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A two-stage framework for automated operational modal identification using OPTICS-KNN-based clustering

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Theoretical derivation

Developing a two-stage automated operational modal analysis framework that addresses the challenge of automated identification of closely spaced modes.

Automate Operational Modal Analysis

COV-SSI

$$\mathbf{H}=\left[\mathbf{U}_1 \quad \mathbf{U}_2\right]\begin{bmatrix}\mathbf{S}_1 & \mathbf{0}_{n\times(li-n)}\\ \mathbf{0}_{(li-n)\times n} & \mathbf{S}_2\end{bmatrix}\begin{bmatrix}\mathbf{V}_1^{\mathrm{T}}\\ \mathbf{V}_2^{\mathrm{T}}\end{bmatrix}\approx \mathbf{U}_1\mathbf{S}_1\mathbf{V}_1^{\mathrm{T}}$$

Modal Assurance Criterion

Modal frequency: $$\frac{f^{(m+1)}-f^{(m)}}{\max\left(\left|f^{(m+1)}\right|,\left|f^{(m)}\right|\right)}\leq\delta_f$$

Mode shape: $$1-\mathrm{MAC}(\boldsymbol{\psi}^{(m)},\boldsymbol{\psi}^{(m+1)})\leq\delta_\psi$$

Damping ratio: $$\frac{\xi^{(m+1)}-\xi^{(m)}}{\max\left(\left|\xi^{(m+1)}\right|,\left|\xi^{(m)}\right|\right)}\leq\delta_\xi$$

Ordering points to identify the clustering structure

Step Ⅰ: Modal analysis by SSI-COV

- Obtain the output data $\mathbf{Y}$, and preprocess the output data
- Assemble the block Hankel matrix **Eq. (5)**
- Apply SVD to $\mathbf{H}$ estimate $\mathbf{O}_i$ **Eq. (7)**
- Estimate $\mathbf{C}$ by the first rows of $\mathbf{O}_i$ **Eq. (6)**
- Explore the $\mathbf{O}_i^{\uparrow}$ and $\mathbf{O}_i^{\downarrow}$ to estimate $\mathbf{A}$ **Eq. (9)**
- Estimate the f_p, ξ_p and $\boldsymbol{\psi}_p$ from $\mathbf{A}$ and $\mathbf{C}$ **Eq. (11)**

Step Ⅱ: Pre-processing

- Remove spurious modes under HVC and SVC **Eqs. (12), (15) ,and (17)-(20)**
- Remove spurious modes under UVC **Eq. (21)**

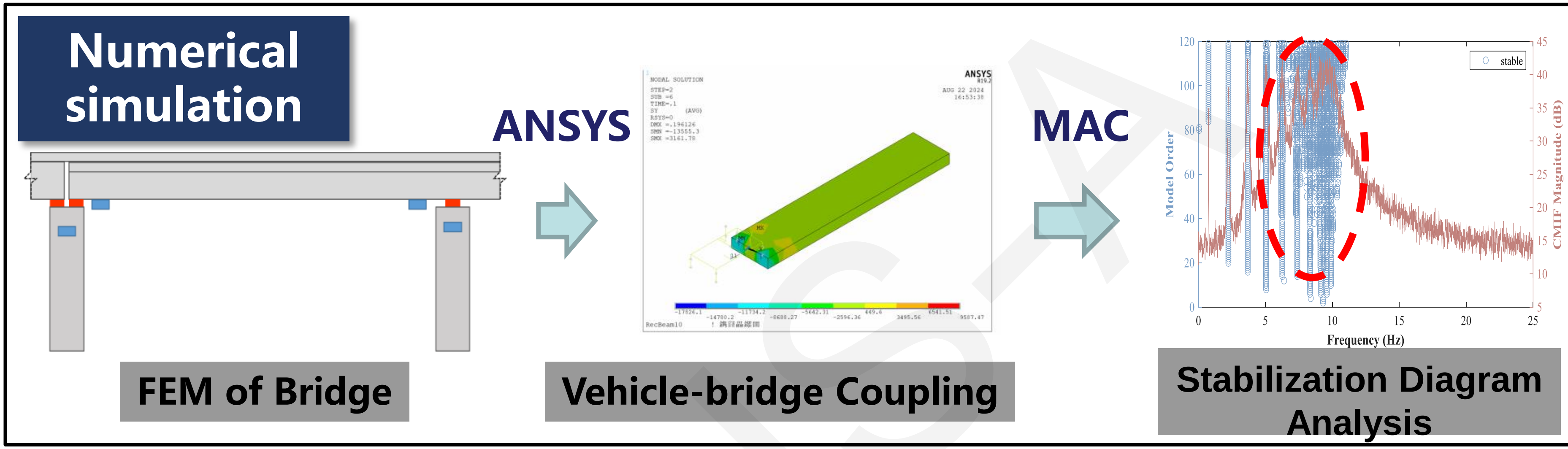
Step Ⅲ: Physical mode clustering

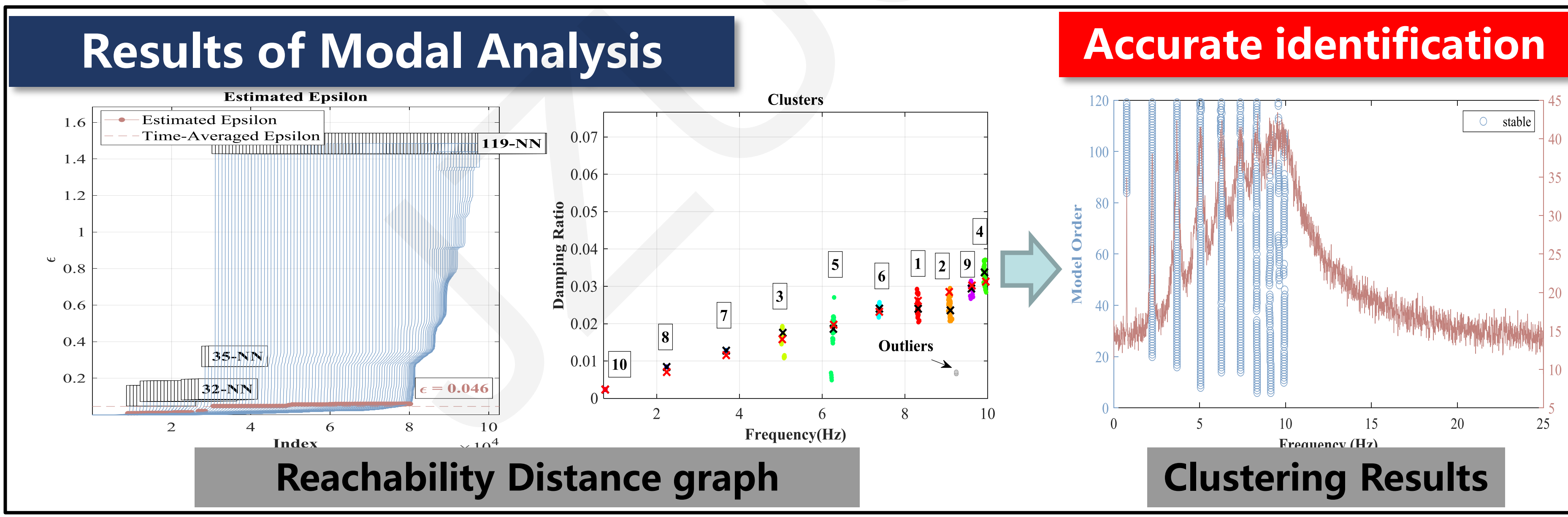
- Estimate the optimal *epsilon* by KNN method **Eqs. (22)-(25)**
- Group modes by improved adaptive clustering
- Select mean of each cluster as representatives of physical modes

$$RD_{MinObj}\left(X,X_p\right)=\begin{cases}Undefined & \text{if } \left|N_{\varepsilon\to\infty}\left(X\right)\right|< MinObj\\ \max\left(CD_{MinObj}\left(X_p\right)\right), dist(X,X_p) & \text{otherwise.}\end{cases}$$

$$CD_{MinObj}\left(X\right)=\begin{cases}Undefined & \text{if } \left|N_{\varepsilon\to\infty}\left(X\right)\right|< MinObj\\ \min\limits_{\varepsilon}\left(\left|N_{\varepsilon}\left(X\right)\right|\right)\leqslant MinObj & \text{otherwise.}\end{cases}$$

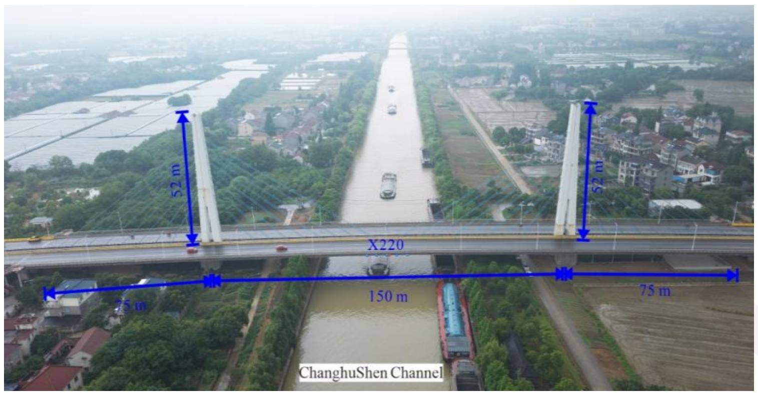
Numerical verification



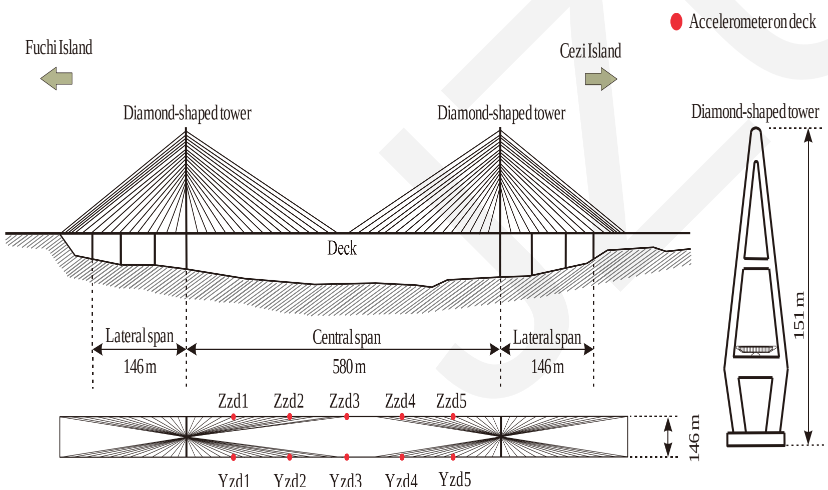


Application to field measurement

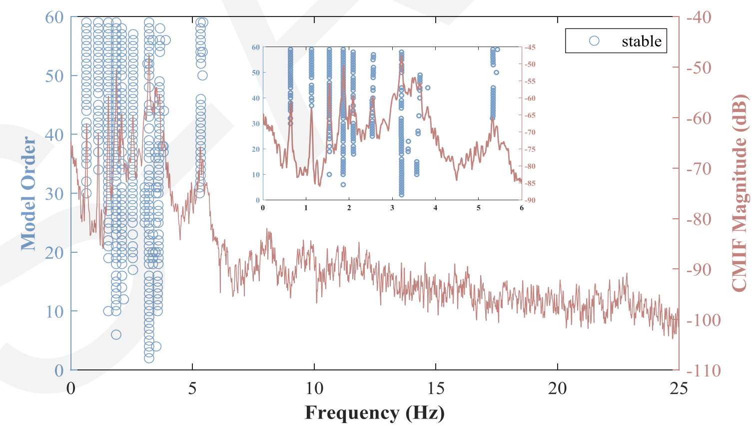
The application of an automated modal parameter identification method effectively tracked the time-varying characteristics of the dynamic parameters of the Taoyaomen Bridge, providing a scientific basis for the overall condition assessment of the bridge structure.



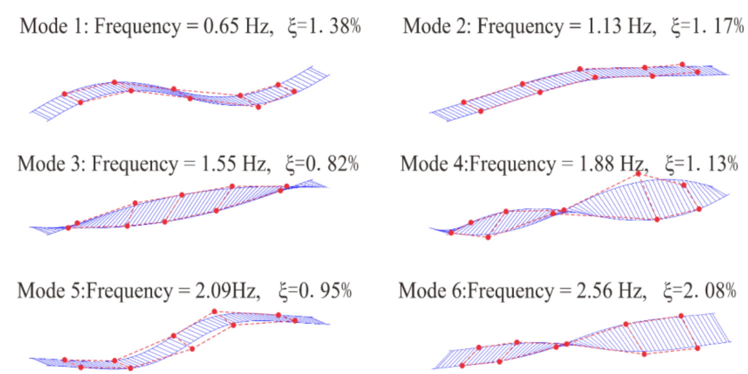
Large-span bridge



Arrangement of Accelerometers



Stabilization Diagram



The first six modal shape

Conclusions

- According to the identified results of the modal parameters from the ten-story frame and the Taoyaomen Bridge, the frequencies and damping ratios of each mode remain within a narrow range, validating that the proposed approach can effectively remove spurious modes and identify physical modes.
- The proposed approach performs well in identifying closely spaced modes, as demonstrated by numerical verification on the shear frame. These modes have been successfully discovered without the need for specifying the number of clusters or a threshold value for clustering.
- Six mode shapes of the Taoyaomen Bridge were identified, and the modal parameters were continuously tracked over several days. The results show that the practicability of the approach is confirmed by analyzing extensive datasets collected from SHM systems.