

Substructure-Based Damage Detection Using an Unscented Kalman Filter in the Time Domain

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***Keywords: Substructuring, Damage detection, Unscented Kalman filter**

1. Introduction

Structural damage detection is essential for ensuring structural safety, and its importance is even greater for high-reliability facilities such as nuclear power plant buildings. In recent years, many response-based approaches have been developed to identify the location and severity of damage by comparing measured responses with numerical-model predictions. However, reproducing real structures with complete fidelity in numerical models remains challenging, and modeling uncertainties in boundary conditions and material properties can significantly degrade the reliability of damage estimation [1].

To mitigate these limitations, substructure-based damage detection has attracted increasing attention. By isolating a region of interest as a substructure, this framework reduces the influence of modeling uncertainties originating from the remaining parts of the structure. A key challenge, however, is the accurate treatment of interface effects, because the interface degrees of freedom (DOFs) transmit the interaction between the substructure and the rest of the structure. This issue becomes more critical under operational conditions, where the input excitation is typically unmeasured and interface quantities cannot be directly prescribed.

In this study, we propose a practical approach for handling interface effects under operational conditions. The method assumes white-noise excitation and uses response correlations to extract impulse-response-type information. The feasibility and effectiveness of the proposed framework are demonstrated through a numerical case study.

2. Methodology

2.1. Substructuring Formulation and DOF Partitioning

Under operational conditions, the ambient excitation acting on the structure is assumed to be white noise. With this assumption, correlations of the measured responses can be interpreted in a free-vibration-type form, which enables a consistent substructuring formulation without explicit input measurements. Based on this idea, the full set of DOFs is partitioned into the internal DOFs of the substructure, the interface DOFs on the substructure boundary, and the DOFs outside the substructure. The equations of motion are then reorganized from the substructure perspective using this DOF decomposition.

With this partitioning, the response of the substructure internal DOFs can be interpreted as the superposition of two components. The first component represents the free response associated with the internal DOFs. The second component represents a forced response induced by the interface motion, where the interface DOFs act as an equivalent excitation to the substructure. This forced-free interpretation motivates the next step, in which the interface response is reconstructed from limited measurements to enable a stable substructure-based estimation procedure.

2.2. Reconstruction of the interface DOF response

In practice, it is not feasible to instrument all interface DOFs, and therefore the interface response must be reconstructed. To this end, modal shapes are first extracted from a baseline global (or substructure) model within the frequency band of interest. Using these modes, the modal matrix associated with the boundary DOFs, Φ_b , and the modal matrix associated with the measured DOFs, Φ_{meas} , are constructed. Next, the acceleration impulse responses obtained from response correlations (correlation-based IRFs) are used, together with all available internal measurements and the measured subset of interface channels, to estimate the initial conditions of the selected modal coordinates (q, \dot{q}) via a windowed stacked least-squares procedure. To ensure continuity across windows, the estimate from the previous window is incorporated as a prior. The estimated initial conditions are then propagated in time using a Kalman-filter-based smoother to obtain the modal time histories $q(t)$ and $\dot{q}(t)$, from which $\ddot{q}(t)$ is computed through the modal equations. Finally, the reconstructed (q, \dot{q}, \ddot{q}) are projected onto Φ_b , to recover the displacement, velocity, and acceleration responses at all boundary DOFs. For the boundary acceleration channels that are directly measured, the reconstructed signals are replaced with the measurements to enforce consistency at the instrumented interface. The resulting interface responses are subsequently used to perform forced-free decomposition of the internal substructure responses and to estimate stiffness changes associated with damage.

2.3. Damage detection using an Unscented Kalman Filter

After reconstructing the interface responses, damage detection is performed by estimating the stiffness scaling factors of the target substructure members using an

unscented Kalman filter (UKF) in the time domain. In the proposed forced-free formulation, the measured internal responses are interpreted as the superposition of a boundary-driven forced component and an internal free component. Using the reconstructed boundary displacement/velocity/acceleration as inputs, the forced component of the internal acceleration response is computed from the substructure model. The remaining component, obtained as the difference between the measured internal acceleration and the forced response, is treated as the free-response part, which is governed by the substructure dynamics.

The unknown parameter vector is defined as the set of member stiffness scaling factors, denoted by θ , associated with the selected elements in the substructure. The UKF treats θ as a slowly varying (random-walk) state to capture stiffness reduction due to damage, while the measurement is the internal acceleration response within a sliding time window. For each time window, sigma points of θ are generated and propagated through a nonlinear mapping that reconstructs the predicted acceleration response. Specifically, for each sigma point, the algorithm (i) assembles the substructure matrices based on the candidate θ , (ii) computes the boundary-driven forced acceleration using the reconstructed interface inputs, (iii) estimates the initial conditions of the free component (and an optional low-order bias term) via a weighted least-squares fit to the residual, and (iv) rolls out the free response over the window to obtain the predicted internal acceleration. The predicted measurement ensemble is then used to update θ through the standard UKF update, and a conservative update factor is applied to improve stability under limited and noisy measurements.

Damage is finally identified from the estimated stiffness ratios. For each damage case, the member exhibiting the smallest estimated stiffness ratio (equivalently, the largest inferred stiffness reduction) is selected as the damaged member. In addition to the point estimates, the UKF provides parameter covariance information that can be used to assess the confidence of the identification, especially when multiple members yield similar stiffness reductions under low-sensitivity conditions.

3. Numerical Case Study

3.1. Target Structure

A numerical case study was conducted on a two-dimensional (2D) truss structure to evaluate the performance of the proposed framework. The substructure selected for damage detection is highlighted in red in Fig. 1, and the instrumented DOFs at the interface nodes are indicated. In addition, the member numbering of the substructure elements considered for damage detection is shown for clarity.

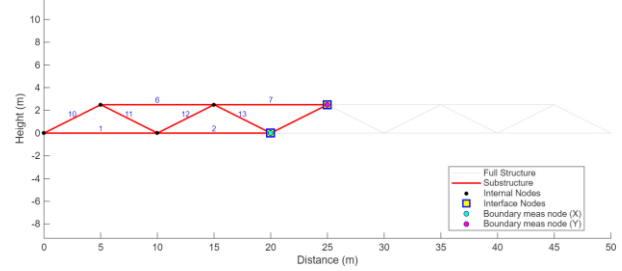


Fig. 1. Schematic of the 2D truss structure and the selected substructure (red). The instrumented internal DOFs (y-direction), the two instrumented interface acceleration DOFs (one x-direction and one y-direction), and the numbering of the target members are indicated.

Damage scenarios were defined for the eight truss members that constitute the substructure. In each scenario, the stiffness of a single member was reduced by 25% relative to the baseline value and treated as damage. This procedure was repeated for all eight members, resulting in a total of eight damage cases. For the estimation stage, the initial model was assigned unit stiffness scaling factors for all members, and the measured responses were used to estimate the member stiffnesses. Damage was then identified by locating the member exhibiting the largest stiffness reduction (i.e., the smallest estimated stiffness ratio).

3.2. Simulation setup

Operational conditions were emulated by applying broadband ambient excitation, treated as a white-noise-type input, to the global 2D truss model. Acceleration responses were collected at a limited set of measurement DOFs, consisting of selected internal DOFs in the y-direction and two instrumented interface acceleration DOFs (the x-direction acceleration at one interface node and the y-direction acceleration at another interface node). Correlation-based acceleration impulse response functions (IRFs) were then computed using multiple reference channels. Since full instrumentation at the interface is impractical, the interface responses were reconstructed offline using a modal basis extracted from a baseline model within a selected frequency band. Modal initial conditions (q_0, \dot{q}_0) were estimated from acceleration-only IRFs using a windowed stacked least-squares formulation with high overlap and prior continuity between adjacent windows, and the modal time histories were refined using a Kalman-filter-based smoother. The reconstructed (q, \dot{q}, \ddot{q}) were projected onto the interface modal matrix to obtain interface displacement, velocity, and acceleration, while the two instrumented interface acceleration channels were enforced by replacing the reconstructed signals with the corresponding measurements.

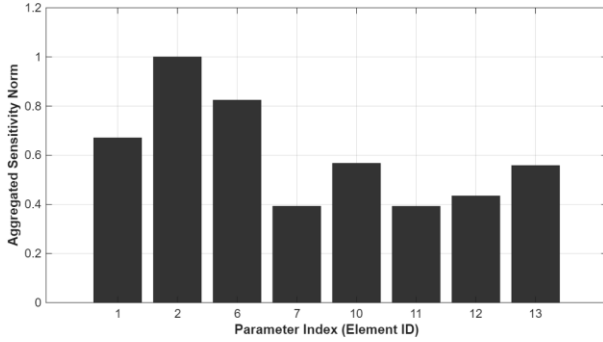


Fig. 2. Aggregated sensitivity norm of the measured responses with respect to member stiffness perturbations for the target substructure members.

Before performing damage detection, a member-level sensitivity analysis was conducted to examine how the measured responses vary with stiffness changes in each truss member. The sensitivity was quantified by the response variation induced by a prescribed stiffness perturbation, and the aggregated sensitivity norms are shown in Fig. 2. As shown, Members 1, 2, and 6 exhibit relatively high sensitivity, whereas Members 7, 11, and 12 show comparatively low sensitivity.

3.3. Damage detection results

Table I summarizes the estimated stiffness ratios of the target members for each damage case. In each case, damage was identified as the member exhibiting the smallest estimated stiffness ratio (i.e., the largest inferred stiffness reduction). Using this criterion, the damaged member was correctly identified in six out of eight cases. Misidentification occurred in Case 4 and Case 6, where a different member showed the minimum stiffness ratio than the true damaged one. Consistent with the sensitivity analysis, clearer identification was obtained when damage occurred in highly sensitive members (e.g., Case 3 and Case 5), whereas cases involving low-sensitivity members (notably Cases 4 and 6) were more prone to ambiguity, leading to competing members exhibiting comparable or smaller estimated stiffness ratios.

Table I: Estimated stiffness ratios of the target substructure members for each damage case .

Member (Element ID)	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
1	0.89	1.02	1.00	0.99	0.99	0.97	0.98	0.98
2	1.05	0.89	1.01	1.01	1.02	0.98	0.99	1.00
6	1.02	1.02	0.77	1.03	0.93	0.99	0.99	0.94
7	1.01	1.01	1.00	0.98	1.00	1.01	0.99	0.99
10	0.97	0.98	0.92	0.96	0.90	0.99	0.95	0.97
11	0.99	0.99	0.99	1.00	1.02	0.97	1.01	1.00
12	0.95	0.95	0.95	0.95	0.95	0.97	0.92	0.97
13	0.98	0.97	0.94	0.98	0.98	0.96	0.98	0.89

4. Conclusions

This study presented a substructure-based damage detection framework in the time domain using a UKF under operational conditions. By assuming broadband

ambient excitation and extracting correlation-based impulse-response-type data, the proposed approach enables substructuring without direct input measurements. Interface effects were handled through an offline reconstruction procedure that estimates modal initial conditions from acceleration-only data using a windowed stacked least-squares formulation and a Kalman-filter-based smoother, and then projects the reconstructed modal responses onto the interface DOFs. The feasibility of the framework was demonstrated using a numerical case study on a 2D truss substructure with eight single-member damage scenarios. The damaged member was correctly identified in six out of eight cases based on the minimum estimated stiffness ratio criterion. The sensitivity analysis further indicated that damage occurring in highly sensitive members led to clearer identification, whereas cases involving low-sensitivity members were more prone to ambiguity and occasional misidentification. Future work will focus on improving robustness for weakly observable members, for example through enhanced measurement configurations, refined interface reconstruction, and uncertainty-aware decision rules for damage localization.

ACKNOWLEDGEMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (Ministry of Science and ICT) (No. RS-2022-00144434).

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