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Scattering of the anelastic response to simulated ground motions

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ABSTRACT: Three series of ten accelerograms were generated from the elastic normalized spectrum of the G.N.D.T. Italian Recommendations using the SIMQKE stationary-modulated procedure. The accelerograms were applied to seven different elasto-plastic S.D.O.F. systems. The structural responses were statistically evaluated, showing a considerable scattering. The scattering was attributed to various "dissymmetries" recognized in the signal time-histories. Some techniques were proposed and applied to analyse the dissymmetries. The main acceleration-impulse time-duration was individuated as the major cause determining the behaviour of the most "anomalous" accelerograms. At the same time, a statistical evaluation of the spectral composition of the simulated signals was performed, showing a limited influence on the overall non-linear response.

1 INTRODUCTION

The dynamic analysis of non linear systems requires a probabilistic definition of *seismic excitation. Thus the use of* artificially generated ground motions is necessary. Various techniques were defined to this purpose. Every procedure is characterized by a different stochastic definition of the intensity, frequency containt and time-duration properties of the generated signals.

A largely applied technique is the "uniformly modulated" process which restricts the non-stationarity to the only intensity parameter. The generation of ground motion is performed starting from a given power spectrum density function S(w) of a stationary Gaussian stochastic process, and modulating the amplitude with an envelope time-dependent function. This method, for example, is applied by the well-known automatic program SIMQKE (Gasparini & Vanmarcke 1976). Such a simulation procedure gives satisfactory results for linear-elastic analyses but can cause considerable scattering for non-linear applications (Carli 1987, Cerami & Ricciardi 1989). At the same time the great simplicity of the above technique makes it competitive compared to "non-uniformly modulated" processes (Kanai 1957, Priestley 1967, Kiureghian & Crempien 1989). These last methods take into account non-stationarity also in terms of frequency, according to the real nature of seismic ground motions.

The most general non-uniformly modulated models are the "evolutionary" ones presented by Priestley, where the acceleration time-history is defined by:

$$x(t) = \int_{-\infty}^{+\infty} [m(w,t)e^{iwt}]\ dZ(w) \qquad (1)$$

where: dZ(w) is a complex random process and m(w,t) is a deterministic function, representing the power spectral density time-modulation in a given frequency band dw centered on w, S(w)dw.

Experimental research (Pinto & Pegon 1991) showed that the non-stationary characteristics of ground motion can influence the non-linear response of structures. The values of the mean and of the maximum displacements due to non-stationary inputs are generally greater than the values obtained with stationary inputs generated on the basis of the same linear elastic response spectrum. In an uniformly modulated process, where the modulating function is only time dependent, the acceleration time-history is given by:

$$x(t) = m(t)\int_{-\infty}^{+\infty} e^{iwt}\ dZ(w) \qquad (2.a)$$

or

$$x(t) = m(t)s(t) \qquad (2.b)$$

where: s(t) is a stationary gaussian zero mean process.

The aim of this research is a critical evaluation of the uniformly modulated methods for the analysis of mechanically non-linear structures, in view of design applications. In particular, three series of ten accelerograms generated with the SIMQKE procedure were considered. The response of various non-linear S.D.O.F. oscillators was statistically evaluated, showing considerable scattering. This phenomenon was studied taking into account the specific characteristics of every signal. Some techniques of investigation were defined to this purpose, mainly to show possible "anomalies" of the single accelerograms compared to the main values of the response distribution.

2 THE ANALYSIS OF THE STRUCTURAL RESPONSE TO THE SIMULATED ACCELEROGRAMS

The three series of ten artificial accelerograms were generated according with the three different intensity envelope functions presented by the SIMQKE procedure: exponential, compound and trapezoidal.

The ground-type "S2" elastic-normalized response spectrum of the Italian "G.N.D.T." Recommendation (1984) was adopted as reference spectrum for the signal generation (Figure 1).

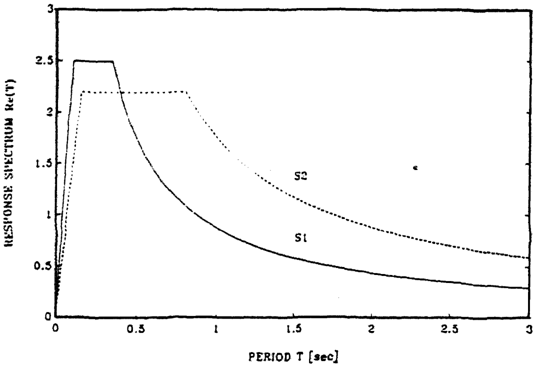


Figure 1. G.N.D.T. Italian Recommendation elastic normalized spectra

The thirty accelerograms were applied to seven different elastic S.D.O.F. systems, characterised by the following vibration periods: T = 0.4, 0.7, 1.0, 1.3, 1.6, 1.9, 2.2 s. Seven elasto-plastic oscillators were then considered, defined by a bilinear force-displacement kinematic hardening constitutive law. The yield threshold "f_y" of every system was fixed at the 20% of the maximum force, "f_{em}", globally registered for the correspondent elastic oscillator.

The responses, in terms of maximum displacements, of both elastic and elasto-plastic oscillators were statistically evaluated. Normal gaussian displacement probability functions for the three different series were defined. Figures 2.a,b, 3.a,b, 4.a,b, show the resulting curves for the elasto-plastic filters, respectively for the exponential (Figure 2.a,b), the compound (Figure 3.a,b) and the trapezoidal (Figure 4.a,b) envelope families.

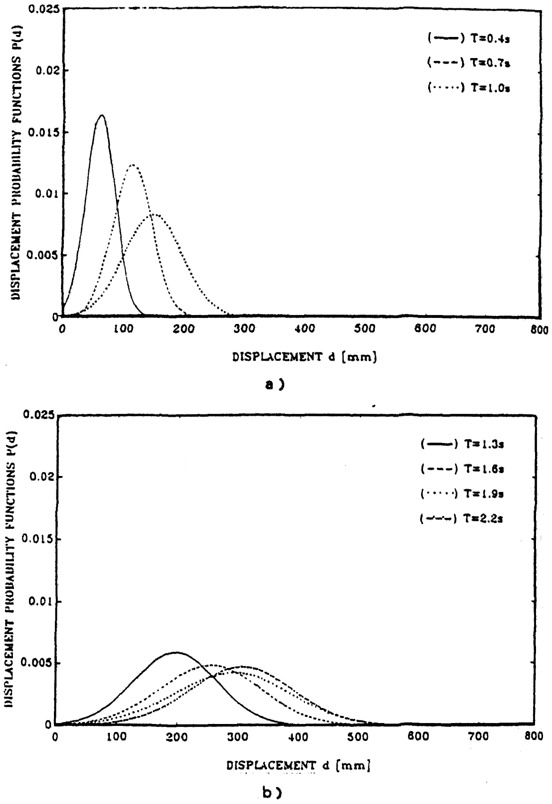
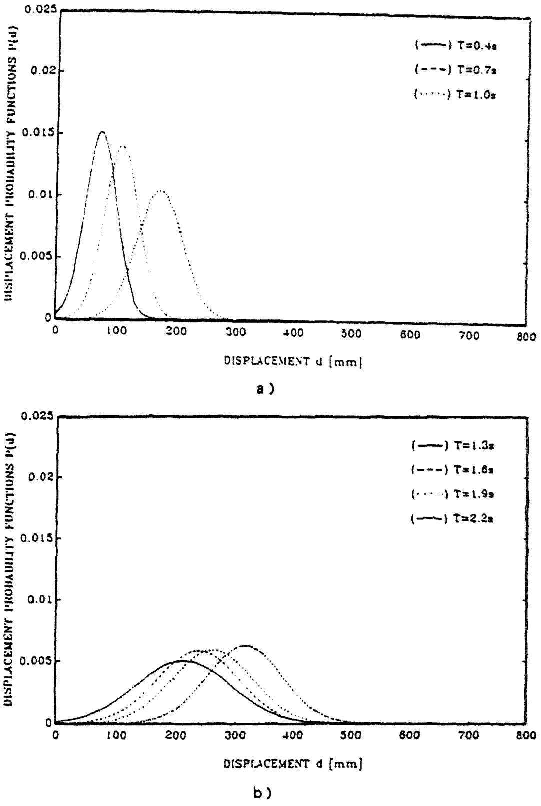


Figure 2. Displacement response probability functions for the exponential family.

The figures show a trend to a progressive flattening of the curves for increasing values of the oscillator periods. This trend is exactly followed for the three lowest periods (Figures 2.a, 3.a, 4.a). Some discrepancies can be observed for the remaining four periods (mainly for T = 1.6 s, in the trapezoidal series, Figure 4.b).

On the whole, however, the probability curves are quite smooth for all the oscillators and the envelope families.

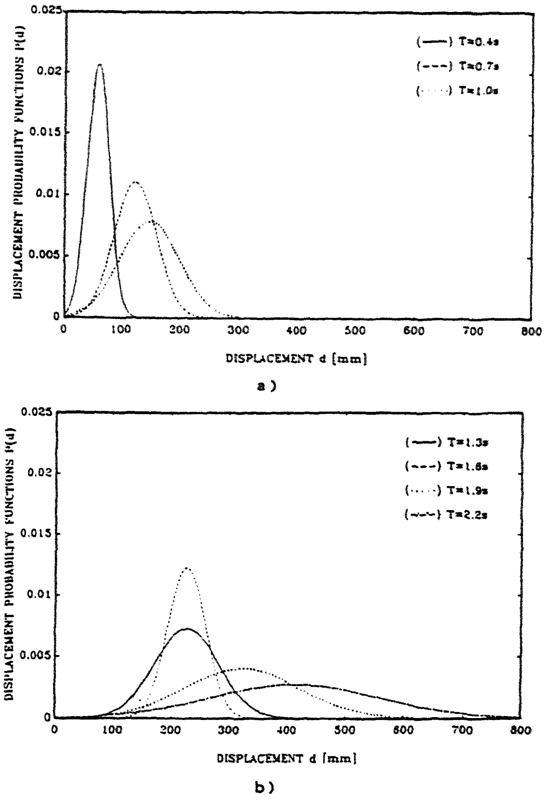
A considerable scattering is found in the elasto-plastic responses, as witnessed by the mean square root values, S_p, of the considered distributions, reported in Table



a)

b)

Figure 3. Displacement response probability functions for the compound family.



a)

b)

Figure 4. Elasto-plastic displacement response probability functions for the trapezoidal family.

1. Here are also presented the mean square root values of the elastic displacement probability functions, S_e, and the values of the ratio $R = S_p/S_e$.

This last is an index that permits to quantify the increase of the response scattering which takes place passing from the elastic to the elasto-plastic systems. For example, in Figure 5 are represented, in superposition, the displacement probability curves for the elastic and elasto-plastic oscillators with T = 0.4 s.

The difference between the narrow shape of the elastic case and the smooth shape of the elasto-plastic one is evident. The values of S_p and of ratio R demonstrate the great statistical sensitivity of the non linear structural response to artificial input signals generated with frequency-stationary procedures, as the SIMQKE one.

This aspect must be carefully considered for design purposes. In particular, from a technical point of view, a considerably large number of such generated artificial input accelerograms must be used to correctly estimate the anelastic structural

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behaviour (Decanini & Parducci 1981). From a theoretical point of view the major interest is connected to the analysis of the causes determining the "anomalous" behaviour of specific signals.

The main cause pointed out (Sorace & Terenzi) was constituted by the presence of considerable dissymmetries between the *positive and negative parts of the signal* time-histories. The dissymmetries concern, in particular, the distribution of the amplitude peaks and the time-extension of the acceleration impulses.

Some investigation criteria were proposed (Sorace & Terenzi) to quantify the level of dissymmetries. The most efficacious seems to be the one using the "positive" and "negative" power spectral density functions, $G^+(w)$, $G^-(w)$, defined as following:

$$G^+(w) = \lim_{T\to\infty} (1/T) \int_0^T R^+(t)\, dt \qquad (3)$$

$$G^{-}(w) = \lim_{T\to\infty} (1/T) \int_{0}^{T} R^{-}(t)\, dt \qquad (4)$$

A direct evaluation of the different "weight" of the positive and negative parts of the time-histories, as a function of frequency, can be obtained by comparing the diagrams of the two functions.

Oscillator	Se	Sp	R=Sp/Se
	EXPONENTIAL FAMILY		
0.4	5.17	24.30	4.7
0.7	8.49	32.40	3.8
1.0	11.70	48.00	4.1
1.3	26.20	67.70	2.6
1.6	11.26	82.70	7.3
1.9	26.50	94.40	3.6
2.2	10.55	84.80	8.0
	COMPOUND FAMILY		
0.4	4.21	26.40	6.3
0.7	7.74	28.60	3.7
1.0	11.74	38.30	3.3
1.3	18.82	79.40	4.2
1.6	30.16	68.30	2.3
1.9	35.90	67.60	1.9
2.2	32.90	63.80	2.0
	TRAPEZOIDAL FAMILY		
0.4	1.36	19.30	14.2
0.7	8.00	36.10	4.5
1.0	11.18	51.00	4.6
1.3	14.68	54.80	3.7
1.6	24.90	32.50	1.3
1.9	19.23	99.60	5.2
2.2	22.64	145.40	6.4

Table 1. Mean square root values of the elastic and elasto-plastic displacement distributions

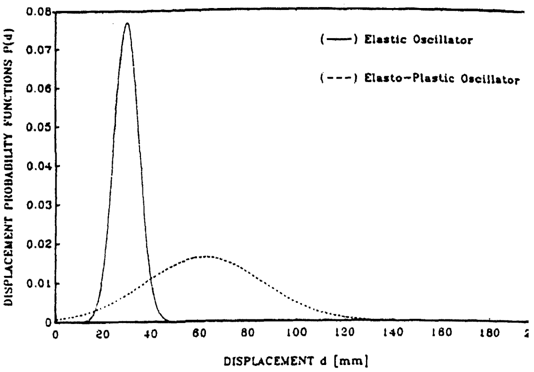


Figure 5. Displacement response probability functions for the elastic and the elasto-plastic oscillators with T = 0.4 s.

Figure 6 shows, for example, the $G^{+}(w)$ and $G^{-}(w)$ functions calculated for the most anomalous accelerogram of the exponential family. The interval considered for the circular frequency w contains the three dominant components of the signal spectral composition.

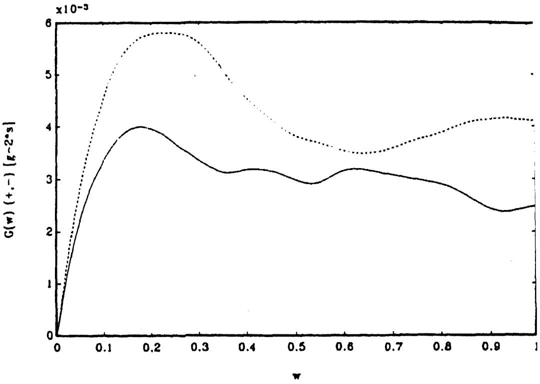


Figure 6. Positive and negative power spectral density functions for the most anomalous accelerogram of the exponential family.

The separation between the two curves quantifies the dissymmetries existing in the signal. Accelerograms giving responses nearer to the distribution mean values are characterized by a much closer correspondence between the two partial functions.

The analysis of the simulated signals by the above techniques directly concerns the acceleration time-history form. On the other hand, the frequency containt is not explicitly taken into account.

Thus, to complete the investigation about the elasto-plastic response, a statistical analysis of the signal spectral composition was performed.

3 STATISTICAL EVALUATION OF THE ACCELEROGRAM FREQUENCY CONTAINT

Figures 7, 8, 9 show the frequency probability curves pertinent to the four signal dominant frequencies, respectively, for the exponential, compound and trapezoidal families.

As a general result, quite large gaussian distributions are registered for the second, third and fourth frequencies. This is a consequence of the specific generation procedure followed by SIMQKE program.

Considerable differencies between the three series can be found by directly comparing the fundamental frequency curves (Figure 10). The level of randomness in the frequency generation process is maximum for the exponential series and minimum for the trapezoidal one. Furthermore, a "transversal" reading of the various curves shows a larger spectral containt for the exponential-shaped time-histories. In fact, this particular envelope function tend to simulate the second group-earthquake ground motions of the well-known classification proposed by Newmark and Roseblueth (1971). This group is characterized by a substantial equipartition of energy over a wide range of frequencies.

An interesting aspect of the fundamental frequency probability curves is represented by the position of the distribution mean values (Figure 10). These are very close for the three envelope series, ranging from about 0.9 Hz to about 1.0 Hz. These values correspond to the descending branch of the reference elastic response spectrum. So, displacement amplification effects, due to resonance-like phenomena, must not be expected, on the average, in correspondence with the maximum spectral ordinates. In a statistical study of non-linear structural problems this can lead to non-conservative results.

Besides, the above frequency interval does not contain the first vibration frequency values typical of "standard" reinforced concrete and steel buildings. The statistical study of the generated signals shows that if a limited group of them is adopted in the analysis, it is possible to obtain only low frequency-dominated input time-histories.

A greater control on the frequency generation process would permit to obtain signals with dominant frequencies of real interest for the specific structural problem under study.

No any correlation between the anomalous response to a signal and resonance effects was found, as a general result of the crossed statistical analysis between the elasto-plastic response and the signal spectral containt.

This confirms the leading role of the time-domain characteristics of the simulated accelerograms on the non-linear structural response definition.

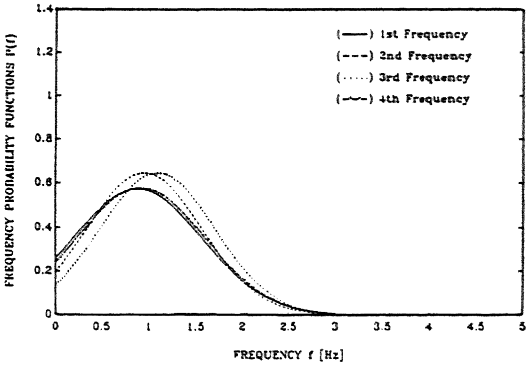


Figure 7. Frequency probability functions for the accelerograms of the exponential family.

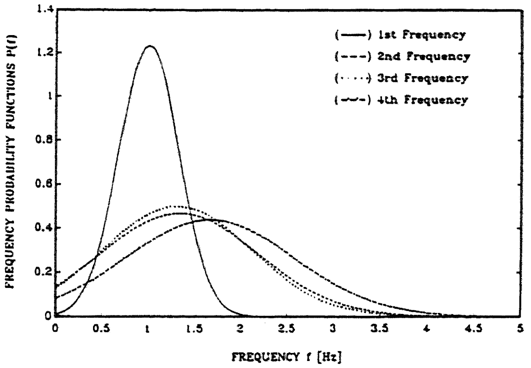
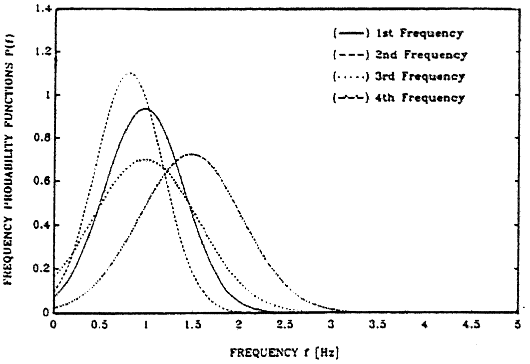


Figure 8. Frequency probability functions for the accelerograms of the compound family.



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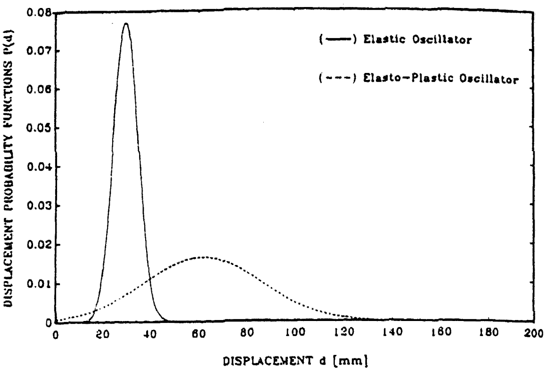

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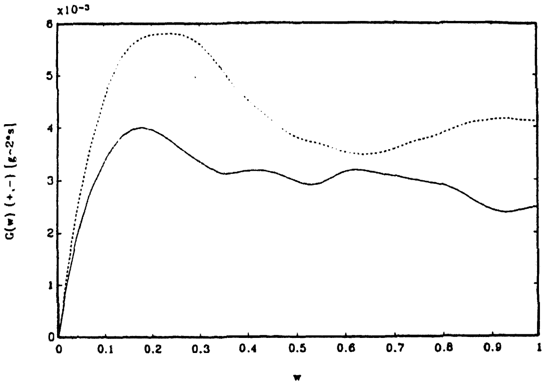

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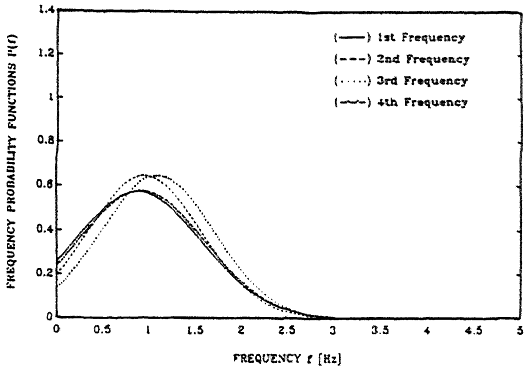

Figure 7. Frequency probability functions for the accelerograms of the exponential family.

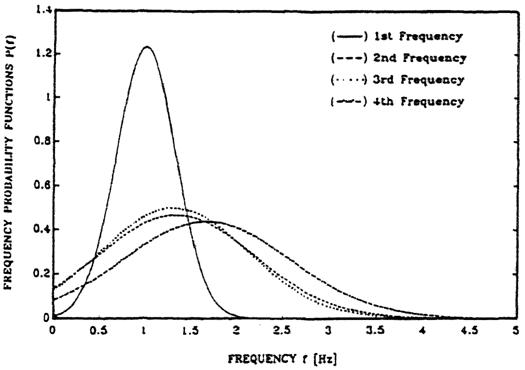

Figure 8. Frequency probability functions for the accelerograms of the compound family.

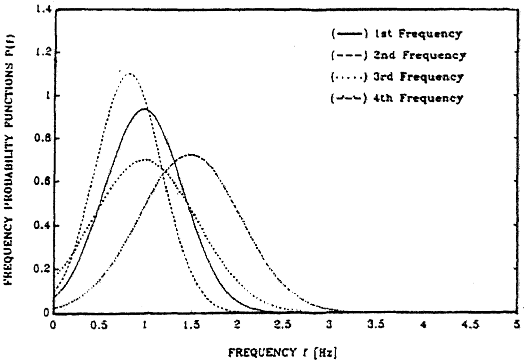

Figure 9. Frequency probability functions for the accelerograms of the trapezoidal family.

This confirms the leading role of the time-domain characteristics of the simulated accelerograms on the non-linear structural response definition.

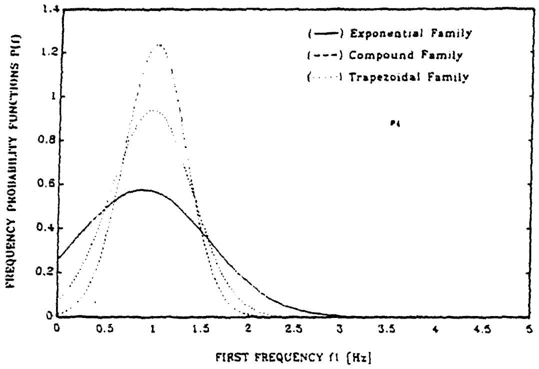

Figure 10. Comparisons between the first frequency probability functions for the accelerograms of the three families.

4. CONCLUSIONS

The investigation criteria defined in a previous work to study the dyssimmetries of simulated accelerograms permitted to point out the acceleration-impulse time-duration as the most influencing element on the structural response.

This was verified also performing a crossed statistical analysis between the displacement response of the considered elasto-plastic S.D.O.F. systems and the signal spectral containt. In fact, as a general result, the anomalous structural response to a single signal cannot be attributed to resonance-like effects.

The frequency composition statistical analysis also put in evidence the particular position of the first frequency-distribution mean values. These are placed in correspondence with the descending branch of the reference elastic response spectrum. As a consequence, non-conservative evaluations of the non-linear structural behaviour for design purposes are possible. A considerable improvement to the SIMQKE uniformly-modulated generation procedure would be represented by a form of control on the frequency-containt definition.

ACKNOWLEDGEMENTS. The present work is included in the research activities developed at the Structural Division of the Institute of Energetics of the University of Perugia, coordinated by Professor A. Parducci.

REFERENCES

Carli, F. 1987. Structural response sensitivity to parameters of modulation functions. Proc. 3th Italian National Congress on Seismic Engineering, Vol.II: 188-198. Rome (in Italian).

Cerami, A. & G. Ricciardi 1989. Generation of spectrum-compatible accelerograms. Ingegneria Simica, Vol.6/3: 12-18 (in Italian)

C.N.R.-G.N.D.T. 1984. Italian technical recommendations for constructions in the seismic areas.

Decanini, L. & A. Parducci. Normalized seismic coefficients of elasto-plastic oscillators for the Friuli 1976 earthquake. Congress on Geodynamics. Udine, Italy (in Italian).

Gasparini, D.A. 1976. SIMQKE: a program for artificial motion generation. Report MIT 07/76, Cambridge, MA.

Kanai, K. 1957. Semi-empirical formula for the seismic characteristics of the ground. Bulletin of the Earthquake Research Institute, University of Tokyo, Vol. 35: 309-325.

Katukura, H., T. Watanabe & M. Izumi 1984. A study on the Fourier analysis of non-stationary seismic waves. Proc. 8th World Conference on Earthquake Engineering, Vol.IX: 525-532. San Francisco.

Kiureghian, A. & J. Crempien 1989. An evolutionary model for earthquake ground motion. Journal of Structural Safety, Vol. 6: 235-246.

Masiani, R. 1987. Artificial accelerograms for non-linear analysis in the time domain. Proc. 3th Italian National Congress on Seismic Engineering, Vol.II: 753-764. Rome (in Italian).

Newmark N. & M. Rosenblueth 1971. Fundamentals of earthquake engineering. New York: Prentice Hall.

Pereira, J. 1974. Probabilistic methods in earthquake engineering. LNEC memorandum N. 422. Lisbon.

Pinto, A.V. & P. Pegon 1991. Models for the quantification of seismic action: overview and numerical methods. CEC, JRC, STI (TN N.I.91.26), Ispra, Italy.

Priestley, M.B. 1967. Power spectral analysis of non stationary random processes. Journal of Sound and Vibration, Vol. 6: 86-97.

Sorace, S. & G. Terenzi 1991. Analysis of the dissymmetry characteristics of seismic signals generated by automatic procedures. Institute of Energetics Publications, Structural Division, N.01/1991. Perugia, Italy.

Vanmarcke, E. 1975. On the distribution of the first passage time for normal stationary random processes. Journal of Applied Mechanics, Vol.42: 215-220.