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A Study on Robust Optimal Sensor Placement for Containment Buildings in Nuclear Power Plants

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1. Introduction

The importance of real-time monitoring and safety diagnosis technology is increasing to ensure the seismic performance of nuclear power plants [1]. However, the current earthquake monitoring sensor system has limitations in identifying the dynamic characteristics of structures. To address this limitation, multiple accelerometers must be optimally placed. The sensor system of nuclear power plant structures should be robust in signal acquisition even when their signal-to-noise ratio is weak, and the contribution of the mode is mainly concentrated in the low-order mode [2]. Thus, analyzing the robustness to noise by mode is essential. This study presents an optimal sensor placement methodology for evaluating the robustness to noise by mode using Modal Assurance Criterion (MAC).

2. Methods and Results

This section presents an optimal sensor placement methodology by evaluating the robustness to noise based on the OPR-1000 nuclear power plant containment model. Some of the results by the methodology in this section are contained in the reference [3].

2.1 Input Ground Motion and FE Model

The USNRC RG 1.60 design response spectrum, which exhibits a strong response from the first natural frequency (4.57 Hz) of the nuclear power plant containment building, was utilized to generate input seismic motion. The earthquake time-history data was generated by utilizing SAP 2000's 'Time history matched to response spectrum' function to consider the response spectrum frequency components, based on the time history of the Gyeongju Earthquake(2016). The time-history data was sampled at a frequency of 100 Hz, and a total time duration of 30 seconds was included.

As an analysis model, the lumped mass model of the OPR-1000 containment building was used. The model has a total height of 65.84m and is comprised of 14 nodes, including the ground point, and 13 beam elements. Detailed physical properties such as the mass and elastic modulus of each element are described in the reference [4]. Although this model contains rotational degrees of freedom for each node, the rotational degrees of freedom have been eliminated through Guyan reduction to place an accelerometer in the translational degrees of freedom. [5]. The natural frequency, mode shape, and mode participation mass ratio were obtained through eigen analysis, and the results are presented in Table 1.

Table 1: Modal parameters of the model [3]

Mode	Natural freq. (Hz)	Modal participation mass ratio (each mode / cumulative)
1	4.57	71.9% / 71.9%
2	13.53	19.3% / 91.2%
3	25.06	4.6% / 95.8%
4	37.39	2.0% / 97.8%
5	43.13	0.6% / 98.4%

2.2 Optimal Sensor Placement for Different Number of Sensors

The target mode for optimal sensor placement was chosen up to the 3rd mode, taking into account the modal participation mass ratio (95.8%, cumulative). As a cost function for optimization, auto MAC was selected, which could directly represent the linear independence of mode shape with minimal calculation effort. The optimization results are presented in Table 2, and it can be observed that the criteria (auto MAC < 0.25) [6] is met with three or more sensors. Therefore, it was found that at least three sensors were required to consider three target modes.

Table 2: Optimal sensor placement results for different numbers of sensors [3]

Sensor Numbers	Sensor nodes	Maximum MAC off-diagonal value
2	4, 10	0.3947
3	6, 9, 12	0.0119
4	3, 7, 10, 12	0.0196
5	6, 7, 9, 11, 12	0.0002
6	1, 3, 7, 8, 11, 12	0.0279
7	5, 6, 7, 9, 10, 11, 13	0.0009
8	2, 3, 6, 7, 9, 10, 11, 13	0.0003
9	1, 2, 3, 4, 7, 8, 9, 11, 13	0.0016
10	1, 2, 3, 5, 6, 8, 9, 10, 12, 13	0.0110
11	3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13	0.0050
12	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13	0.0069
13	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13	0.0106

2.3 Optimal Sensor Placement Considering the Robustness to Noise

To account for noise, numerical analysis was conducted by repeatedly applying Gaussian white noise to both the input and output data 100 times. Since the mode shapes may change with each application of Gaussian white noise, their stability was evaluated using auto MAC and cross MAC as indicators.

The distribution of the average value of the auto MAC is shown in Figure 1, considering the change in the signal-to-noise ratio (SNR) and the number of sensors. As the SNR decreases and noise prevails, the average value of the auto MAC increases, indicating a decrease in mode independence. Additionally, an increase in the number of sensors leads to a decrease in the average value of the auto MAC, implying that more sensors provide more information and better mode independence.

Auto MAC is a useful metric for evaluating the overall robustness of the target mode. However, there are limitations in analyzing the effects of noise on individual modes. To address these limitations, we computed cross MAC that can evaluate the consistency of the mode shape matrix obtained by eigen analysis and the mode shape matrix obtained by input/output data. After calculating the cross MAC, it was observed that the 3rd mode, which has low modal contribution, was less consistent compared to the 1st and 2nd modes. In addition, as shown in Figure 2, the mean value tended to decrease as SNR decreased. This indicates that, as with auto MAC results, the reliability of mode shape estimation decreases as the SNR decreases.

However, as the number of sensors increased, the mean value of the cross MAC tended to decrease. Although the cross MAC for the 6-sensor configuration was significantly lower than for other configurations due to poor mode independence, in general, the cross MAC had decreasing trend as the number of sensors increased. This is contrary to the expected logic that increasing the number of sensors should improve the accuracy of mode shape estimation by increasing the amount of information. This phenomenon is attributed to mathematical reasons, namely that the inner product of arbitrary vectors tends to become orthogonal as the dimensionality of the data increases [7].

To address the issue, we applied absolute value to the mode shape matrix extracted in the complex number form to remove the distorted phase information. The sign of the mode shape was determined based on the normal mode obtained through eigen analysis. Additionally, we employed spline interpolation to unify the dimensions of mode shapes extracted from a small number of sensors. Table 3 shows the mean and standard deviation of the 3rd mode cross MAC after removing the phase distortion from the data of 3 sensors, 3 sensors with spline interpolation, and 13 sensors. After removing the distorted phase information, the cross MAC for 13 sensors improved significantly (0.3483 → 0.7286). Additionally, by interpolating the information of the 3 sensors to unify the dimensions, the cross MAC for 3 sensors decreased. This approach helped to mitigate the issues caused by dimension differences. Still, the mode shape estimation performance for the 3 sensors was similar to that of the 13 sensors, which is believed to be due to the model nature that the shape of the 3rd mode is similar to the shape of the spline curve.

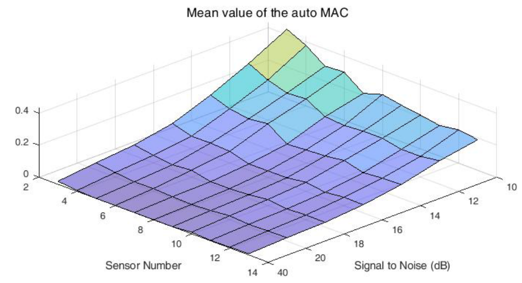

Fig. 1. The mean value of the auto MAC for the different SNR and sensor numbers

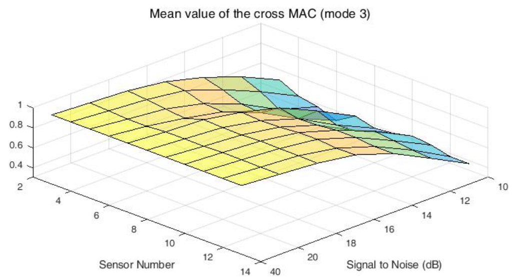

Fig. 2. The mean value of the cross MAC(mode 3) for the different SNR and sensor numbers

Table 3: The mean value of the cross MAC(mode 3) after phase distortion correction (3 sensors, 13 sensors)

Number of sensors	Mean value	Standard deviation
3	0.7924	0.1476
3 (interpolated)	0.7299	0.1276
13	0.7286	0.0911

3. Conclusions

This study presented an optimal sensor placement methodology considering noise level and mode contribution for modal parameters estimation of nuclear power plant containment buildings. It was possible to efficiently evaluate the robustness of noise by mode through auto MAC, cross MAC distributions, correction of phase information distortion, and spline interpolation.

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