MULTIPLE TIME HISTORY SEISMIC EVALUATION

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SUMMARY

This paper presents an evaluation of the effectiveness of multiple time history analysis. On occasion, it has been suggested for critical structures that more than one time history should be used to account for phasing effects. Five independent time histories were used to analyze the response of 120 three degree-of-freedom structures. The phasing relationships were evaluated using first order statistics. It is shown that on the average one time history is probably adequate, using two provide good assurance, and using combinations of more than two, provide diminishing returns.

BACKGROUND

Critical structures which must continue operation or maintain a safe condition with a high degree of probability under earthquake-induced forces and motions have been required to be analyzed by the time-history method (Refs. 1 and 2). A synthetic earthquake motion whose response spectrum conservatively envelopes a specified smoothed design response spectrum is generally used. Presumably a multi degree-of-freedom (dof) structure designed to the time history will be as conservative a design as a single-dof system designed to the smoothed spectrum. However, in studying the response of multi-dof structures analyses (Refs. 3 and 4) have shown that phasing effects could result in both "over and under" conservative designs. These phasing effects can be described as: a) the phase relationships between the input motion frequencies and the modal frequencies and b) the phase relationships between the independent modes responding in phase (magnification) or out of phase (diminution).

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Donovan et al (Ref. 3) analyzed a large number of 2-dof systems for response to five artificial earthquakes and concluded that use of a single time history might underestimate relative displacements as much as one-fourth of the average observed and by as much as one-half of the maximum observed as a result of the phasing effects. Vanmarcke et al (Ref. 4) studied a more limited set of 4-dof models for 39 real and 15 synthetic earthquake time histories. The ratios of the largest observed response to the smallest were significant, ranging from 3.35 to 78.7.

OBJECTIVE AND SCOPE

The objective of the present study was to determine more precisely the extent to which phasing effects cause magnification or diminution of the response of multi-dof structures to artificial earthquakes. A family of 120 3-dof structures was selected with natural frequencies in the ratios 1.0:1.5:2.0, with fundamental frequencies varying from 0.10 Hz to 15.15 Hz, and with damping equal to 2.0% of critical in all modes.

Five statistically independent, modified recorded, digitized earthquake time histories (acceleration vs time), developed by Aramayo and Carley (Ref. 1) and used in the design of the Gas Centrifuge Enrichment Plant (Ref. 2) were selected for this study. Using a recent version of the SAP-V computer program, the linear elastic dynamic response of each structure was determined, and pseudo-velocity response spectra were plotted for each displacement (3 relative to ground, 2 interstory). In each case the time histories were scaled to a maximum acceleration of 1.0g. Means and standard deviations were calculated, and relative frequencies were tabulated for the response quantities.

RESULTS

To estimate phasing effects it was necessary to develop a scheme for comparing multi-dof results to single-dof results. The design response spectrum (Refs. 5 and 6) provides a convenient basis of comparison for single-dof structures. The design response spectrum of Reference 6 was the target spectrum for modifying the five time-histories used.

For the 3-dof structures, there are five displacement response quantities of interest. For each of these a convenient and logical basis of comparison is the response spectrum generated from the design spectrum by the square root of the sum of the squares (SRSS) method (Ref. 7). In this method a natural frequency is calculated for each mode, and the design spectrum is used along with the orthogonalized mode shapes, participation factors, and generalized masses to estimate the maximum response for each mode treated as a single-dof system. The square root of the sum of the squares of the modal maxima is then used to estimate the total response. The SRSS method provides an expected value approximation to the total response.

Table 1 summarizes the results of this study and allows comparison between the single-dof results and the multi-dof results. The results shown in the single-dof column of Table 1 represent the phasing relationships between the input motion frequency and the modal frequencies. These results can also be considered as the effects of the frequency content and amplitude of the input motion. They also represent the inherent conservatism (i.e., conservatism with respect to the smoothed design response spectrum), or lack of it, in the input motion. The results shown in the multi-dof columns represent both phasing relationship effects. The effects of magnification or diminution from modes in or out of phase can be easily determined by ratioing these results with the single-dof results. The bottom line of Table 1 indicates the extent to which the overall phasing relationships, per se, effect the response of these 3-dof systems for the average of these earthquakes. Magnification ranges from 1.1137 (mass 3 to base) to 0.923 (mass 1 to mass 2). In the extreme case (GATH.15A, mass 3 to base) the magnification due to modal phasing alone was 1.1357. The largest diminution (GATH.09A, mass 1 to mass 2) was 0.9639.

TABLE 1.-Observed Response/SR SS Response
(Average of N Observations)

Time	Single	Multi-dof*					
History	dof	1	2	3	1 v. 2	2 v. 3	N
GATH.02A	1.2095	1.2159	1.2401	1.3534	1.2115	1.2203	120
GATH.04A	1.1079	1.1088	1.1572	1.2401	1.0982	1.1196	120
GATH.09A	1.2100	1.1910	1.2228	1.3153	1.1663	1.1892	120
GATH.10A	1.1787	1.1945	1.2241	1.3079	1.1855	1.1841	120
GATH.15A	1.1337	1.1395	1.1782	1.2875	1.1337	1.1436	120
AVERAGE	1.1680	1.1700	1.2045	1.3008	1.1590	1.1714	600

*Column numbers 1, 2 and 3 represent model mass points - mass 1 being the top mass and mass 3 being near the base.

Assuming these artificial earthquakes to be statistically independent, an estimate of the conservatism, or lack of it, inherent in a design based on any combination of them was estimated by determining the relative frequency (probability) of all responses being below the SRSS response, with the results shown in Table 2. Single-dof results are provided for comparison.

Design of a multi-dof system based on a single time history will be, on average, somewhat safer than that of a single-dof system based on the same earthquake (0.158 vs 0.190) but a particular time history might give unconservative results (.315 vs .190), especially if the structure has an unfortunate combination of natural frequencies with respect to that time history - again, frequency content of the input motion as the primary effect rather than modal phasing. Any two time histories in combination appear to give reasonable conservatism.

TABLE 2.-Relative Frequency
All Observed Responses < SRSS Response
(N Observations)

Case	Range		Average	N
	Min	Max		
Single-dof				
1 at a time	.140	.244	.190	120
Multi-dof				
1 at a time	.016	.315	.158	600
2 at a time	.0004	.0914	.0294	1200
3 at a time	.0000232	.0227	.00589	1800
4 at a time	.000000580	.00544	.00122	2400
5 at a time	.0000000568	.000805	.00025	3000

CONCLUSIONS

The five artificial earthquakes used in this study can be considered representative of those used in analysis and design of nuclear facilities, but the sample of five is small rather than exhaustive. For further generality, a larger sample of structural models should be considered, including a wider range of natural frequency ratios and a larger number of degrees of freedom. Nevertheless, based on the limited data developed here, reasonable conclusions can be drawn.

In the time history method, much of the spread in multi-dof system response is due to the conservatism and variability inherent in the time history used. Phase reinforcement, per se, may cause some magnification in the responses of multi-dof systems in comparison with single-dof systems. This effect is less than previously indicated, and was observed to range from a 3.6% diminution to a 13.6% magnification.

Design of multi-dof systems using a properly developed single time history will be reasonably conservative on the average, but may be unconservative frequently enough to be avoided. Design of multi-dof systems based on a combination of any two time histories will provide reasonable conservatism, and the use of combinations of more than two provides diminishing returns.

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