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Performance evaluation of three sensor placement methods

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ABSTRACT

In this paper, we evaluate the performance of three sensor placement methods: maximum and minimum points; maximum determinant; and minimum condition number. The virtual sensing approach is explained using the mode superposition method. Virtual sensing for the strain field estimation is carried out for a jacket structure under wave loads. The results of virtual sensing are evaluated by comparing the estimated strains with the measured strains at virtual sensing points according to the three sensor placement methods.

1. INTRODUCTION

As mechanical structures become larger and more advanced, structural safety has become more important, and a structural health monitoring system has been developed (Farrar & Worden, 2007; Mishra, Lourenço, & Ramana, 2022). Most of the structures are exposed to repetitive loads for long periods of time, making consideration of fatigue essential. Offshore plants are one type of structure that is prone to fatigue due to the constant and repetitive loading caused by waves (Pedersen et al., 2019).

Because offshore structures are installed in deep water, monitoring their health state through direct measurements is difficult and expensive. Virtual sensing is a technique that utilizes the measured response of a structure at a few points and a corresponding numerical model of the structure to estimate the response of all areas of the structure. Virtual sensing can estimate the response of entire areas of a structure, which means the response inside materials that are difficult to measure with sensors and the response

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on materials exposed to extreme environments could be estimated. In addition, responses that are smaller or larger than the measurement range of the sensors could be estimated. Virtual sensing has been used to estimate strain and temperature fields in structures and is expected to be used in many engineering fields more and more (Brunello, Urgolo, Pittino, Montvay, & Montanari, 2021; Go, Lim, & Lee, 2023; Yu, Kwak, Park, & Lee, 2010).

Virtual sensing based on mode superposition is a widely used method. In mode superposition-based virtual sensing, the estimation accuracy depends on the type of basis selected, signal processing, sensor placement, etc. In this study, we compare virtual sensing results for a jacket structure under wave loads according to various sensor placement methods and suggest the best sensor placement method.

2. Virtual sensing procedure

Fig. 1 describes the concept of virtual sensing on a jacket structure, one type of offshore structure. The responses of the structure are measured at a few points using sensors from the actual structure. The measured response is extended to the response of the entire area by virtual sensing based on mode superposition method. The estimated response can predict the actual response with high accuracy.

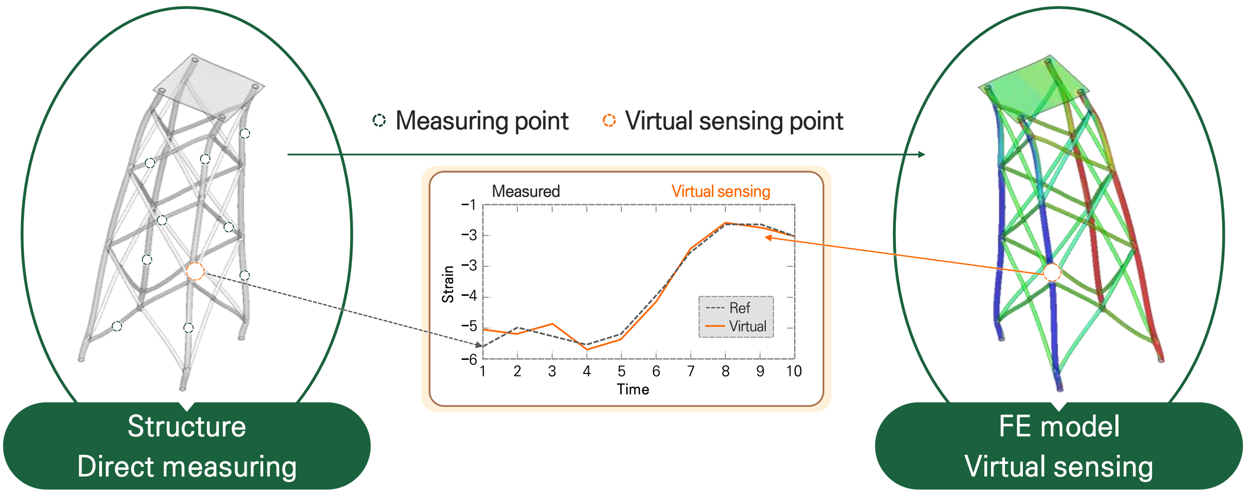

Fig. 1 Concept of virtual sensing.

In this paper, we use strain gauges to measure the structural response of strain and estimate the strain field of a jacket structure. The generalized coordinate vector $\mathbf{q}$ is calculated based on a least square solution to minimize the error between the measured strain and estimated strain as

$$\mathbf{q} = (\mathbf{\Psi}^{\mathrm{T}}\mathbf{\Psi})^{-1}\mathbf{\Psi}^{\mathrm{T}}\hat{\boldsymbol{\varepsilon}} \quad \text{with} \quad \mathbf{\Psi} = [\mathbf{\Psi}_1 \quad \mathbf{\Psi}_2 \quad \ldots\ldots \quad \mathbf{\Psi}_N], \tag{1}$$

where $\mathbf{\Psi}$ is the strain basis matrix at strain gauge positions with N strain bases and $\hat{\boldsymbol{\varepsilon}}$ is the measured strain vector. The strain field is estimated using the calculated generalized coordinate vector $\mathbf{q}$ and the strain basis matrix at a material point $\mathbf{x}$ as

$$\boldsymbol{\varepsilon}(\mathbf{x}) \approx \mathbf{\Psi}(\mathbf{x})\mathbf{q} \tag{2}$$

3. Virtual sensing conditions

In order to apply virtual sensing to a jacket structure, strain is measured from an experimental scale jacket structure deformed by wave loads. For the strain basis, 2 static deformed shapes by waves in the x-direction and y-direction are selected to reconstruct the quasi-static behavior by wave loads, and dynamic mode shapes form mode number 1 to 5 are selected to reconstruct the dynamic behavior by free vibration.

The measured strain is the result of superposition of quasi-static strain component and dynamic strain component. To match each strain component to the corresponding basis of the static deformed shape and dynamic mode shape, measured strain signals are divided to low and high frequency strain component considering the wave frequency applied and natural frequency of the jacket structure (Iliopoulos, Weijtjens, Van Hemelrijck, & Devriendt, 2017; Skafte, Kristoffersen, Vestermark, Tygesen, & Brincker, 2017). The total procedure and conditions for virtual sensing is described in Fig. 2.

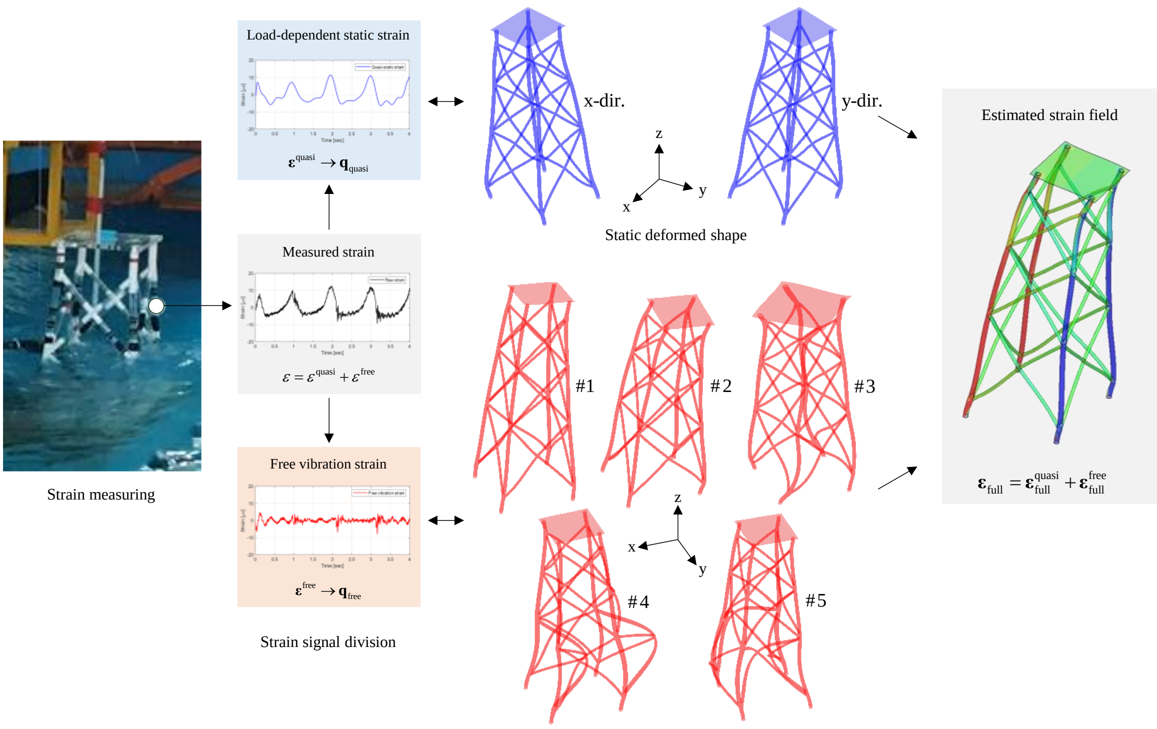

Fig. 2 Virtual sensing procedure with conditions.

10 strain gauges are applied in the axial direction at each pipe member of the jacket structure. The sensor placement of 10 strain gauges is determined using the following 3 methods: Points where the maximum and minimum axial strain occurs for each basis (Max-Min)(Yildirim, Chryssostomidis, & Karniadakis, 2009); Points where the determinant of $\mathbf{\Psi}^{T}\mathbf{\Psi}$ in Eq. (1) is maximized (Max-Det)(Lee & Eun, 2021); and Points where the condition number of $\mathbf{\Psi}^{T}\mathbf{\Psi}$ in Eq. (1) is minimized (Min-Cond)(Rapp, Kang, Han, Mueller, & Baier, 2009; Willcox, 2006). The 10 sensor points are selected among 26 possible sensing points according to each method. Fig. 3 represents the selected points (colored in yellow) on the jacket structure for each sensor placement method.

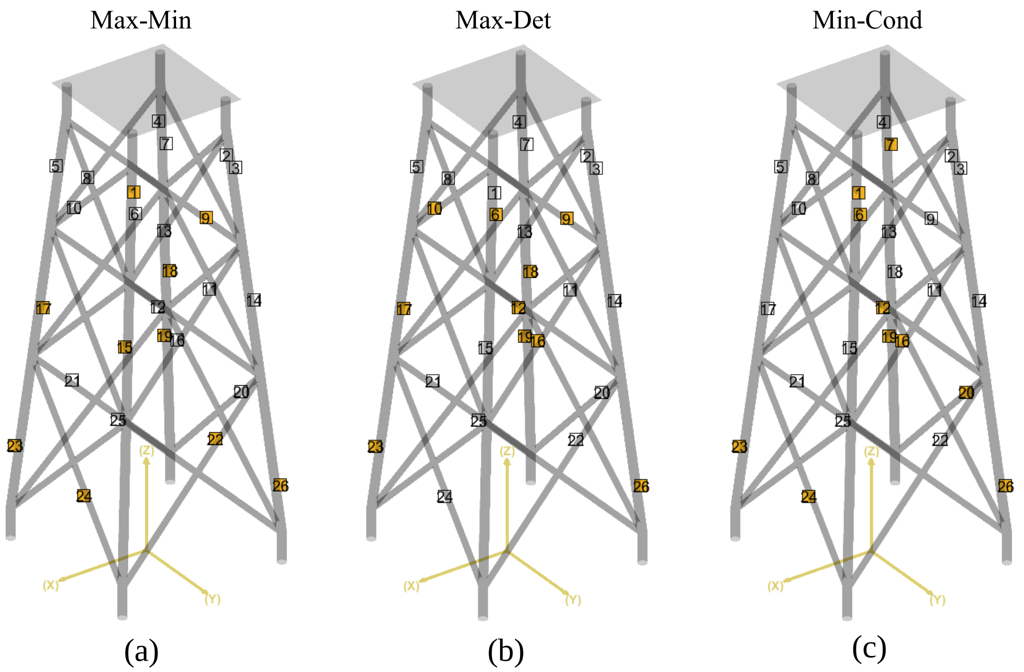

Fig. 3 Sensor placements for 3 methods: (a) Max-Min; (b) Max-Det; (c) Min-Cond.

4. Virtual sensing results

The estimated strain from the virtual sensing is compared with the strain directly measured from the strain gauge at virtual sensing points: Sensor 19 and 26. Fig. 4 represents the comparison of the estimated strain and measured strain at the virtual sensing points for each method. The sensor placement of the Min-Cond method estimates strains better than the others do. Depending on how the sensors are placed, the estimated strain error become large; especially, the error varies a lot in the deep water point as shown in Sensor 26 results.

For the sensor placement of the Min-Cond method, the estimated strains are nearly identical to the measured strains even in the deep-water virtual sensing points. Of course, the estimation accuracy at other virtual sensing points: Sensor 11-14, 17, 21, 22, and 25 have the same extent of accuracy as much as the points shown in Fig. 4

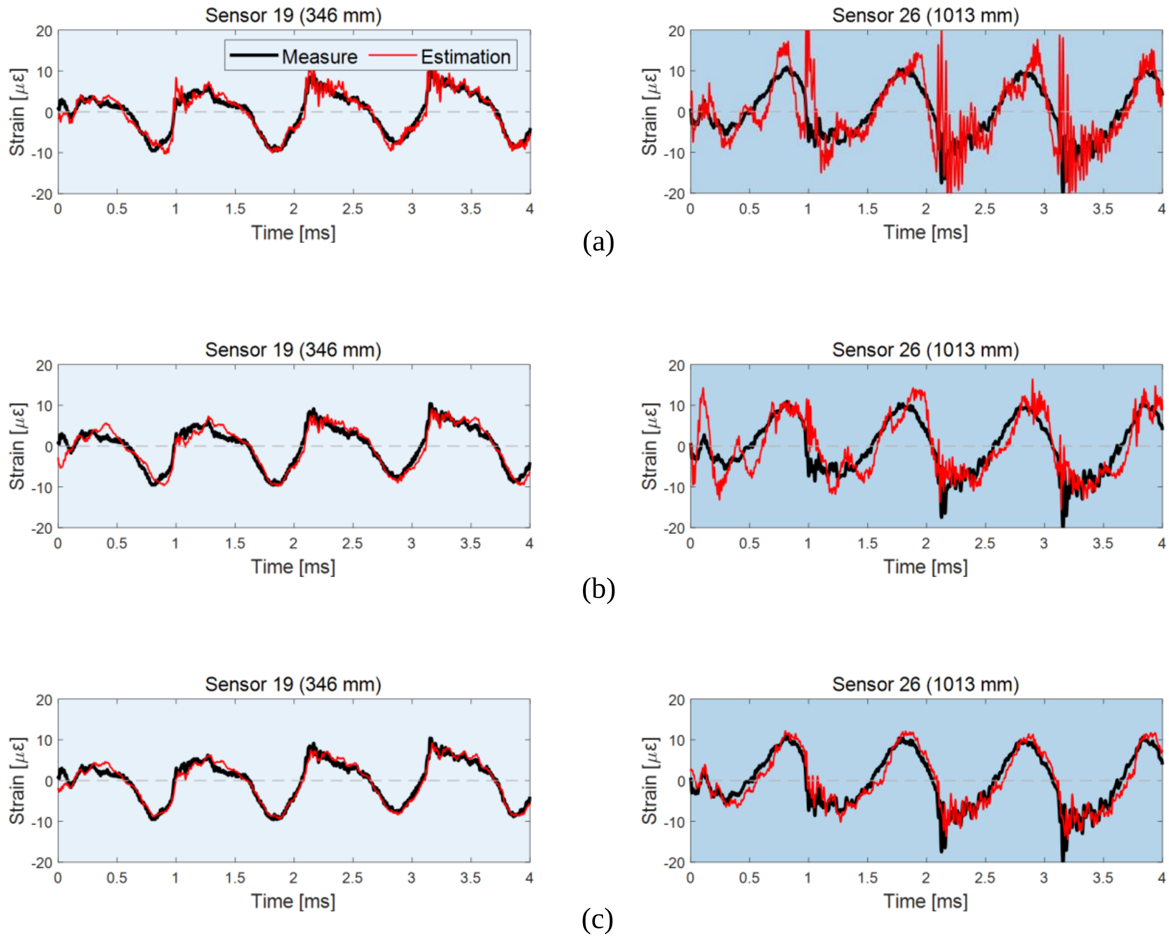

Fig. 4 Virtual sensing results at Sensor 19 and 26 for 3 methods:
(a) Max-Min; (b) Max-Det; (c) Min-Cond.

5. Conclusions

In this paper, virtual sensing based on the mode superposition method is carried out for strain field estimation of the jacket structure. Virtual sensing results according to various sensor placement methods are evaluated. The sensor placement of the Min-Cond method showed a high estimation accuracy, where the estimated strains are in good agreement with the measured strains even in the deep-water virtual sensing points.

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