Structural Damage Assessment by Regularized Output Error Estimator

Inho YEO
Research Associate
Seoul National Univ.
Seoul, Korea

Sooboong SHIN
Assistant Professor
Donga Univ.
Pusan, Korea

Hea Sung LEE
Associate Professor
Seoul National Univ.
Seoul, Korea

Sung-Pil CHANG
Professor
Seoul National Univ.
Seoul, Korea

Abstract

1. Introduction

During the last decade, various damage assessment algorithms based system identification (SI) schemes have been proposed to detect damage in structural systems using measured mechanical responses of structures. In most of SI schemes, the stiffness properties of a structure are estimated by the minimization of the output error estimator (OEE), which represents least squared errors between computed responses by mathematical models and measured responses of structures. Damage in a structure is identified using degree of reduction in stiffness properties of members estimated by the SI. Unfortunately, the conventional OEE have been troubled with the ill-posedness characterized by non-uniqueness and discontinuity of solutions when the measured data are noisy or sparse. This paper presents the regularized output error estimator (ROEE) to alleviate the ill-posedness of the conventional OEE caused by noise in measured data. A statistical approach is introduced to assess damage using the data perturbation method. A parameter grouping technique is employed to overcome the sparseness of measured data and locate damage.

2. System Identification Scheme

For reliable damage assessment, a stable SI scheme is mandatory since damage is identified using the results of the SI scheme. However, the conventional OEE yields severely oscillating results due to the ill-posedness when measure responses are noisy or sparse. In this paper, a regularization technique proposed by Tikhonov is employed to overcome the ill-posedness of the conventional OEE. In the regularization technique, a positive definite regularization function is added to the OEE. The OEE modified by the regularization function is referred to as the ROEE. The minimization is performed for the ROEE. The proposed regularization function is defined as the Frobenius norm of the difference between the estimated stiffness matrix and the baseline stiffness matrix that represents the stiffness matrix of an undamaged structure. The relative magnitude of the regularization function to the OEE is adjusted by a regularization factor. The magnitude of regularization factor is very important to obtain physically meaningful and numerical stable results. The regularization factor is determined by using the variable regularization factor scheme (VRFS) for a consistent regularization effect.

The SI scheme yields a physically meaningful solution only when the number of independent measured displacements is larger than that of independent system parameters. In large-scale structures, however, the number of independent system parameters becomes much larger than the number of measured displacements if a stiffness parameter is assigned to each member in a structure. Since a structure usually consists of a few groups of members with different stiffness parameters, the number of system parameters can be reduced by representing members with similar stiffness properties by a group with minimum system parameters. This approach is referred to as the parameter grouping technique. The binary search scheme is employed herein to localize the damaged members from the other members.

The recursive quadratic programming (RQP) and the Fletcher active set strategy are adopted to solve the constrained optimization problem of the ROEE. A line search technique is applied to accelerate the convergence.

3. Statistical Damage Assessment

Although the ill-posedness of the parameter estimation can be alleviated by the regularization technique, damage cannot be accessed directly using the results of the SI. This is because the changes in stiffness properties of structures estimated by the SI may be caused by noise in measurements as well as by actual damage. If a sufficient number of measured data sets are available, the effect of noise on the results of estimated stiffness properties of structures may be reduced by averaging measured responses. Since only the limited number of measured data sets is available in real situations, artificial data sets are generated by the perturbing the given data with a small magnitude. A series of the system identification is performed with generated data sets. The aforementioned procedure is referred to as the data perturbation method. The statistical features of the system parameters obtained by the data perturbation method are utilized for damage assessment.

The Kolmogorov-Smirnov goodness-of-fit test is applied to check if distributions of system parameters agree with the normal distribution. Since the ROEE produces normally distributed parameters from the data perturbations, a hypothesis test can be applied to determine the damaged members by useful properties of the normal distribution. Damage in the current structure can be assessed based on the hypothesis test by comparing the distributions of system parameters of the current structure with those of the baseline structure. Although the measurement data for the baseline structure is not available, the statistical distributions of system parameters in the undamaged structure can be reasonably assumed based on the characteristics of the ROEE. Based on results of the hypothesis test, a new damage index and severity of damage are proposed.

4. Numerical Simulation Study

Detailed numerical studies on a bowstring truss structure are presented to demonstrate the effectiveness and validity of the proposed method. Cross sectional areas of truss members are taken as the system parameters. To simulate measured data, proportional random errors are generated, and added to the analytical displacement. The binary search scheme is applied to update the system parameters from the four initial groups of top, bottom, diagonal, and vertical members.

Three damage cases including single damage and multiple damage are considered in this paper. Damage in the structure is simulated by reducing cross-sectional areas of selected members. The proposed algorithm identifies damaged members and estimates damage severity very accurately for all damage cases.

5. Conclusions

A new damage assessment algorithm for structures has been developed using a regularized output error estimator (ROEE). The ROEE is formulated by adding a regularization function to the least squared error between measured and computed displacements.

Simulation studies for the bowstring truss are rigorously carried out to investigate the effects of the regularization on the parameter estimation. The most desirable feature of the ROEE is the fact that it provides a normal distribution for each structural parameter from perturbation iterations, which cannot be achieved by the OEE without the regularization. To check the normal distribution of each parameter, the Kolmogorov-Smirnov goodness-of-fit test is applied.

The consistent normal distribution of any parameter from ROEE leads to a systematic statistical evaluation of damage, which allows engineers to judge damage in a structure in a more reliable manner. Using the benefits of normal distributions of parameters, a hypothesis test is proposed to detect damage. Damage severity is computed for the members determined as damaged ones from the hypothesis test. From the results of the example, it can be concluded that the proposed algorithm can detect and assess damage successfully in a highly advantageous way of statistical evaluation. The proposed algorithm can be applied to any types of framed structures although damage detection only for a truss structure is presented in this study.