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EXTENDED ABSTRACT

New Formulation for Dynamic Analysis of Nonlinear Time-History of Vibrations of Structures under Earthquake Loading

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1. Introduction

A fast and efficient numerical scheme is presented for time-history analysis of single-degree-of-freedom (SDOF) structural systems undergoing seismic excitation (Chopra, 2003). The new method is called Newton-Cotes-4P-θ Method. It uses the most known 4-point Newton-Cotes quadrature in its body to solve the vibration equation. Nonlinear analysis is covered as well as linear analysis. Any arbitrary external loadings of type force or seismic signals are welcome. The significant advantages of the new formulation are its great simplicity, running speed, and appropriate precision level compared with its counterparts such as Duhamel integral and Newmark-β methods. The accuracy level of the Newton-Cotes-4P-θ is close to the semi-analytical method of Duhamel integration and its speed is similar to the Newmark-β algorithm. Notably, against the nonlinear Newmark-β method, the new method does not require a standalone procedure to handle nonlinear analysis; instead, it simply triggers iteration of the same computation used in its first processing round. Moreover, the Newmark-β method loses its performance dealing with stiff (T_n>1.5 sec) and near-conservative (ζ<0. 02) systems; however, the Newton-Cotes-4P-θ method does not loos its accuracy and keeps its well-performed analysis in this case. Numerical results reveal the superiority of the Newton-Cotes- 4P-θ method against its counterparts such as the Duhamel integral, Newmark-β, and Wilson-θ methods (Babaei et al., 2021; Babaei et al., 2022; Babaei et al., 2023).

2. Methodology: Proposed Newton-Cotes-4P-θ method

To formulate the Newton-Cotes-4P-θ method, we first recall the basics from the kinematics of particles in Dynamics. Then, we use the multistep numerical integration formula of the Newton-Cotes rule to estimate the velocity and displacement in their basic relations. Careful assessment of the Newton-Cotes integration showed that they lose their efficiency when analyzing high-frequency systems. So, a series of modifications are made in the body of Newton-Cotes to improve its performance when dealing with these systems. This modification lies effective and noticeably increases the accuracy of the numerical method in a way that it can robustly analyze linear and nonlinear systems possessing any type of nonlinearity in its component. Finally, simplifying the nonlinear algorithm of Newton-Cotes-4P-θ, we achieve the linear version of this technique. The Linear Newton-Cotes-4P-θ method is merely able to analyze linear systems and it cannot properly handle nonlinear problems.

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3. Results and discussion

According to Figs 1 to 3 the presented Newton-Cotes-4P method provides a more accurate response compared to the Newmark-β method.

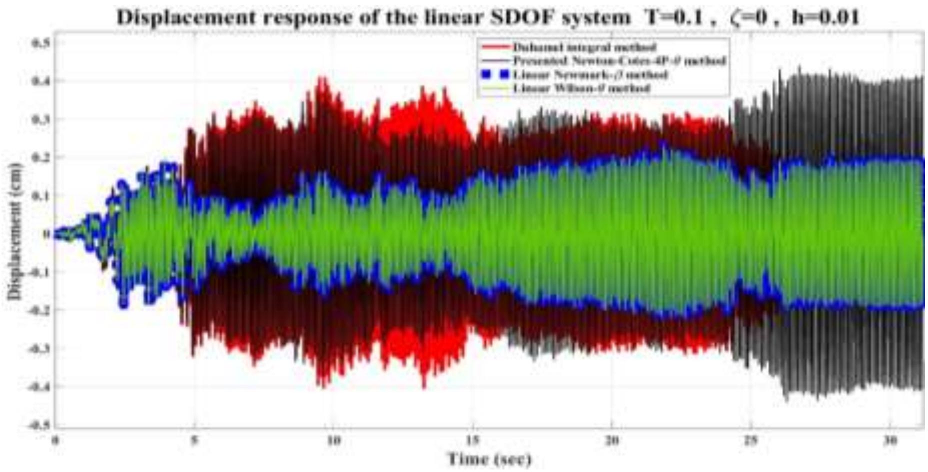

Fig. 1. Displacement time-history response of the linear SDOF system

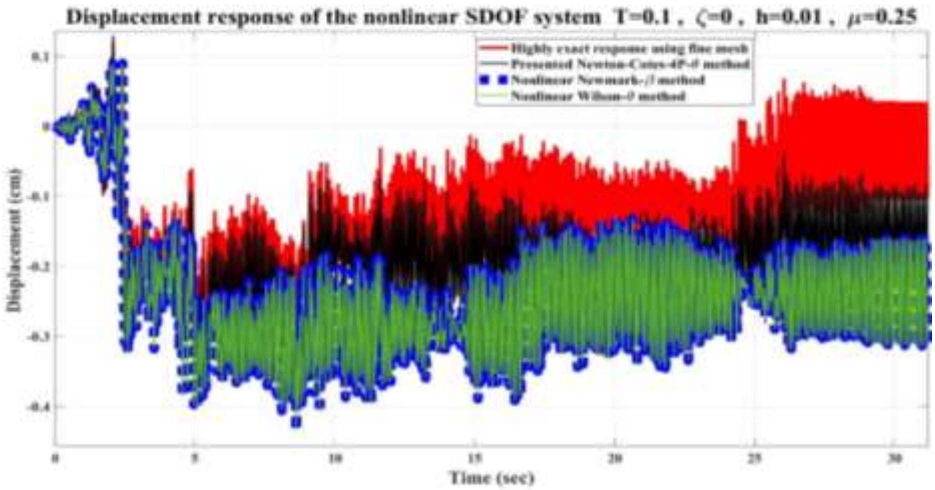

Fig. 2. Displacement time-history response of the nonlinear SDOF system

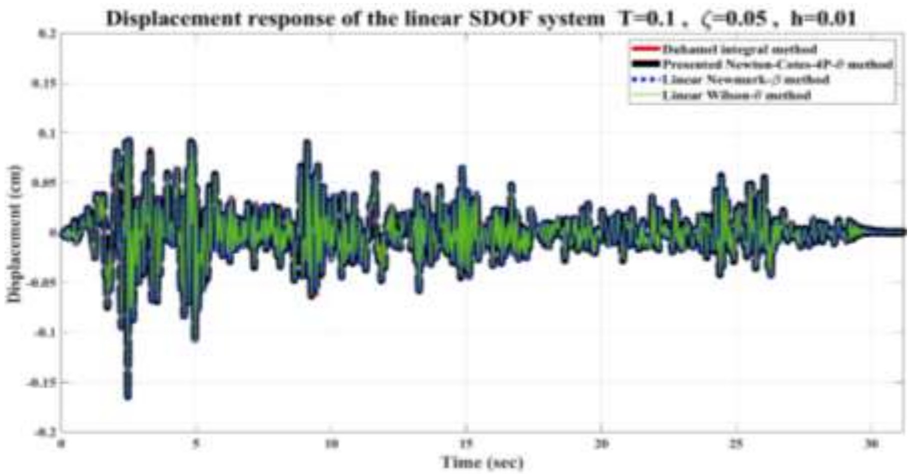

Fig. 3. Displacement time-history response of the linear damping SDOF system

In the first example, the response from the Newton-Cotes-4P-θ method completely matches the exact response obtained from the Duhamel integral while Newmark loses the correct response. Moreover, a significant error, about 40 percent, is detected by the displacement response given by the Newmark-β method in Table 3. Example II is a challenging one for which both of the methods have significant errors; but, the response of the new method is again more reliable than Newmark's response.

Table 1. Peak responses and run-times of linear and nonlinear analyses in the examples

Item	Highly exact response Duhamel integral method or using fine mesh		Presented Newton-Cotes-4P-θ method		Linear Newmark-*β* method or Nonlinear Newmark-β method		Low exact response Linear Wilson-θ method or Nonlinear Wilson-θ method	
Max Displacement (cm)	Linear	Nonlinear	Linear	Nonlinear	Linear	Nonlinear	Linear	Nonlinear
	0.4104	0.3149	0.4140	0.347500470	0.2301	0.4347	0.2297	0.4347
Max Velocity (cm/sec)	Linear	Nonlinear	Linear	Nonlinear	Linear	Nonlinear	Linear	Nonlinear
	NC*	8.0184	27.5466	8.260706207	13.7125	8.2166	13.6879	8.2166
Max Acceleration (cm/sec^2)	Linear	Nonlinear	Linear	Nonlinear	Linear	Nonlinear	Linear	Nonlinear
	NC*	404.4226	1560.8602	412.6025804	849.3479	402.3668	847.5628	402.3668
Number of iteration	Linear	Nonlinear	Linear	Nonlinear	Linear	Nonlinear	Linear	Nonlinear
	1	5	2	3	1	5	2	3
Run time (sec)	Linear	Nonlinear	Linear	Nonlinear	Linear	Nonlinear	Linear	Nonlinear
	0.3856	0.1359	0.0008	0.0013	0.0005	0.0014	0.0010	0.0010
NC*: Not computed								

4. Conclusions

In this study, a greatly simple and efficient numerical formulation so-called Newton-Cotes-4P-θ method was developed for computing the dynamic response analysis of the structures. Both linear and nonlinear versions of the method were proposed in this study. The great advantage of the new formulation is that it does not change its formulation for linear and nonlinear analyses. Against the Newmark-β method, it has no standalone mechanism to deal with the nonlinearity; instead, it just repeats the same formulas used for the linear analysis. Results reveal that the proposed method satisfactorily estimates the seismic response of linear and nonlinear damped SDOF systems. It was also shown that the proposed Newton-Cotes-4P-θ method can reliably estimate the displacement time-history response of the SDOF systems. So, the proposed method can be identified as an efficient analysis tool for estimating the seismic demands of linear damped systems. Further studies in the development of the proposed procedure for more accuracy and simplicity are still underway.

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