Evaluation of Floor Response Spectra at Unmeasured Degrees of Freedom in Nuclear Power Plant Auxiliary Buildings via Seismic Response Reconstruction

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Keywords : floor response spectrum, dynamic response reconstruction, modal expansion, proper orthogonal decomposition

1. Introduction

Ensuring the functional continuity of nuclear power plants during seismic events is essential to prevent severe socio-economic losses. This necessitates a thorough equipment-level seismic evaluation that begins by accurately estimating local seismic demands like the floor response spectrum. In particular, previous studies have revealed that for large and irregular structures like nuclear auxiliary buildings, the floor response spectrum can vary significantly depending on the specific location, even within the same floor [1].

However, directly measuring seismic responses at all potential equipment locations is practically impossible due to economic and physical constraints [2]. To address this, a target-oriented modal expansion method utilizing a proper orthogonal decomposition (POD) basis can be applied to reconstruct unmeasured time-domain seismic responses. Because time-domain accuracy does not inherently guarantee reliability in the frequency domain, this study evaluates the floor response spectrum derived from these reconstructed responses. Ultimately, this verifies the practical applicability of the reconstruction method for equipment seismic design in nuclear facilities.

2. Time-domain Seismic Response Reconstruction

In this section, the proposed seismic response reconstruction method is introduced. This method reconstructs acceleration responses at unmeasured degrees of freedom (DOFs) in the time domain by utilizing a POD basis and an iteratively reweighted least squares (IRLS) algorithm. Furthermore, the application of this method to a nuclear power plant auxiliary building model is described.

2.1 Proposed time-domain response reconstruction method

The proposed framework aims to estimate time-domain seismic responses at unmeasured target nodes using limited sensor measurements. Conventional modal expansion relies on global eigenmodes. However, because eigenmodes are defined over all structural DOFs, they are inefficient for projecting only the dynamic responses of target nodes, which inherently leads to an increase in the required number of sensors. Therefore, the proposed method substitutes eigenmodes with a POD basis, defined as the left singular vectors of the dynamic response matrix at the target nodes. This presents a framework specialized exclusively for reconstructing dynamic responses at these specific nodes.

However, the POD basis only minimizes the average error of the extracted data, lacking robustness against unseen seismic excitations or individual target nodes [3, 4]. Furthermore, a conventional POD basis, obtained from a normalized and concatenated response matrix of multiple earthquakes, also struggles to ensure uniform reliability. This is because its performance is biased toward earthquakes with similar frequency contents within the training scenarios. Therefore, an IRLS algorithm is utilized to explicitly minimize the worst-case error by adaptively assigning higher weights to excitation-node pairs with larger projection errors. Ultimately, the optimized basis and weighting matrix enable robust time-domain response reconstruction at unmeasured target nodes from sparse sensor data.

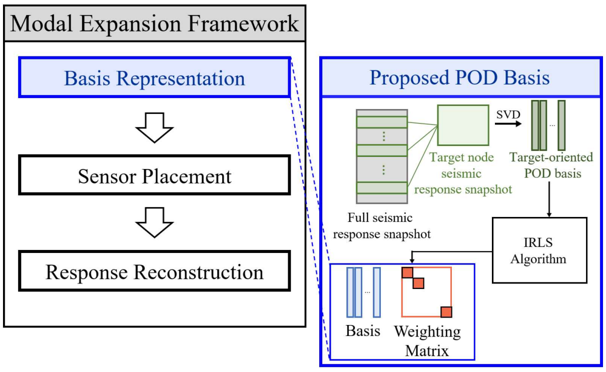


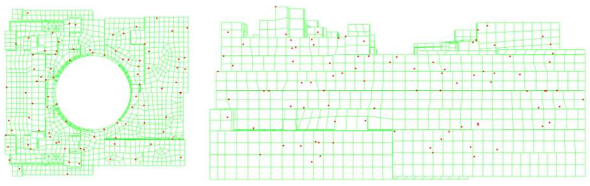
Fig. 1. Framework of proposed response reconstruction method.

2.2 Application to the nuclear power plant auxiliary building model

To validate the proposed method, a high-fidelity finite element (FE) model of a nuclear power plant auxiliary building is utilized. The model comprises seven floors discretized with shell elements, totaling 15,649 nodes and 66,852 degrees of freedom under a fixed base condition. Both the seismic excitation and response evaluation are restricted to the global x-direction.

For the response evaluation, 90 unmeasured target nodes are selected. To rigorously assess the reconstruction performance, these nodes are not chosen randomly. Instead, they are selected to maximize modal diversity based on their modal contributions. This configuration intentionally creates a challenging target set with highly heterogeneous dynamic behaviors, ensuring a conservative and reliable validation of the proposed framework.

Regarding the input seismic excitations, 22 pairs of the FEMA P-695 far-field ground motion set are utilized to ensure a conservative evaluation across a broad frequency range. Specifically, the first horizontal components (component 1) are used as training cases to extract the basis, while the second horizontal components (component 2) are employed as test cases to verify the reconstruction performance.



(a) Top view (b) Side view

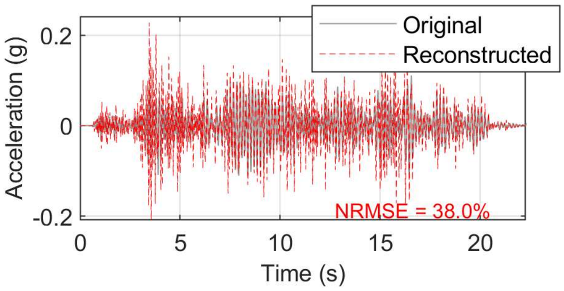
Fig. 2. Nuclear power plant auxiliary building FE model with 90 target nodes.

Table I summarizes the statistical results of the reconstructed seismic responses at the unmeasured degrees of freedom using 13 basis vectors and 16 sensors. Sensor placement follows the effective independence (EFI) criterion of Kammer [5]. Specifically, the optimal sensor locations were distinctly applied for each basis. Furthermore, Fig. 3 illustrates the time-history comparison for the worst-case scenario, which exhibits the maximum normalized root mean square error (NRMSE).

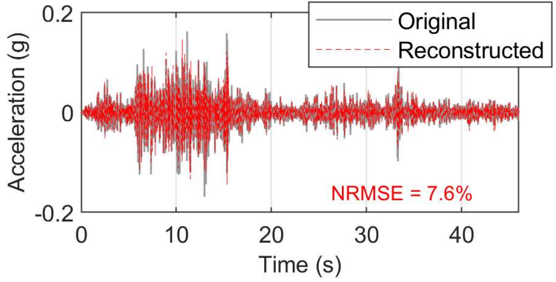
Table I: Statistical summary of time-series response errors

	NRMSE (%)		
	Eigenmode	Conventional POD basis	Proposed POD basis
Max.	38.012	7.585	3.059
Min.	1.560×10^{-4}	9.681×10^{-5}	0.045
Mean	3.529	0.509	0.674

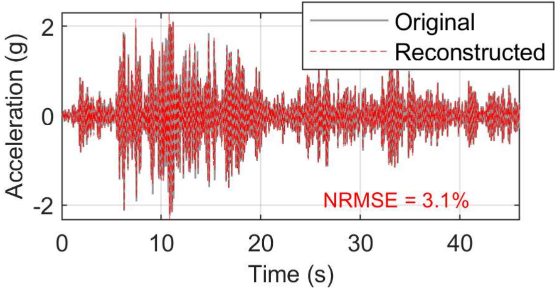
As shown in Table I, the eigenmode basis exhibits a significantly large worst-case error of 38.012%, as it primarily focuses on the global behavior of the entire structure rather than the specific target nodes. In contrast, the POD-based approaches demonstrate substantially lower error levels by concentrating on the local dynamics of the target locations. Notably, the proposed POD basis achieves a maximum NRMSE of 3.059%, which represents an approximate 60% reduction compared to the worst-case error of the conventional POD basis (7.585%). Furthermore, the time-history comparisons of these worst-case scenarios in Fig. 2 clearly illustrate this performance gap. While the 38.0% error of the eigenmode basis results in a severe mismatch with the actual time-series data, the proposed POD basis maintains a highly accurate trajectory even in its worst-case scenario at the 3.1% error level.



(a) Eigenmode



(b) Conventional POD basis



(c) Proposed POD basis

Fig. 3. Time-series comparison for the maximum NRMSE case of each basis method.

3. Evaluation of Floor Response Spectrum

In the previous section, it was demonstrated that utilizing the proposed POD basis instead of eigenmodes enables the accurate and robust reconstruction of unmeasured time-domain responses. Building upon these results, this section verifies whether the floor response spectrum derived from the reconstructed time-series closely matches the exact spectrum obtained from the actual responses.

3.1 Derivation of floor response spectrum

To evaluate the frequency-domain characteristics of the reconstructed seismic responses, the floor response spectrum is derived. Considering that the target nuclear auxiliary building is a reinforced concrete structure, a damping ratio of 5% is applied. The reconstructed acceleration time-history responses at the unmeasured target nodes are used as input motions to a series of single-degree-of-freedom systems to calculate the absolute maximum spectral acceleration across the frequency range.

3.2 Evaluation of reconstructed floor response spectra

Table II summarizes the statistical errors between the FRS derived from the original time-series and the FRS derived from the reconstructed time-series, evaluated in terms of NRMSE. And Fig. 4. illustrates the FRS for the worst-case NRMSE of each basis method. Similar to the time-domain results, the eigenmode basis exhibits severe inaccuracies, yielding an unacceptable maximum NRMSE of 45.238%. While the conventional POD basis significantly reduces the overall mean errors, it shows a maximum NRMSE of 8.919%. Such a high level of NRMSE can lead to unreliable seismic evaluations for critical equipment. In contrast, the proposed POD basis effectively suppresses these worst-case errors, restricting the maximum NRMSE to 2.420%. This remarkable reduction in the maximum NRMSE demonstrates that the proposed framework provides robust and highly reliable FRS estimations, which is essential for ensuring the structural safety of unmeasured target nodes.

Table II: Statistical summary of floor response spectra errors

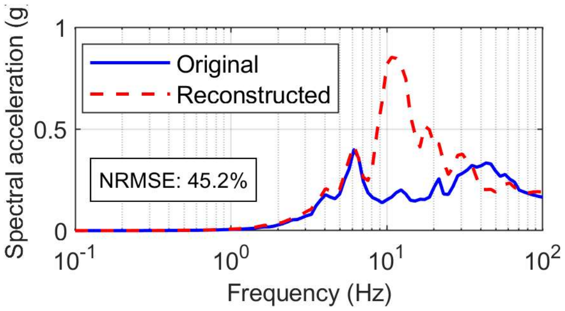
	NRMSE (%)		
	Eigenmode	Conventional POD basis	Proposed POD basis
Max.	45.238	8.919	2.420
Min.	3.033×10^{-4}	7.870×10^{-5}	0.024
Mean	3.900	0.474	0.443

4. Conclusions

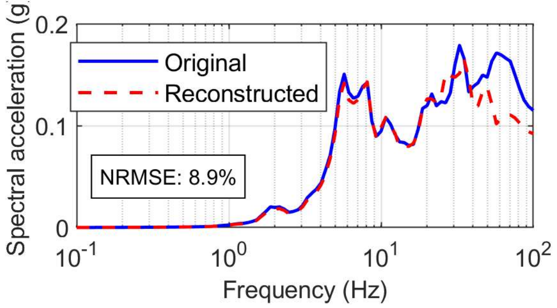
This study verified the floor response spectrum estimation performance of a framework that robustly reconstructs unmeasured time-domain seismic responses based on measured data. The numerical results demonstrated that the proposed algorithm, which aims to accurately match time-series responses, also successfully reproduces the overall trends of the exact floor response spectra. However, because the objective function of the algorithm focuses on minimizing the worst-case NRMSE in the time domain, it does not explicitly optimize frequency-domain characteristics. Therefore, a quantitative analysis of the correlation between time-domain reconstruction errors and frequency-domain spectral accuracy is required in future studies.

ACKNOWLEDGEMENTS

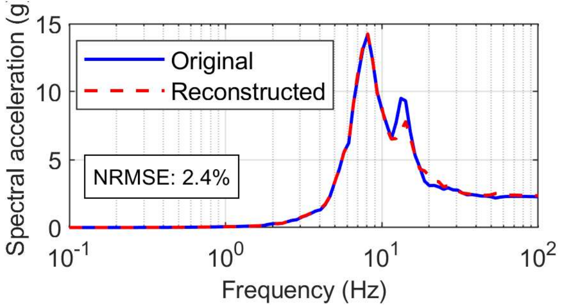
This research was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (No. RS-2022-00144425). All authors approved the final version of the manuscript.



(a) Eigenmode



(b) Conventional POD basis



(c) Proposed POD basis

Fig. 4. Floor response spectra comparison for the maximum NRMSE case of each basis method.

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