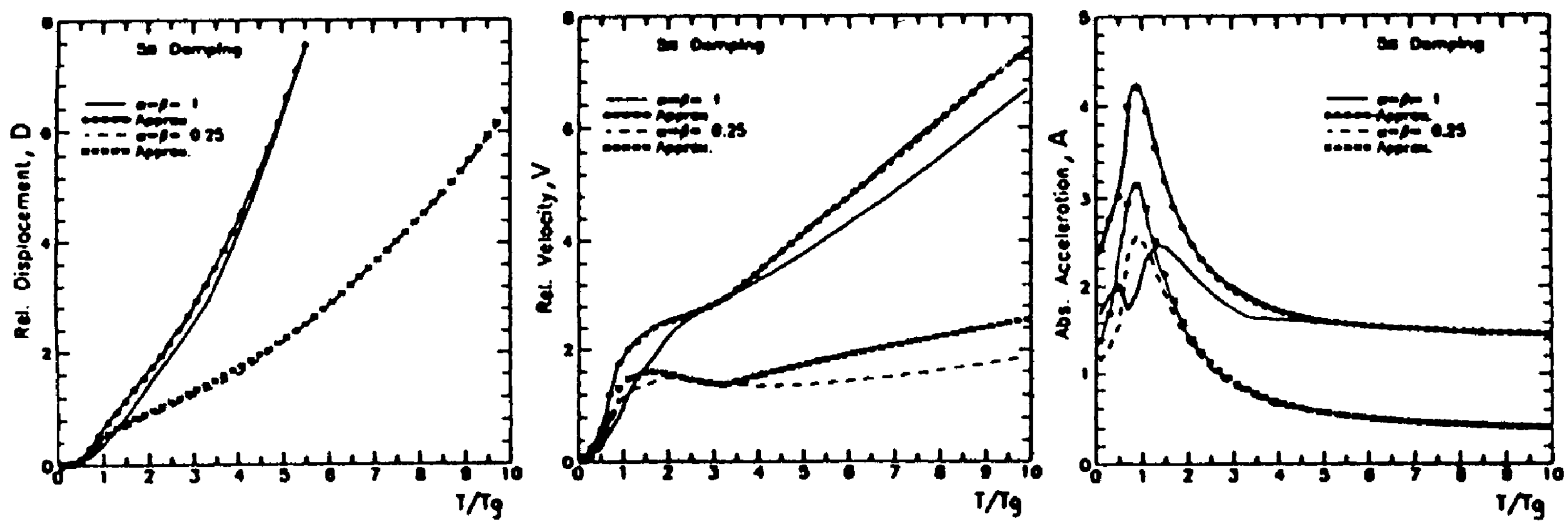


Fig. 15.- SRSS Method for correcting response spectra for initial base motion of oscillator. (Ventura and Blázquez, 1990).

Preliminary results, obtained for sine wave inputs, are encouraging for long period systems, specially with the SAV Method.

8.- Influence of computational algorithm

For a given digitized accelerogram, the error associated with the forced part of the solution of equation (1) comes a result of two facts:

a) the assumption made on the variation of a(t) between the sampling points

b) the amplitude of the time integration step, $\Delta\tau$, used to evaluate Duhamel's formula.

Frequency domain analysis of time integration operators illustrates their performances at different frequency regions. Figure 16 (adapted from Preumont; Ref. 7) clarifies this point. In this figure the displacement and velocity transfer functions for various linear integration operators (recursive filters) are portrayed. It is concluded from Fig. 16 that, in general, Nigam-Jennings and Newmark β= 1/4 methods can be used advantageously in the long spectral range, since they deamplify high frequency noise. However, from a practical viewpoint the errors associated with the size of the integration step are very critical, since there are operators which become unstable as the ratio $\Delta\tau/T$ increases.

Blázquez and Kelly (Ref. 1) have conducted sensitivity analysis of the accuracy of the numerical spectral response for a simulated earthquake with 10 sec. duration and no initial conditions. Five algorithms have been tested for T = 5 sec. and ζ = 0%, namely: 3rd and 4th order Runge Kutta methods, Newmark- β = 1/4 and β= 1/6 methods, and Nigam-Jennings method (standard in U.S. processing of strong-motion records). For $\Delta\tau$= T/20 the maximum relative error (in %) of the peak response (forced vibration) computed at integration points of Duhamel's formula is as follows: for the displacement: RK-3=1.56; RK-4=0.9; N-1/4=1.76; N-1/6=0.87; N-J=0.89, whereas for the velocity: RK-3=2.99; RK-4=2.36; N-1/4=1.87, N-1/6=2.09; N-J=2.36. If $\Delta\tau$= T/20, these figures are reduced by a factor of about 4 or 5. Although these results are only preliminary, they seem to indicate that the 4th order Runge Kutta method and the Nigham-Jennings method perform similary and are more accurate than the other computational algorithms at relatively large integration intervals, $\Delta\tau$, where stability problems often arise. Besides, for a given $\Delta\tau$, the velocity response consistently shows more error than the displacement response, regardless of the method ussed.

In summary: integration of a seismic signal is a process equivalent to low-pass filtering, and therefore enhances both long period errors and high-frequency noise which may be present in the record. Nevertheless, integration errors themselves are less critical than digitization and/or initial conditions errors.

9.- Design recommendations for base-isolated structures

Very recently, in the 1990 version of the SEAOC Code (California), an Appendix (L) named "Tentative General Requirements for the Design and Construction of Seismic-Isolated Structures" has been included. This Appendix has been synthesized from two source documents elaborated by ad hoc working groups of SEAOC, in particular the paper entitled "Tentative Seismic Isolation Design Requirements", published by the Northern Section of SEAOC (Sept. 1986).

In the final report two possible methods for determining the design earthquake for base-isolated structures are recommended:

a) computing the minimum lateral displacements which the structure must be able to take in the horizontal plane (in two orthogonal axes) and, from them, computing the minimum shear forces acting on the structure, both above and below the isolation system (pseudostatic method).

b) computing, by dynamic methods either in the frequency (elastic superstructure) or time domain (inelastic superstructure), the maximum forces and displacements of the response of the structural system to the seismic action.

In the first type of analysis, suitable for rigid buildings founded on rock of stiff soil far away from active faults, the minimum horizontal displacement (in inches) in the j-direction is given by the formula:

$$(D_{min})_j = \frac{10ZNS_I(T_I)_j}{B} \qquad (8)$$

in which:

Z =seismicity factor of the zone

N =factor of proximity of the structure to active faults

S_I =site-soil profile factor (varies between 1, for rock, and 2.7 for soft clays with thickness 40ft)

$(T_I)_j$ = period of seismic-isolated structure, in seconds, in the j-direction

B =damping factor related to the effective damping of the isolation system.

The total maximum displacement, in inches, of the structure in the j-direction is estimated as:

$$(D_{max})_j = 1.5\,(D_T)_j \qquad (9)$$

where $(D_T)_j$ depends on the minimum displacement, $(D_{min})_j$, and the mechanical characteristics of both the structure and the isolation system.

For base-isolated structures meeting one or several of the conditions specified below:

a) $T_I > 3$ sec

b) soft foundation soil

c) located in areas of high seismicity or closer than 15 km from some active fault,

the SEAOC Recommendations require to use dynamic analysis, either time history or response spectrum analysis. In the second case, the calculation is based, in principle, in the ATC normalized acceleration spectra, and not in the velocity and displacement acceleration spectra, as should be desirable.

The initial version of this document (Sept, 1986) contained provisions for calculating the design response spectra, by scaling the ATC spectra with the factor $D_{max}=\{(D_{max})_j\}_{max}$, a method extremely uncertain, if not incorrect, as has been demonstrated herein. In any case, that procedure and equation (8) do not take into account the dependence of the long period spectral ordinates on important factors, such as magnitude, epicentral distance, earthquake type, record processing, etc., and thus it must be applied with a rather conservative criterion.

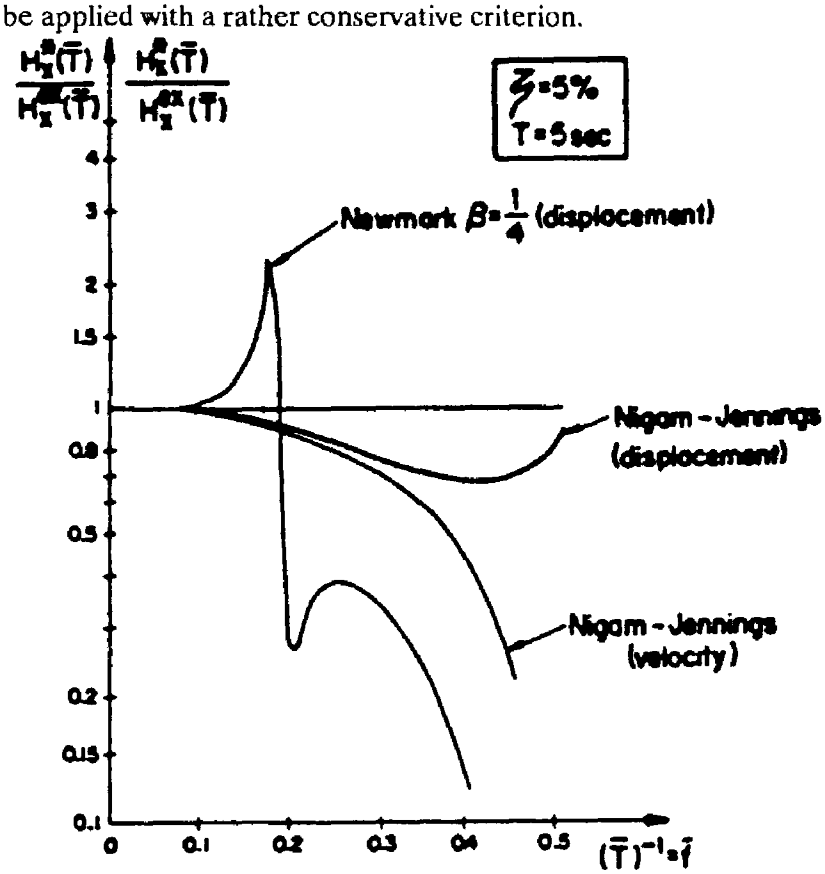


Fig. 16.- Frequency domain analysis of time integration operators used for computation of response spectra (Preumont, 1982).

10.- CONCLUSIONS

In the seismic design of long period systems the following points should be taken into consideration:

a) Digital accelerographs are preferred to optical ones for measuring accurately acceleration signals, as well as their integrals.

b) For analog accelerograms the digitization process introduces both high and low-frequency errors. High-frequency noise poses a severe limitation on the computed displacement records (T < 16 sec).

c) Spurious long period noise (due to baseline distorsions) is enhanced by integration of the accelerogram traces. The integration process is equivalent to low pass filtering of the signal.

d) For long period systems the hipothesis of zero-initial conditions is quite incorrect, and introduces contaminating noise which magnifies the spectral velocities and (even more) the spectral displacements.

e) The fact of leaving aside initial conditions yields the asymptotic limit $(PSV)_{T=\sigma} \rightarrow v_0$, instead of $(PSV)_{T=\sigma} \rightarrow 0$; the lower the damping the greater the deviation from the theoretical behavior.

f) Velocity and pseudovelocity response spectra are divergent for low-frequency/large damping systems, and are not exchangeable (Ref. 2).

g) All integration schemes can introduce errors in long period response spectra,although those that deamplify high-frequency noise are preferable. The greater the integration interval the greater the error.

h) Spectral ordinates for high periods are very sensitive to magnitude, epicental distance, mechanics of the earthquake (within the source zone) and site conditions. The common practice of scaling a fixed spectral shape by a peak motion parameter is misleading in this region.

i) Design Recommendations for Base-Isolated Structures are still being developed and many points need further clasification. In particular, spectral analysis of such structures (in the velocity or displacement region) still remains not well understood.

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