Problems in the Identification of Base Isolation Systems from Earthquake Records

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ABSTRACT

This work extends some recently obtained results on the identification of base isolation systems from earthquake response records. The identification is carried out by means of the Covariance Matrix Adaptation - Evolution Strategy (CMA-ES). By extending the number of iterations in each run and the number of runs it is shown that the obtained results have engineering significance. The design of a fictitious problem on the basis of a real seismic isolation system has allowed for the evaluation of the error on the individual system parameters. Some information on the completeness of the data used for the identification has also been provided. The work is concluded by the description of some open problems that the authors are facing and are determined to solve using the recent advances in computer science and technology.

Categories and Subject Descriptors

J.2 [**Computer Applications**]: Engineering

General Terms

Algorithms, Performance, Reliability

Keywords

Evolution Strategies, CMA-ES, Structural Identification

1. INTRODUCTION

Seismic isolation is one of the most effective technologies for the protection of buildings and other constructions from earthquakes. Several types of seismic isolators have been used in the applications including Low, Medium and High Damping Rubber Bearings, Sliding Bearings and the so called Friction Pendulum. The basic principle is the interposition of devices of low lateral stiffness between the foundation and the superstructure. This is achieved through the use of the seismic isolators mentioned above and results in a considerable lengthening of the fundamental period of oscillation for the structure. As a consequence the seismic forces acting on the superstructure are considerably reduced although at the expense of an increased relative displacement between the superstructure and the foundation, which must be accommodated by the seismic isolators. All the seismic isolators must satisfy the design requirements and this is normally assured by qualification and acceptance laboratory tests. However the properties of the seismic isolators can be affected by aging and by damage due to the action of earthquakes. Therefore it may be important to be able to identify the properties of the isolators some years after the installation or after an earthquake has occurred. Two ways have been used in the literature for the identification of the properties of base isolation systems, i.e. full scale free vibration tests [8] and recorded response from earthquake ground motion [5]. In both cases a model of the base isolation system is required and an optimization algorithm must be used for the identification of the properties of the isolators. The optimization problem is formulated as the minimization of the following functional: $e^2 = \langle \mathbf{a} - \mathbf{a}^e, \mathbf{a} - \mathbf{a}^e \rangle / \langle \mathbf{a}^e, \mathbf{a}^e \rangle$, where $\mathbf{a}$ is the model acceleration vector depending on the system parameters and $\mathbf{a}^e$ is the experimental acceleration vector obtained either from vibration tests performed on the building or from records of actual earthquake responses.

2. PREVIOUS WORK

Previous work by the senior author started with some full scale free vibration tests run on a base isolated building in the town of Solarino, in Eastern Sicily, in the summer of 2004 [6]. The initial identification work based on linear equivalent models led to unsatisfactory results [7]. A more sophisticated non-linear model led to better results [8]. The Least Squares method was used for the identification, but it re-

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Table 1: Identified Structural Parameters for a Real-World Application using the CMA – ES(4, 8)

property/run	1	2	3	4	5	6	7	8	9	10
$m(ton)$	716.0	782.5	665.6	755.5	691.4	626.7	759.5	767.6	739.5	720.3
$k_0(N/mm)$	8338.2	7674.9	6526.4	7558.1	6919.6	6275.9	7595.1	7677.5	7396.6	7206.0
$k_1(N/mm)$	1102.3	1194.7	1018.2	1153.8	1057.2	955.8	1161.3	1173.4	1130.2	1101.4
$Q(kN)$	44.4	48.5	41.6	47.6	43.4	40.0	47.8	48.3	46.5	45.3
$\zeta(\%)$	4.1	4.6	4.6	4.5	4.5	4.4	4.5	4.5	4.5	4.5
fitness	0.0823	0.0814	0.0815	0.0809	0.0809	0.0809	0.0809	0.0809	0.0809	0.0809
iter (maxIter)	84(86)	120(122)	92(100)	69(72)	232(241)	119(179)	102(106)	156(300)	319(322)	88(95)
time.iter (min)	11	11	10	18	17	17	17	18	16	17
computer	pc-1	pc-1	pc-1	pc-2	pc-2	pc-2	pc-2	pc-2	pc-3	pc-2

Table 2: Statistics of the Results of Table 1

	average	std	c.o.v. (%)
$m(ton)$	722.5	49.2	6.8
$k_0(N/mm)$	7316.8	607.5	8.3
$k_1(N/mm)$	1104.8	75.3	6.8
$Q(kN)$	45.3	3.0	6.6
$\zeta(\%)$	4.5	0.1	3.1

quired a cumbersome interactive procedure. Contacts with researchers from the computer science community led to the use of several kinds of Evolution Strategies [1, 2]. Among all the methods that were used the CMA-ES outperformed the others by several orders of magnitude. In those applications the number of parameters to be identified varied according to the model from a minimum of 6 to a maximum of 9. The number of parameters is at a minimum for this kind of problem because a one degree of freedom model can be used for the system. In general at least 3 parameters are needed for the description of each isolator and even if all isolators of one group could be considered as having the same properties, often there are several different groups of isolators in an isolation system. It is easy to understand that the number of parameters can become relatively large when considering real seismic isolation systems. For instance in a recent application considering a very simple base isolated building in Japan (Figure 1), with only 4 isolators of the same type, the number of parameters varied from a minimum of 5, when all isolators where assumed to be identical, to a maximum of 14, when each isolator was considered as having different properties from the others [5].

3. RECENT RESULTS

Some results obtained with reference to a building in Japan after identification by use of earthquake response records have been extended in the present work considering a larger number of identification runs. While in the previous study [5] the number of runs was limited to 4, in the present work this number has been extended to 10. The small number of runs considered before, and even now, is due to the large computer time needed for each iteration. The obtained results are shown for the present case in Table 1. For the meaning of the identified parameters the reader may refer to [5]. The number of identified parameters is only 5 because the 4 isolators were considered as having the same properties, although this is not necessarily the case because of manufacturing imperfections, earthquake damage and aging. However, this choice was made in order to obtain results

Figure 1: Photograph of the exterior of the considered base isolated building in Japan.

in a reasonable time. In the table the fitness measures the distance between the recorded acceleration and the one simulated by the model. For an exhaustive definition of the fitness the reader is referred to the above quoted work. An additional information given in the table is the iteration at which the minimum distance was obtained and the maximum number of iterations considered in the identification run. This was stopped when no evident improvement in the fitness was being achieved. Three different personal computers were used in performing those runs and the different times per iteration reflect the characteristics of such computers[1]. The statistics of the identified parameters calculated on the basis of the 10 runs are shown in Table 2. It may be worth noticing how the coefficient of variation evaluated for each parameter on the basis of the 10 runs is generally smaller than that calculated in [5] on the base of only 4 runs. Because the coefficient of variation appears to be within the range of engineering uncertainties (±10%) the identified values may be considered satisfactory. However, the obtained values for the system parameters cannot be checked against known values. Therefore no conclusion can be reached on

[1]pc-1: Intel(R) Pentium(R) CPU G850 @ 2.90GHz (2Core), RAM DDR3 4096 MBytes
pc-2: Intel(R) Core(TM)2 Quad CPU Q8200 @ 2.33GHz (4Core), RAM DDR2 4096 MBytes
pc-3: Intel(R) Core(TM)2 CPU 6600 @ 2.40GHz (2Core), RAM DDR2 2048 MBytes

Table 3: **Parameter Error (%) for the Fictitious Problem when 2 Acceleration Components are considered, $\mathbf{CMA-ES(5,11), maxIter = 250}$**

run	1	2	3	4	5	6	7	8	9	10
e_m	3.31	-2.17	-1.54	3.86	0.00	1.08	0.42	2.54	2.68	3.62
e_{k_0}	-14.75	-4.01	-0.83	-5.89	-11.01	1.52	-12.52	3.18	-14.03	-9.06
	4.68	-4.18	-1.77	13.33	-1.44	-0.15	-5.79	1.03	12.47	4.69
	19.85	13.42	-1.60	13.91	18.64	9.60	9.48	3.31	14.74	23.85
	6.28	-13.11	-2.17	-4.47	-5.13	-7.22	12.21	2.65	0.04	-2.79
e_{k_1}	6.91	-4.84	-2.34	1.70	-0.25	-1.39	0.70	0.84	0.04	7.74
	0.69	-1.40	-3.63	4.44	3.39	-3.32	-4.06	3.36	1.28	1.53
	2.01	-2.84	-3.16	4.92	2.50	8.33	0.42	3.35	3.51	9.90
	3.78	0.41	3.07	4.27	-5.34	0.94	4.84	2.58	5.88	-4.72
e_Q	13.76	1.89	-1.56	18.56	16.36	12.55	10.05	3.46	12.19	12.51
	-8.63	-5.07	-1.18	-5.11	-0.95	1.43	0.20	1.26	-4.59	-3.26
	0.20	0.48	-3.52	-3.76	-7.32	-12.48	-2.18	3.30	-2.32	-3.73
	8.73	-5.86	0.04	7.19	-6.72	4.19	-6.02	2.29	6.31	9.84
e_ζ	0.49	-0.55	0.01	0.17	0.53	0.26	1.02	-0.26	0.08	0.02
$\Sigma\|e_i\|/N$	6.72	4.30	1.89	6.54	5.69	4.61	4.99	2.39	5.73	6.95
$\sqrt{\Sigma e_i^2}/N$	2.36	1.58	0.59	2.19	2.16	1.70	1.77	0.70	2.07	2.43
fitness	5.02E-06	1.35E-05	1.50E-06	3.21E-06	6.24E-06	8.40E-06	3.20E-06	3.83E-07	3.28E-06	3.86E-06
iter	250	250	246	246	249	244	51	250	223	245
time.iter	24 ’	35 ’	35 ’	23 ’	24 ’	35 ’	33 ’	48 ’	24 ’	32 ’

the reliability of the obtained solutions. To try to spread some light on the reliability of the results obtained by this method a fictitious problem was constructed. To the 4 isolators were given different properties and suitable values were given to the other two parameters, i.e. the mass of the system m and the damping ratio ζ. The model with the given characteristics was subjected to the given ground motion and the response was calculated. This response was then used as data for the identification procedure. In this way the results could be controlled both in terms of fitness of the solution and in terms of error on the individual parameters. The maximum number of iterations for each run was set equal to 250 and 10 different runs were performed. The results in terms of fitness and parameter error are shown in Table 3. It may be seen as the fitness ranges from values of the order of 10^{-7} to values of the order 10^{-5}. Generally the error on the individual parameters can reach values approaching the order of $\pm25\%$. However, this error is smaller when the fitness is smaller. For instance, in the run when the minimum fitness was reached the maximum error on individual parameters was 3.46%. This clearly shows that run 8 providing the smallest fitness also provides the smallest error on the individual parameters. Nevertheless, the experiment cannot be considered totally successful because in some runs the error on the individual parameters resulted beyond what is considered acceptable in engineering practice. While investigating the reason for such a large error on individual parameters, in spite of good values for the fitness function, the idea came that the data used for the identification could not be sufficient. In fact for a dynamical system having 3 degrees of freedom only 2 components of acceleration had been recorded during the earthquake. The same 2 components generated numerically from the model have been used for the calculation of the results shown in Table 3. Therefore the fictitious problem was modified by considering 3 independent components of acceleration, as shown in [5]. By using the known system parameters the three independent acceleration components were generated and used as data for the identification problem. The results of 10 identification runs are shown in Table 4, which is the counter part of Table 3 for the case when 2 independent acceleration components are considered. In the present case the fitness values range from a maximum value of the order of 10^{-5} to a minimum value of the order of 10^{-8}. The maximum error on individual parameters in this case was of the order of 8% against 24% for the previous case. More relevant is the fact that in the case of minimum fitness (best fitness) the maximum error on the individual parameters is only of the order of 2%. This clearly shows that the intuition about data insufficiency was correct.

The identification runs presented in this section were performed by implementing the CMA-ES rank-μ update with default setting [3] in MATLAB [4].

4. OPEN PROBLEMS

The results presented in the previous section were obtained by using personal computers. Considering the time required for each iteration and the number of iterations performed in each run, the waiting time for a run turned out to be of the order of a working week. This is clearly unacceptable for conducting this research, where the number of parameters can be quite large. Data recently become available on base isolated buildings in the Fukushima power plant permit the identification of seismic isolation systems including a large number of isolators (45 in one case and 20 in another case). This extends considerably the dimension of the identification problem and consequently the run time. Therefore it is evident that in order to be able to produce meaningful results all the recent advances in computer science must be exploited in the present research. The structure of the CMA-ES is such that it lends itself easily to parallel computing. Although this feature is already implemented in the CMA-ES code, it has not yet been used in the present research. To take advantage of this feature a

Table 4: Parameter Error (%) for the Fictitious Problem when 3 Acceleration Components are considered, $\mathbf{CMA-ES(5,11), maxIter = 250}$

run	1	2	3	4	5	6	7	8	9	10
e_m	-1.60	4.84	-0.84	0.44	3.74	-0.42	0.30	-1.40	1.68	0.64
e_{k_0}	-1.58	6.41	-8.40	-7.34	4.00	-0.35	-7.43	-8.07	1.86	-6.10
	-1.63	3.41	6.50	7.73	3.89	-0.59	7.40	6.49	1.37	8.31
	-1.63	3.88	4.96	6.96	3.71	-0.61	6.19	3.78	1.34	5.72
	-1.53	6.55	-7.89	-6.57	3.61	-0.20	-6.50	-8.13	2.13	-5.98
e_{k_1}	-2.00	5.35	0.22	-5.75	1.30	-2.05	-5.12	-5.35	-1.80	-3.21
	-1.19	4.46	-2.28	5.82	6.10	1.16	4.80	2.13	5.06	4.15
	-1.20	4.70	-2.72	5.05	6.16	1.32	4.56	2.04	5.16	4.27
	-2.05	4.73	1.22	-3.29	1.34	-2.17	-3.22	-4.73	-1.72	-2.64
e_Q	-1.53	7.23	1.85	5.55	3.52	0.26	5.69	-6.07	2.80	-2.01
	-1.67	2.34	-2.40	-2.72	4.01	-1.11	-3.30	3.30	0.74	3.35
	-1.64	2.73	-3.74	-5.12	4.04	-1.08	-5.41	2.40	0.66	2.49
	-1.56	7.17	0.94	4.24	3.45	0.25	4.82	-5.57	2.66	-1.78
e_ζ	-0.07	0.40	1.08	1.49	-0.29	0.15	1.12	0.00	-0.09	0.73
$\Sigma\vert e_i\vert/N$	1.49	4.59	3.22	4.86	3.51	0.84	4.70	4.25	2.08	3.67
$\sqrt{\Sigma e_i^2}/N$	0.42	1.32	1.11	1.42	1.03	0.28	1.37	1.30	0.67	1.14
fitness	7.09E-08	1.08E-05	7.91E-05	8.97E-05	7.15E-07	3.35E-07	9.06E-05	2.35E-05	5.01E-07	2.76E-05
iter	231	243	226	246	249	250	249	249	249	220
time.iter	24 ’	25 ’	24 ’	35 ’	36 ’	26 ’	32 ’	36 ’	24 ’	61 ’

large network of computers must be available for use. The next step in this research is therefore to take advantage of these features and see what gains can be achieved in terms of running time.

5. CONCLUSIONS

By extending the results of some recent work it has been shown that significant results can be obtained in the identification of seismic isolation systems from earthquake response records. The extension has come from an increase in the maximum number of iterations set for the CMA-ES code and for the maximum number of identification runs considered. The completeness of the identification data has also been analysed and it has been shown that much better results are obtained when the identification data are complete. The obtained results are of great interest in the field of earthquake engineering and are of extreme use for the society when dealing with post-earthquake structural assessment. However, these results require considerable computational effort and running time. Important developments can be achieved by optimising computational performance exploiting recent advances in computer science and technology.

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