결함탐지를 위한 무선 센서망 운용 시뮬레이션
Numerical Wireless Sensor Simulation for Structural Damage Localization

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Key words : Wireless sensor system, Clustering algorithm, Optimization, Damage Localization

1. Introduction

This study proposes an algorithm using both theoretical and heuristic functions relating to the functional transition of wireless sensor system [1~5] between active and inactive modes. For this goal, we have two assumptions: First, all the sensors are scheduled to switch from sleeping mode to duty mode in a random manner. However, for energy saving purposes, the duration of the sleeping mode is set to be much longer than that of the sensing mode. Thus, only a limited number of sensors are actually awake while all the other sensors are asleep. The second assumption is that each wireless sensor can only communicate with the nearest neighboring sensor. Here, the communication means triggering (activating) the other sensor from sleeping to duty (sensing) mode and transmitting the collected data to neighboring sensors. Therefore, measured data is transferred from point *a* to *b* through a multi-hop network. This study explains the procedural steps for the initial clustering of massively distributed wireless sensors followed by a numerical simulation of a plate structure having a stiffness-reducing damage. It will be shown that a concise and logical algorithm enables a small set of local wireless sensors to progressively search for the correct location of damage without relying on any type of global communication or control. Section 2 and 3 show the underlying theory and computational steps for implementing a decentralized structural health monitoring system through a wireless sensor system.

2. Wireless Sensor Clustering

In this section, the concept of sensor clustering is explained, which is a crucial step for the success of damage detection. For example, the whole surface of a structure should be divided into several sub-domains in order to assign an appropriate duty-cycle for each sensor node. The number of sub-domains and their geometrical boundaries significantly affects the success of the initial guess for detecting the damage occurrence.

To minimize the power expenditure of a wireless sensor node involved in data processing and transmission, one can schedule only a small number of sensors in the entire population to be in the active (sensing) mode while the other sensors are in sleep (watch-dog) mode. This can be achieved by randomly initiating the duty-cycle for each sensor node, which will statistically guarantee that some number of sensors are in sensing mode at all times. However, it is still possible that some of the covered areas of the activated sensors are seriously biased to a specific region of the structure, which is undesirable for the robustness of a structural health monitoring system. Therefore, it is important to incorporate a clustering technique [6~8] to divide the overall areas into several sub-domains where at least one of the sensors are guaranteed to be in duty mode at all times. This will avoid extreme bias of active sensor locations in a global perspective. Within a sub-domain, each sensor randomly initiates its duty-cycle.

The proposed clustering process is successfully converged within several iterations, placing sensors and dividing the overall area of the plate into four groups (A~D) as shown in Figure 1. Each cluster has at least one master sensor on duty mode at all times. The master sensors, denoted as a solid mark in the figure, become the starting point of damage detection. The master sensor in each cluster activates its neighbor sensor nodes to collect the measured strain values.

3. Numerical Simulation

Having confirmed the presence of damage, this section illustrates the computational steps for the damage tracking process and ad hoc communication among the nearest sensors. Switching and regrouping the logic for a master sensor and its neighbors are also explained.

Figure 2 illustrates the contour of von Mises stress on the plate that was caused by damages at two elements located in the middle of the plate. Apparently, the stress concentration occurs on the edge of the damaged elements and its contour develops around them. The analysis results reveal that the maximum plane stress on the damaged edge amounts to roughly 56 MPa. It should be noted that only some of the strongest stress contours are visually expressed in the figure, meaning every sensor in the plate can detect strain value changes at all different levels after the damage occurs. Here, we assume that the excessive stress concentration, which typically occurs at a singular point or crack vicinity, is the damage to be detected in order to maintain the health of a structure. The measured strain value from an individual wireless sensor serves as a damage evident feature because the damage detection approach introduced in this paper relies on the computing and networking functionality of off-the-shelf wireless sensors mounted on the surface of a structure [9]. In the end, detecting an unusual increase in strain value from a strain sensor confirms the presence of damage in a structure.

Figure 3 illustrates the active sensors after five iterations of damage tracking process in searching for the optimal point or damage origin. If the measured strain value exceeds a certain threshold, the master sensor in each cluster alerts four of the nearest standby sensors constituting an activated monitoring group as represented by solid diamonds. The master sensor is denoted as a double diamond in the figure.

A simple decision-making logic needs to be implemented in each sensor node, i.e., performing pair comparisons between their sensor readings. This pair comparison decides which sensor becomes a master sensor in the following time step. As soon as newly elected master sensor begins to collect the measured data, all other sensors in the group become inactivated and change to sleeping mode. Thus, local sensors constantly vote for a new master sensor in its group by comparing their maximum sensor readings. This voting system serves as an efficient searching strategy and a powerful driving device for autonomous damage tracking. It is obvious that constantly updating the candidate for the master sensor's role and waking its neighbor sensors eventually narrows down the true location of the unknown damage without relying on centralized data traffic to a remote host station. The iterative damage tracking loop ends after an on-duty sensor group completely encompassed the correct location of damage. At this point, the master sensor finds no measured strain value from its neighboring sensors that exceed its own measured data.

4. Conclusions

This research demonstrates the potential capability of a wireless sensor system implemented for decentralized structural health monitoring. First, the clustering technique divides all the sensors into several sub-groups where a master sensor activates neighbor sensors as the measured strain value exceeds a predetermined threshold indicating damage occurrence within a structure. Iteratively changing the role of master sensor among the activated sensor group effectively localizes the structural damage, similar to the steepest gradient searching in an optimization problem. The proposed approach exploits the intrinsically decentralized technique, i.e., only allowing data communication between the physically closest sensors, which is critical to the success of a coarsely populated, multi-hop wireless sensor network. The perimeter line of a sensor group searching for the steepest gradient in a damage-sensitive structural response, eventually encompasses the true location of the damage. An exemplary numerical simulation using a plate FE model provides the potential success of adopting a wireless sensor system to an autonomous damage detection problem.

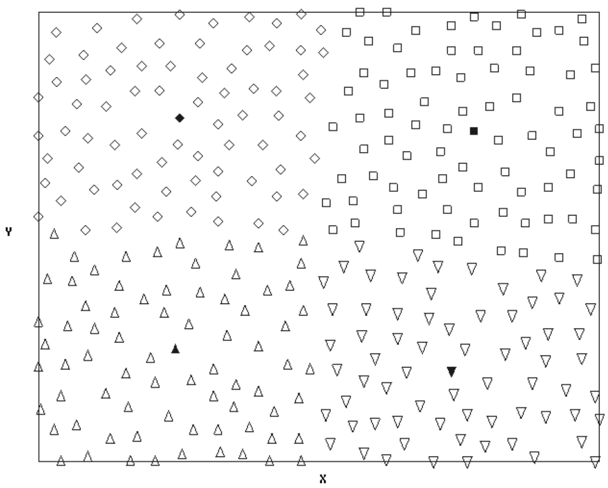

Fig. 1 Four clusters A (upper triangle), B (square), C (diamond), D (low triangle) and a master sensor (solid) for each cluster are assigned after 8 iterations.

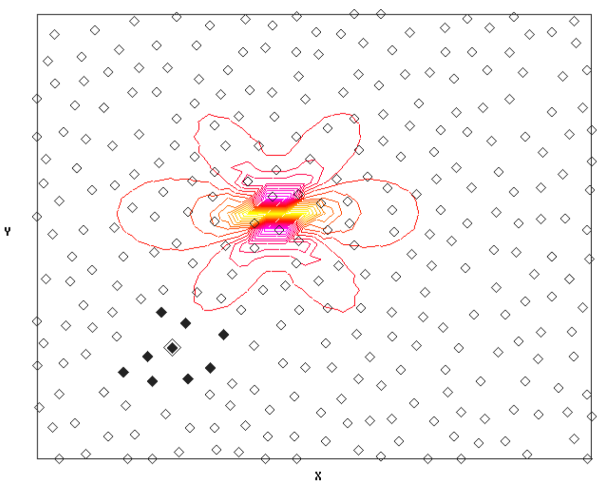

Fig. 2 True damage location is distinguished by von Mises stress contours generated by ABAQUS FE simulation. Initial stage of damage tracking process: one of the mater sensors (double diamond) activates 8 neighboring sensors (solid diamond). Activated sensors communicate each other to find the biggest gradient of measured strain value.

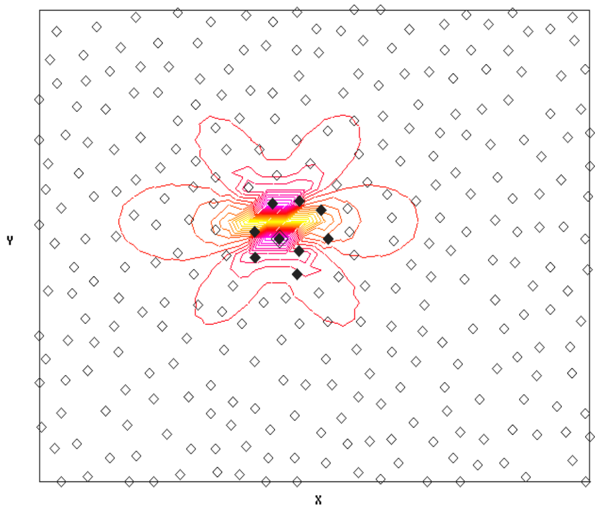

Fig. 3 After five iterations of damage tracking process: mater sensor (double diamond) does not activate neighboring sensors (solid diamond) any longer because no more gradient can be found.

Acknowledgements

The authors gratefully acknowledge research support through the KISTI Research Fund of 2007 (K-07-L04-C02).

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