Proceedings of the 33rd European Safety and Reliability Conference (ESREL 2023)
Edited by Mário P. Brito, Terje Aven, Piero Baraldi, Marko Čepin and Enrico Zio

doi: 10.3850/978-981-18-8071-1_P062-cd

Comparative Study on Optimization Methods in Finite Element Model Updating

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Finite element model updating has been widely studied in the civil engineering field owing to its applicability to damage detection, system identification, and digital twin construction. Its general scheme is to find the best-fit model with sensor data by updating various model parameters, such as elastic modulus, mass density, and rotational stiffness. It is definitely an optimization problem where lots of algorithms can be introduced. Not only first-order optimization methods but also second-order methods can be utilized. In many studies, zero-order optimization methods have been introduced to find global optimum even though those are computationally expensive. In this study, the optimization methods are compared in terms of accuracy and computational cost in a finite element model updating problem with a numerical example of Euler-Bernoulli beams.

Keywords: Finite Element Model Updating, Modal Analysis, System Identification, Euler-Bernoulli Beams, Nelder-Mead Simplex Method, Optimization, Digital Twin.

1. Introduction

Finite element model updating is a technique that has gained significant attention in civil engineering due to its applicability in damage detection, system identification, and digital twin construction. The general approach involves updating various parameters of the finite element model to obtain the best-fit model that matches the sensor data. The parameters that can be updated include elastic modulus, mass density, and rotational stiffness. This process can be viewed as an optimization problem, where the objective is to minimize the difference between the predicted and actual sensor data. Researchers may sometimes select an optimization method without conducting an extensive preliminary study. However, as digital twins that can be computationally expensive models have frequently introduced to many types of structures nowadays, the optimization performance would become an important issue.

2. Optimization Methods

In this study, we aim to investigate the computational cost and performance of various optimization methods in finite element model updating. We evaluate the performance of different optimization methods using a numerical example of a beam structure. The optimization methods considered in this study are first-order optimization methods, such as a gradient descent and a momentum method, second-order optimization methods, such as a Newton's method, and zero-order optimization methods, including a particle swarm optimization and a Nelder-Mead simplex method (Nelder et al. 1965).

3. Comparative Study

In this study, a simply-supported beam model (Kim et al. 2016) is constructed using MATLAB to investigate the performance of optimization methods in finite element model updating. The model consists of twenty meshes with rectangular cross-sections; where, an elastic modulus of 200 GPa, and a mass density of 7850 kg/m^3. The boundary conditions of the system are manipulated by two rotational springs attached at the supports of the beam, and those rotational stiffnesses are the target variables.

Table 1 shows the performance of different optimization methods based on their accuracy and computational cost, where the epoch denotes the number of updating during optimization process, the FEA means finite element analysis, and the error is root-mean-squared errors between optimized and true values. Our investigation reveals that the first-order methods require a large number of finite element analyses to find the optimal solution, and their performance is highly sensitive to the choice of the learning rate. Therefore, a carefully designed hyperparameter is required for optimal results. On the other hand, the second-order method converges to the optimal solution in fewer epochs, but the number of FEA per epoch is higher in order to estimate Hessian matrices. In addition, we found those first- and second-order methods can be improved by introducing the line search method. In contrast, the zero-order methods demonstrated excellent performance in terms of computational cost, and are consistent with the recent trend in finite element model updating which favors zero-order optimization methods.

Table 1. Performance of optimization methods

Order	Method	Epoch	Number of FEA	Error (%)
0	Nelder-Mead simplex	36	69	1.00
0	Particle Swarm	44	900	1.00
1	Gradient Descent	10,000	30,000	1.06
1	Gradient Descent with line search	10,000	1,436,100	1.01
1	Momentum	6,081	18,246	0.97
1	Momentum with line search	979	2,940	0.97
2	Newton	123	1,612	0.97
2	Newton with line search	13	182	0.98

4. Conclusions

In this study, we evaluated performances of various optimization methods for finite element model updating using a simply-supported beam model designed in MATLAB. Our findings suggest the zero-order methods and second-order with line search demonstrated superior performance in terms of accuracy and computational cost. These results may strengthen the validity of a recent trend of introducing zero-order optimization methods for finite element model updating. The authors think not only the traditional zero-order methods but recently developed zero-order optimization methods, such as La-MCTS (Wang et al. 2020), or a deep meta-learning-based optimization named 'learn to optimize (Li and Malik 2016)' could be further investigated for their potential applicability in finite element model updating.

Acknowledgement

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (NRF-2021R1C1C2008770).

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