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ON THE PERFORMANCE OF A COMPUTATIONAL COST REDUCTION TECHNIQUE WHEN APPLIED TO COOLING TOWERS TRANSIENT ANALYSIS

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Abstract. *Time integration is a versatile tool in transient analysis of structural systems. Considerable computational cost is a weak point for time integration. To reduce the computational cost of analyses against digitized excitations, a technique is proposed in 2008. Experiences on the implementation of the technique in seismic analysis of frames, multistory buildings, silos, bridges, space structures, reservoirs, etc. implies the adequate performance of the technique. The objective in this paper is to study the performance in implementation in seismic analysis of cooling towers. The study is in progress; still the achieved results display the good performance of the technique, when applied to a cooling tower analysis against earthquake records.*

1 INTRODUCTION

Time integration is the most versatile tool to analyze the transient behaviors of semi-discretized structural models. Nevertheless, the computational costs are considerable, and the responses are approximations. In a review on the time integration process, after discretization of the mathematical models in space, by methods such as finite elements, finite volumes, and boundary elements, we arrive at the semi-discretized models, typically stated below:

$$\begin{gathered}\mathbf{M}\ddot{\mathbf{u}}(t)+\mathbf{f}_{\text{int}}(t)=\mathbf{f}(t), \qquad 0<t\le t_{end} \\ \text{Initial conditions:} \quad \left| \begin{array}{l} \mathbf{u}(t=0)=\mathbf{u}_0 \\ \dot{\mathbf{u}}(t=0)=\dot{\mathbf{u}}_0 \\ \mathbf{f}_{\text{int}}(t=0)=\mathbf{f}_{\text{int}_0} \end{array}\right. \\ \text{Additional constraints: } \mathbf{Q}\end{gathered} \tag{1}$$

where, t and t_{end} imply the time and the duration of the dynamic behavior, $\mathbf{M}$ is the mass matrix, $\mathbf{f}_{\text{int}}(t)$ and $\mathbf{f}(t)$ stand for the vectors of internal force and excitation, $\mathbf{u}$(t), $\dot{\mathbf{u}}(t)$, and $\ddot{\mathbf{u}}(t)$ denote the vectors of displacement, velocity, and acceleration; $\mathbf{u}_0$, $\dot{\mathbf{u}}_0$, and $\mathbf{f}_{\text{int}_0}$ define the initial status of the model (regarding the essentiality of considering $\mathbf{f}_{\text{int}_0}$ in Eqs. (1), see [1, 2]), and $\mathbf{Q}$ represents the nonlinearity restrictions, e.g. see [3, 4]. Time integration determines the status at discrete time instants $\Delta t, 2\Delta t, 3\Delta t \ldots$. ($\Delta t$ stands for the integration step size), according to approximate formulations, introducing the integration method [5-8]. Because of the approximation, the integration step size cannot be large; and, because of the step-by-step nature, and the resulting high computational cost, the step size cannot be desirably small. Considering this, and the unconditional stability of conventional time integration methods (see [8, 9]), the integration step size is basically being obtained from:

$$\Delta t=\begin{cases}\dfrac{T}{10} & \text{linear problems}\\ \dfrac{T}{100} & \text{nonlinear problems}\\ \dfrac{T}{1000} & \text{nonlinear problems involved in impact}\end{cases} \tag{2}$$

where, T is the smallest period with considerable contribution in the response [5, 7, 9-11]. In some practical cases, e.g. time integration analysis against earthquake records, where,

$$\mathbf{f}(t)=-\mathbf{M}\,\Gamma\,\ddot{\mathbf{u}}_g(t) \tag{3}$$

and $\ddot{\mathbf{u}}_g(t)$ denotes the vector of ground motion at some different degrees of freedom (unless in multi-support excitations, $\ddot{\mathbf{u}}_g$ reduces to a function of time) and Γ is a matrix implying the effect of ground motion at different degree of freedom [12], $\mathbf{f}(t)$ is available as a vector of digitized records, and Eq. (2) is being replaced with

$$\Delta t=\min\,({}_f\Delta t, \frac{T}{\chi}) \tag{4}$$

where, ${}_f\Delta t$ implies the step size, by which, $\mathbf{f}(t)$ is digitized, and in view of Eq. (2),

$$\chi = \begin{cases} 10 & \text{linear problem} \\ 100 & \text{nonlinear problem} \\ 1000 & \text{nonlinear problem involved in impact} \end{cases} \tag{5}$$

When, ${}_f\Delta t$ governs Eq. (4), some additional computational cost, e.g. about

$$\frac{T - \chi\, {}_f\Delta t}{\chi\, {}_f\Delta t} > 0 \tag{6}$$

for linear problems is being dictated to the analysis, specially, in order to take into account the total information of $\mathbf{f}(t)$; see also [13].

In 2008, a technique is proposed for reducing the above-mentioned additional considerable computational cost, while taking into account the total earthquake record, and not sacrificing considerable accuracy (compared to analyses with steps obtained from Eq. (4)) [13-16]. The past experiences on implementation of the technique were successful; see Table 1. In continuation of the different case studies reported in Table 1 and with attention to the importance

System(s) analyzed	The cost reduction (%)	Source
SDOF system	75	[14]
2-DOF nonlinear system	49.27	[14]
Eight storey shear frame	80	[17]
Thirty-storey building	50	[18]
3-component earthquakes	66.7	[19]
Silo	77.65	[20, 21]
Water tank	66.7	[16, 22]
Building in pounding	12.7	[23]
Bridge with linear and nonlinear behaviors	45-80	[24-26]
Power stations	> 50	[27]
Regular residential buildings	50-87	[28, 29]
Bridges with pre-stressed elements, subjected to multi-support excitation and nonlinearities	30-70	[30]
Residential building with irregularities in height	50-80	[31]
Space Structures	>50	[32]
A telecommunication tower	>50	[33]

Table 1: Experiences on the computational cost reduction technique proposed in [14].

of cooling towers in industry as well as the considerably large and complicated structure systems (with high number of degrees of freedom) of cooling towers, in this paper, the authors intention is to answer to the following questions:

1. Whether for cooing tower, ${}_f\Delta t$ can be the governing term in Eq. (4).

2. Whether, if the response to the first question is positive, the performance of the technique proposed in [14] can be adequate, when implemented in transient analysis of cooling towers, against earthquake records.

A real cooling tower, two real ground motions and an integration method, are taken into account as the basis of the study. The models, and the structural behaviors, are briefly addressed in Section 2; the consequence of implementation of the computational cost reduction technique is reported in Section 3; the observations are briefly discussed in Section 4; and finally, the paper is closed in Section 5 with a brief set of the conclusions.

2 THE MODELS

The cooling tower, displayed in Fig.1, is constructed in Gazvin, Iran, with the construction end at about 2011, and the main structural properties as addressed in Table 2. (There is no special reason for the selection of this cooling tower, unless the availability of the computer finite foment model.) With attention to the existing recommendations regarding analysis methods in studies of tall structural system [35], the ground motions are considered, as displayed in Fig. 2, where $\ddot{u}_g$ stands for the ground acceleration, and g implies the gravity constant. The almost exact responses obtained from time integration with very small integration steps are as displayed in Fig. 3 and linear in view of the superposition principle [36].

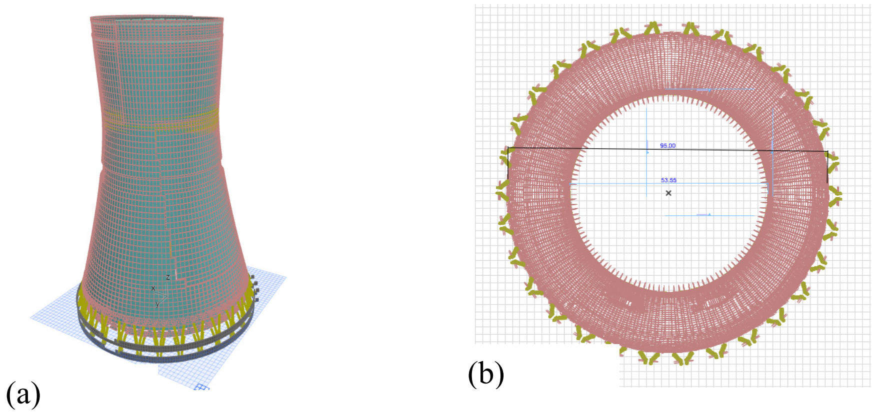

Figure 1: The cooling tower under study: (a) 3 D appearance, (b) planer cross section from top.

Height (m)	External Diameter (m)			Wall thickness (m)	Occupancy	Soil type	Structural system	Finite element
	Base	Top	Mid height					
146	95	59.5	49.5	3	Power Plant (steam)	III [34]	Concrete Shell with Steel Cover	Shell

Table 2: Main structural properties of the cooling tower in Fig. 1.

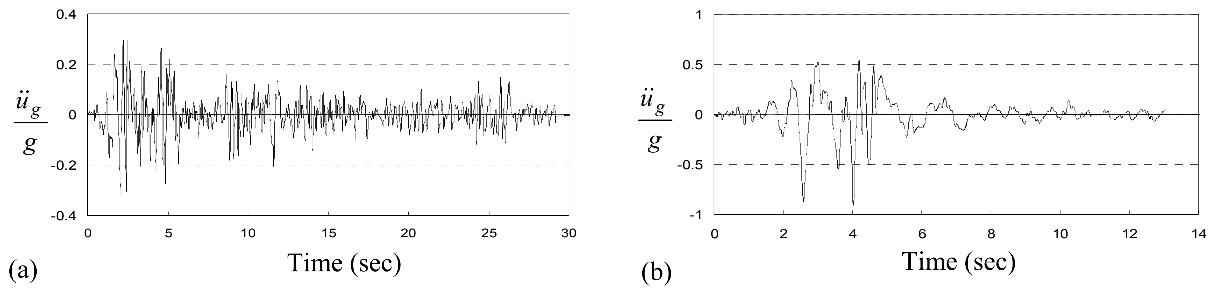

Figure 2: The ground strong motions taken into account: (a) E1 Centro record, (b) a Kobe record.

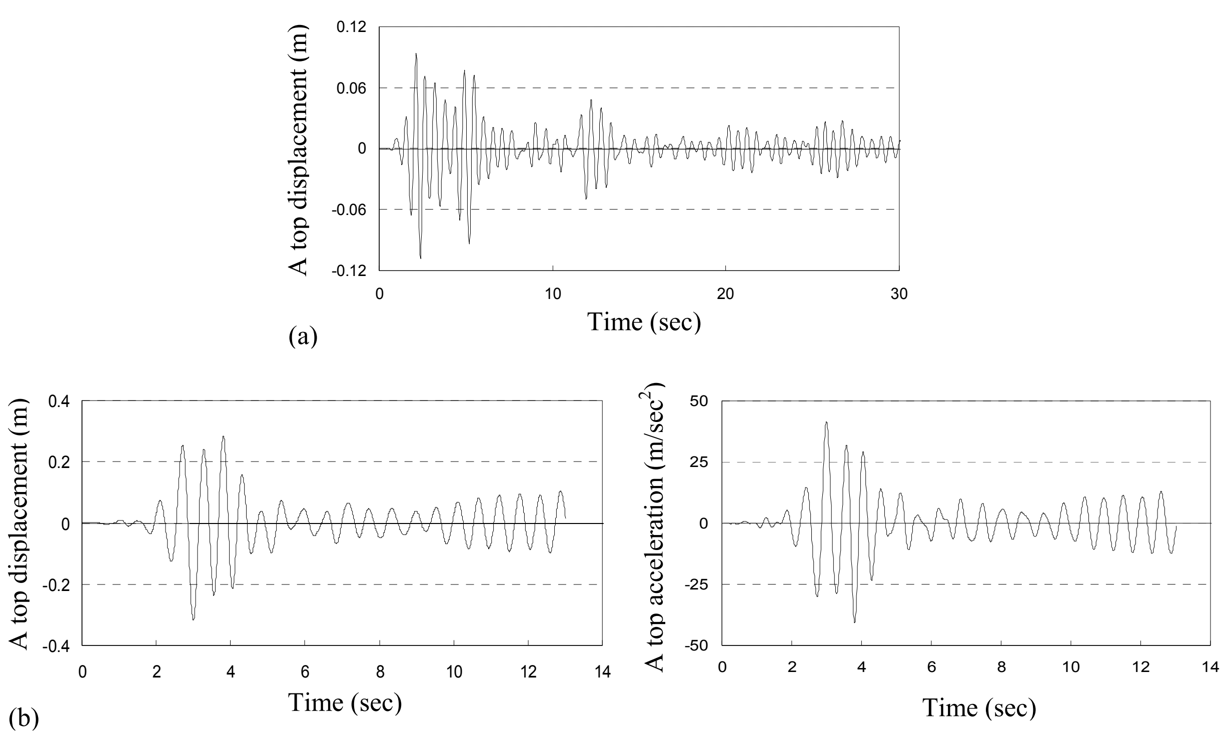

Figure 3: Almost exact responses against: (a) the ground motion in Fig. 2(a), (b) the ground motion in Fig. 2(b).

And finally for time integration analyses (numerical model), the average acceleration method of Newmark [37] with the formulation below [5, 12, 37]:

$$
\begin{aligned}
&\mathbf{M}_i\ddot{\mathbf{u}}_i + \mathbf{C}_i\dot{\mathbf{u}}_i + \mathbf{K}_i\mathbf{u}_i = \mathbf{f}_i \\
&\mathbf{u}_i = \mathbf{u}_{i-1} + \Delta t\,\dot{\mathbf{u}}_{i-1} + \frac{\Delta t^2}{2}\left[(1-2\beta)\ddot{\mathbf{u}}_{i-1} + 2\beta\ddot{\mathbf{u}}_i\right] \\
&\dot{\mathbf{u}}_i = \dot{\mathbf{u}}_{i-1} + \Delta t\,\dot{\mathbf{u}}_{i-1} + \Delta t\left[(1-\gamma)\ddot{\mathbf{u}}_{i-1} + \gamma\ddot{\mathbf{u}}_i\right] \qquad i = 1,2,3\ldots \\
&\gamma = 2\beta = 0.5 \\
&\mathbf{u}_0 = \mathbf{u}(t=0) \\
&\dot{\mathbf{u}}_0 = \dot{\mathbf{u}}(t=0) \\
&\ddot{\mathbf{u}}_0 = \mathbf{M}_1^{-1}\left(\mathbf{f}_0 - \mathbf{C}_1\dot{\mathbf{u}}_0 - \mathbf{K}_1\mathbf{u}_0\right) \\
&\mathbf{f}_0 = \mathbf{f}(t=0)
\end{aligned}
\tag{7}
$$

($\mathbf{M}_i$, $\mathbf{C}_i$, and $\mathbf{K}_i$ respectively represent the mass damping and stiffness matrices at the i th step, γ and β stand for the parameters of the Newmark method, and each top dot implies once differentiation with respect to time) is considered as the analysis tool.

3 RESULTS OF THE NUMERICAL STUDY

As mentioned in the ending lines of Section 2, the behaviors of the cooling tower against both records are linear. Accordingly, in Eq. (4),

$$\chi = 10 \tag{8}$$

With attention to Fig. 3, the values of T are addressed in Table 3. Considering Table 3 and ${}_f\Delta t = 0.02, 0.01$ respectively for the records in Figs. 2(a) and 2(b), obviously ${}_f\Delta t$ is smaller than $\frac{T}{\chi}$ in all cases. Therefore, the response to the first question in Section 1 is positive and we are to proceed to the second question.

Response	Fig. 2(a) as Earthquake record	Fig. 2(b) as Earthquake record
A top displacement	0.25	0.5
A top acceleration	-	0.5

Table 3: Values of *T* in different cases.

In view of the above mentioned values of $T, \chi, {}_f\Delta t$ and the recommendations on the maximum values to be assigned to the enlargement values [24], n

$$n = \frac{\Delta t}{{}_f\Delta t} \tag{9}$$

the selections below:

$$n = 2, 3, 4, 5 \tag{10}$$

are considered in the numerical study. The finite element model of the cooling tower is analyzed by the average acceleration method of Newmark [5, 12, 37], with integration steps equal to

$$\Delta t = n \;{}_f\Delta t \tag{11}$$

while, for changing the records digitized at steps sized Δt to records digitized at $n_f\Delta t$ the technique proposed in [14] is implemented. The resulting responses are as displayed in Figs. 4-6, respectively for top displacements obtained under the effect of the El Centro (Fig. 2(a)) and the Kobe (Fig. 2(b)) record, and a top acceleration because of the Kobe record (Fig. 2(b)). The corresponding reductions of computational costs are addressed in Table 4. Obviously, the performance is adequate. Even, the inaccuracy in the case $n = 5$ and partly $n = 4$, more considerable for analysis against the record in Fig 2 (b) is acceptable, with attention to the fact that with a closer look to Figs. 3,

$$\frac{T}{\chi \;{}_f\Delta t} \begin{cases} < 2 & \text{for the excitation in Fig. 2(a)} \\ \cong 3.2 & \text{for the excitation in Fig. 2(b)} \end{cases} \tag{12}$$

Consequently in response to the second question in Section 1, we can claim that the performance of the computational cost reduction technique can be adequate in transient analysis of cooling towers' structural system against ground motions.

——— Ordinary analysis

-·-·-·-· Ordinary analysis and afterwards implementing the technique proposed in [14]

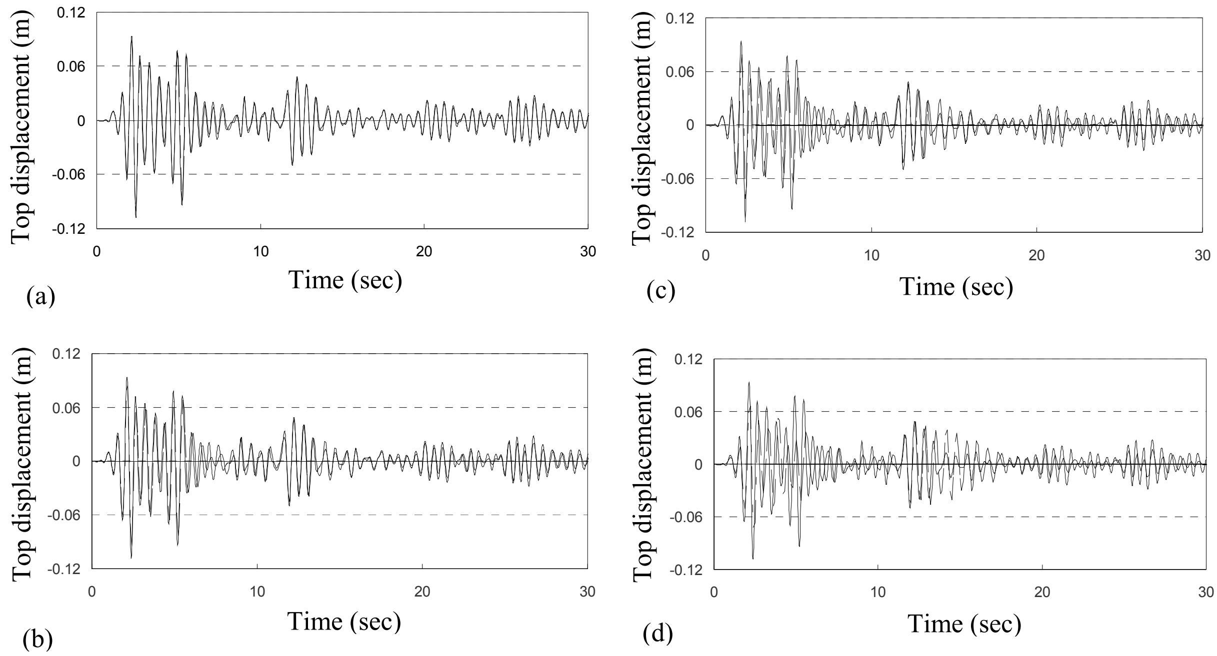

Figure 4: A top displacement obtained from average acceleration analysis of the model introduced in Fig. 1 and Table 2 against the record in Fig. 2(a): (a) $n=2$, (b) $n=3$, (c) $n=4$, (d) $n=5$.

——— Ordinary analysis

-·-·-·-· Ordinary analysis and afterwards implementing the technique proposed in [14]

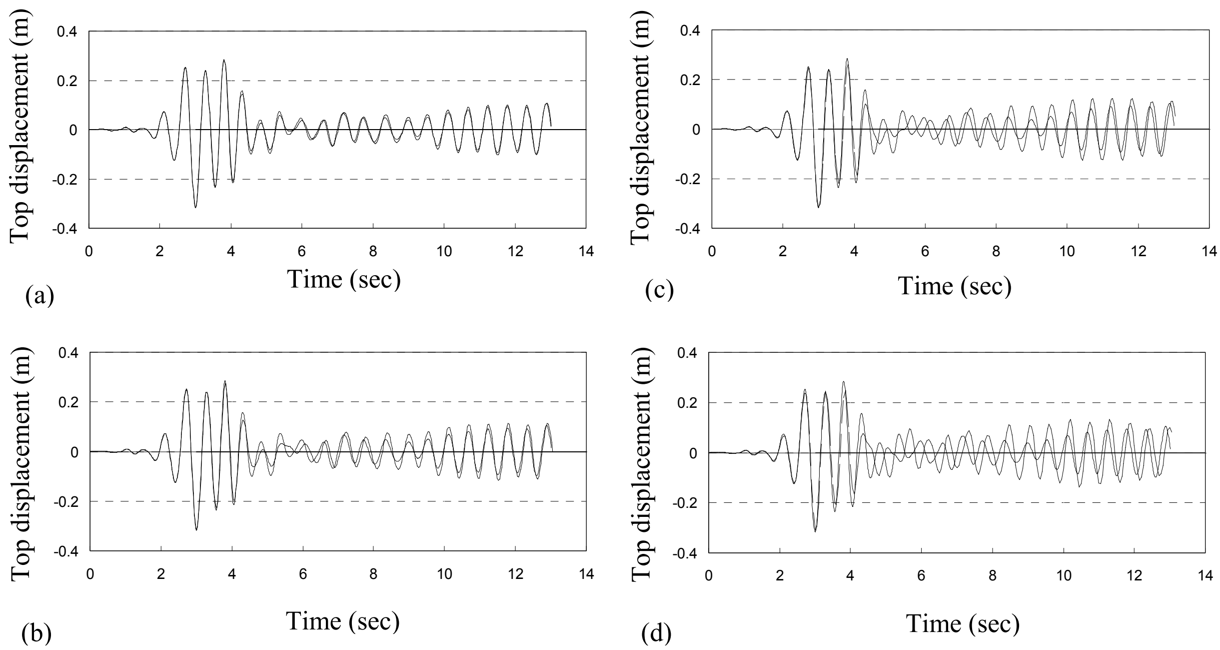

Figure 5: A top displacement obtained from average acceleration analysis of the model introduced in Fig. 1 and Table 2 against the record in Fig. 2(b): (a) $n=2$, (b) $n=3$, (c) $n=4$, (d) $n=5$.

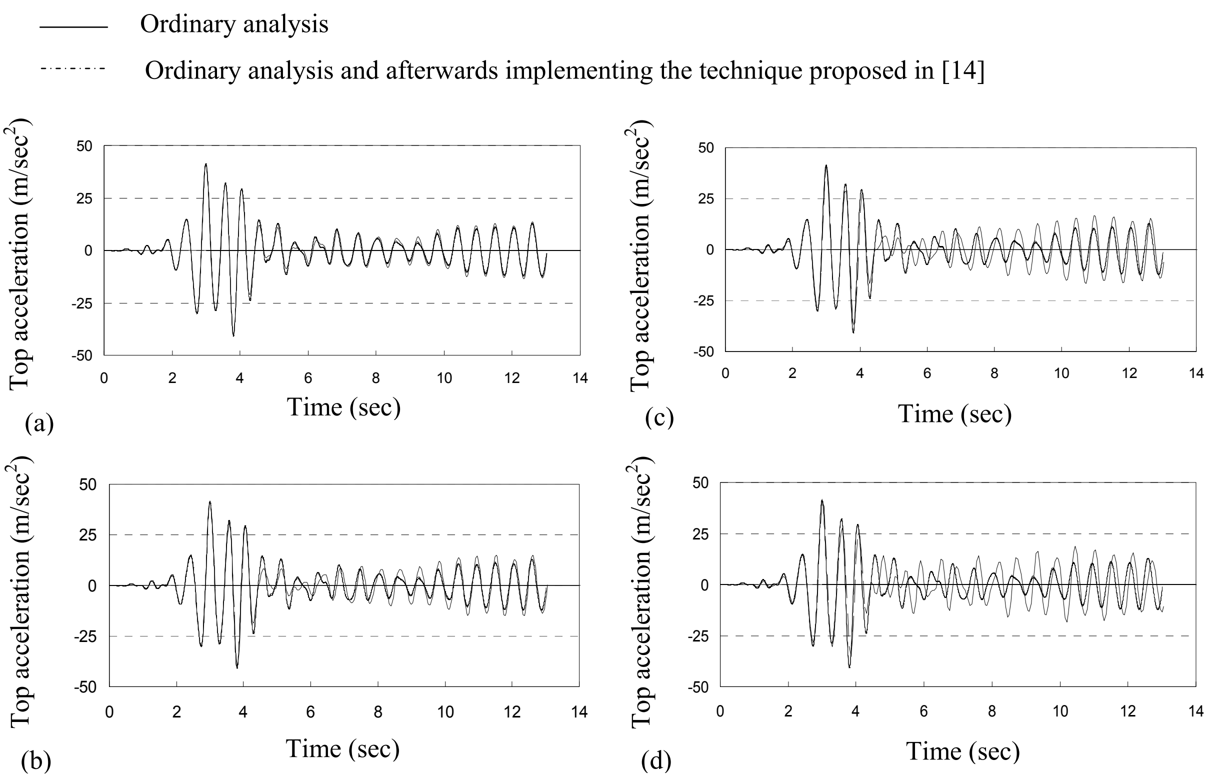

Figure 6: A top acceleration obtained from average acceleration analysis of the model introduced in Fig. 1 and Table 2 against the record in Fig. 2(b): (a) $n = 2$, (b) $n = 3$, (c) $n = 4$, (d) $n = 5$.

n	1	2	3	4	5
Reduction (%)	0	50	67	75	80

Table 4: Reduction of computational costs in Figs. 4-6.

4 BRIEF DISCUSSION

The observations in Section 3 are evidences for adequate performance of the technique proposed in [14]. However, with attention to the vagueness and complexity in the notion and computation of T, the fact that the value of ${}_f\Delta t$ might become smaller in future (see [38, 39]), and finally the less accuracy for the cases $n = 4$ and $n = 5$ when subjected to the excitation in Fig. 2(b), it is reasonable to continue investigations towards advanced techniques for integration step size enlargement, such that the reduction of computational cost can be provided in the price of even less sacrifice of accuracy. For further extensions, it is also essential to study other cases of cooling towers, earthquake records and integration methods.

5 CLOSURE

• In analysis of cooling towers against ground motion records, the step size needed for the accuracy of integration might be larger than the record step size.

• Implementation of the technique proposed in [14] for reducing the cost of transient analysis of cooling towers against earthquake records might considerably reduce the computational cost in the price of negligible loss of accuracy.

• Further investigations both to enhance the performance of the technique proposed in [14] and also to extend the numerical study is essential and recommended.

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