Nondestructive Damage Identification in a Truss Structure Using Time Domain Responses

시간영역의 응답을 사용한 트러스 구조물의 비파괴 손상평가

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국문요약

본 논문에서는 시간영역에서의 응답을 이용하여 복잡한 트러스의 구조물에서 발생할 수 있는 손상의 위치와 크기를 추정할 수 있는 알고리즘을 제안하였다. 일정한 시간동안 획득한 응답데이터를 각 부재별 평균 변형에너지를 구하기 위하여 공간적으로 확장하였다. 이렇게 확장된 평균 변형에너지는 다시 손상 지표를 구축하는데 사용하였으며, 손상 지표는 손상 전과 손상 후의 구조물의 강성의 비이다. 본 논문에서 제안한 방법론의 타당성은 유한요소 모델로 손상을 모의하고 이로부터 얻은 응답데이터를 적용하여 입증하였다. 또한 응답데이터에 노이즈를 추가하여 노이즈가 제안한 알고리즘에 미치는 영향도 분석하였다.

주요어 : 비파괴 손상평가, 트러스 구조물, 평균 변형에너지, 손상위치 탐지, 손상도 추정

ABSTRACT

In this paper, an algorithm to locate and size damage in a complex truss structure using the time domain response is presented. Sampled response data for a specific time interval is spatially expanded over the structure to obtain the mean strain energy for each element of the structure. The mean strain energy for each element is, in turn, used to build a damage index that represents the ratio of the stiffness parameter of the pre-damaged to the post-damaged structure. The validity of the methodology is demonstrated using data from a numerical example of a space truss structure with simulated damage. Also in the example, the effects of noisy data on the proposed algorithm are examined by adding random noise to the response data.

Key words : nondestructive damage evaluation, truss structure, mean strain energy, damage localization, severity estimation

1. Introduction

Damage and other structural faults can reduce the useful life of a structure and promote an abrupt failure of the structure, if the damage is not detected at an early state. Since any structures may be exposed to unexpected extreme loads that may result in a serious damage, during the past two decades significant efforts have been made to locate defects in structures.(1) In recent years, most global nondestructive damage evaluation(NDE) methods utilize modal data(i.e., resonant frequencies and modeshapes) to predict possible damage locations and estimate the severity of the damage.(2) The modal data can be extracted using established experimental modal analysis techniques(input-output methods or output only methods) to estimate the modal parameters(i.e., resonant frequencies, damping, and mode shapes).(3) However, the input-output modal parameter extraction method involves averaging and curve-fitting procedures which introduce additional uncertainties and measurement errors. Furthermore output-only extraction methods are computationally intensive. One potential solution to this problem is to investigate other types of response measures(e.g., static response, time domain response, etc.) that circumvent these difficulties.

In this paper, a time domain based NDE methodology for a truss structure that obviates the computational demands, complexity, and subjectivity associated with current modal parameter extraction methods. In the proposed method, a mean strain energy measure which uses response data for a specified time period is utilized to formulate a damage index for an element in a structure. The damage indices, which represent the ratio of pre-damaged and post-damaged stiffness of the elements, are utilized to identify the locations and corresponding severities of the possible damage locations. The validity of the methodology is demonstrated using numerically generated data from a complex truss structure. Also, in the example, the effects of noisy test data are examined by adding random noise to the response data.

2. Theory

Suppose that dynamic responses of a truss structure are sampled at n locations at time interval Δt from $t_i = t_1$ to t_l

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$=t_{NT}$ where NT is the number of time steps. Then, the sampled dynamic responses for the n sensor locations may be expressed in matrix form as follow:

$$W=[V_1,\ldots,V_i,\ldots,V_{NT}]^T \tag{1}$$

where an nx1 vector, V_i ($=V(t_i)$), represents a configuration measurement of the structure at a certain time t_i. Consequently, there are NT response measurement sets, if a vector, V_i, is regarded as one measurement set. Since damage in a structure causes changes in the dynamic characteristics of the system such as frequencies and mode shapes, the deformed configurations of the pre-damaged and the post-damaged structures at the same time may describe different phases. Thus, the deformed configuration of the pre-damaged structure measured at a certain time should not be compared to the deformed configuration of the post-damaged structure at the same time. To overcome this difficulty, the mean strain energy of the structure over a sampling period is used here instead of the direct comparison between strain energies of pre-damaged and post-damaged structures at the same time.

Considering a truss system with N elements, the corresponding strain energy of the structure at a certain time t_i can be expressed as follows:

$$U_{ij}=k_j(\varDelta_{ij})^2 \tag{2}$$

where k_j represents the stiffness of j^{th} element, $\varDelta_{ij}$ represents the deformation of j^{th} element at time t_i. The mean strain energy for a specified time interval, $\widehat{U}_j$, may be defined as follows:

$$\widehat{U}_j=E[U_{ij}]=\frac{1}{2NT}k_j\sum_{i=1}^{NT}(\varDelta_{ij}^2) \tag{3}$$

The fraction of the mean strain energy for the j^{th} element of the system strain energy is given by:

$$F_j=\frac{\widehat{U}_j}{\widehat{U}}=\frac{k_j\sum_{i=1}^{NT}(\varDelta_{ij}^2)}{k\sum_{j=1}^{N}\sum_{i=1}^{NT}(\varDelta_{ij}^2)} \tag{4}$$

Similarly, for the damaged structure

$$F_j^*=\frac{\widehat{U}_j^*}{\widehat{U}^*}=\frac{k_j^*\sum_{i=1}^{NT}(\varDelta_{ij}^{*2})}{k^*\sum_{j=1}^{N}\sum_{i=1}^{NT}(\varDelta_{ij}^{*2})} \tag{5}$$

The pre-damaged and the post-damaged strain energy for j^{th} element are related by:

$$F_j^*=F_j+dF_j \tag{6}$$

where dF_j is related to the change in the fraction of the strain energy of the j^{th} element. The quantity dF_j can be obtained from the first order expansion[4]:

$$dF_j\approx -F_j\alpha_j \tag{7}$$

where the fractional change in stiffness, α_j, is given by:

$$\alpha_j=\frac{dk_j}{k_j}=\frac{k_j^*-k_j}{k_j} \tag{8}$$

Substituting Eqs. (4), (5), (7), and (8) into Eq. (6) and simplifying yield the damage index for the element j, β_j, as follows:

$$\beta_j=\frac{k_j}{k_j^*}\approx\frac{\sum_{j=1}^{N}\sum_{i=1}^{NT}(\varDelta_{ij}^2)}{\sum_{j=1}^{N}\sum_{i=1}^{NT}(\varDelta_{ij}^{*2})}\left[\frac{\sum_{i=1}^{NT}(\varDelta_{ij}^{*2})}{\sum_{i=1}^{NT}(\varDelta_{ij}^2)}+\frac{\sum_{j=1}^{N}\sum_{i=1}^{NT}(\varDelta_{ij}^{*2})}{\sum_{j=1}^{N}\sum_{i=1}^{NT}(\varDelta_{ij}^2)}\right] \tag{9}$$

Note that the damage index obtained using Eq. (9) is most susceptible to measurement and numerical errors when both numerator and denominator are close to zero. This phenomenon, for example, might be observed at supports when the element size is very small. In such cases, erroneous damage indices may result in severe localization errors. To avoid this problem, we shift the domain of interest in the problem by adding a unity to the denominator and numerator of Eq. (9)[4]:

$$\beta_j=\frac{k_j}{k_j^*}\approx\frac{\sum_{j=1}^{N}\sum_{i=1}^{NT}(\varDelta_{ij}^2)}{\sum_{j=1}^{N}\sum_{i=1}^{NT}(\varDelta_{ij}^{*2})}\left[\frac{\sum_{i=1}^{NT}(\varDelta_{ij}^{*2})+\sum_{j=1}^{N}\sum_{i=1}^{NT}(\varDelta_{ij}^{*2})}{\sum_{i=1}^{NT}(\varDelta_{ij}^2)+\sum_{j=1}^{N}\sum_{i=1}^{NT}(\varDelta_{ij}^2)}\right] \tag{10}$$

Possible locations of damage in a structure can be identified by utilizing classification algorithms with the damage index given by Eq. (10) taken as the feature vector. As presented in a prior study[5], classification of an element as damaged or not damaged can be made on the basis of such schemes as (a) Bayes' rule(from which the well-known Linear and Quadratic Discriminant Analysis are derived)[6], (b) nearest distance[7], and (c) hypothesis testing.[8] In this study, hypothesis testing is used for the classification of an element as being damaged or not damaged. In hypothesis testing, the alternate hypothesis (H_1) and null hypothesis (H_0) are defined as follows:

- H_0 : element j of the structure is not damaged
- H_1 : element j of the structure is damaged

To test the hypotheses, the damage indices, which are shown in Eq. (10), are standardized using the equation:

$$z_j = \frac{\beta_j - \mu_\beta}{\sigma_\beta} \qquad (11)$$

where z_j is the standardized damage index for j^{th} element, while μ_β and σ_β represent the mean and the standard deviation of β_j's. Thus, the one-tailed test to decide on the existence of damage in an element may be restated as follows:

- choose H_0 if $z_j < z_\eta$, or
- choose H_1 if $z_j \geq z_\eta$

where z_η is the threshold value and η is the level of significance of the test. The decision making criterion for assigning the location of damage is thus established using elements of statistical decision making. One can choose a greater threshold value to have a more confidence in the identified damage locations. Note that a typical value for the level of significance in damage localization is 0.05 which corresponds to a z score of $z_{0.05}$=1.645.

Once the possible locations of damage are identified, the corresponding damage severities may be obtained using the corresponding non-standardized damage indices. Using Eq. (9) the severity of damage for the j^{th} element, α_j, may be expressed as:

$$\alpha_j = \frac{k_j^* - k_j}{k_j} = \frac{1}{\beta_j} - 1 \qquad (12)$$

Note that the severity(magnitude) of damage obtained using Eq. (12) represents the fractional stiffness loss for a specific element j of the structure.

3. Verification of Methodology Using Numerical Simulation

The feasibility and performance of the proposed NDE algorithm is examined via a numerical example of a space truss structure. The structure is 4.83m long and consists of twelve evenly spaced bays as shown in Fig. 1. It is modeled using 300 elements and 91 nodes. In the analysis presented here, the structure is assumed to be simply supported. The structure is subjected to three damage scenarios. The damage locations and magnitudes for each scenario are summarized as follows:

- Damage case 1 : reduce the stiffness of Element 87 by 10%

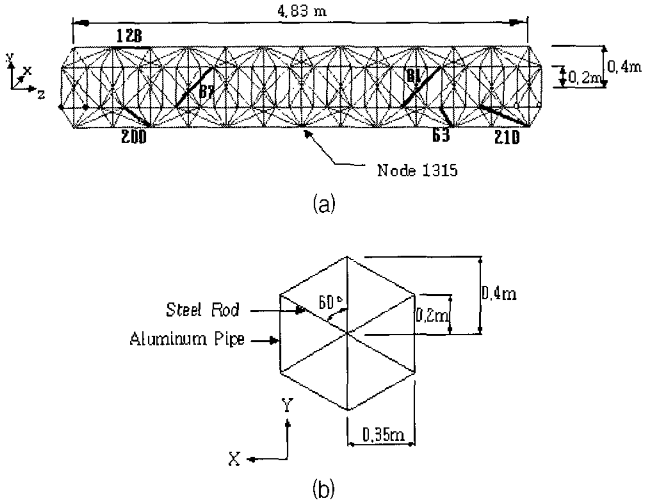


Fig. 1 Schematic of the Example Structure

- Damage case 2 : reduce the stiffness of Element 63 by 5% and Element 200 by 3%
- Damage case 3 : reduce the stiffness of Element 81 by 2%, Element 128 by 5%, and Element 210 by 3%

Note that the damages are simulated by reducing the elastic modulus of corresponding elements.

The sectional and material properties of the members of the structure are summarized in Table 1. Forced vibration analysis was performed to compute time responses using a commercial FORTRAN code[9]. The impulse loading is used to excite the structure at Node 1315 in y direction, which can be seen in Fig. 2. Assuming 0.1% viscous damping, the time response of the structure is obtained using Newmark- β method[10]. The response of the structure is sampled at each node for 1.3 seconds in time interval of 0.002 seconds after the loading has been applied. Consequently, a total of 650 discrete measures of displacements is sampled for each node.

In the field application of modal testing, it is expected

Table 1 Sectional and Material Properties of the Truss Structure

Properties	Steel rod	Aluminum pipe
Elastic modulus(GPa)	200	70
Density(kgf/m^3)	7850	2710
Area(cm^2)	0.316	1.032

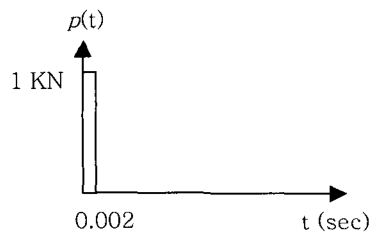


Fig. 2 Dynamic Loading Used to Excite the Structure

that there would be some deviations due to measurement noise. To simulate this condition, a series of random noise generated from a uniform distribution on the interval [-1, 1] is added to the original response of the structure. The degree of noise is determined by a noise/signal(NS) ratio that is a ratio of the random-number series to the amplitude of the response data. In present applications, the effect of different level of noise on damage identification is investigated by applying 1% and 5% NS ratios.

Using the damage index expression, presented in Eq. (10), the determination of the locations of potential damage in the structure is implemented using the following steps. First, the damage indices for each element are calculated using the Eq. (10). Second, the obtained damage indices are standardized using Eq. (11). Third, the presence of damage in Element j is determined according to the pre-assigned classification rules: (a) the element is damaged if $z_j \geq 2$; (b) the element is not damaged if $z_j < 2$. Note that the value of the damage indicator, 2, corresponds to a 98% confidence level for the presence of damage.

The severity of damage is estimated using Eq. (12). The severity of damage for possible damage locations is estimated as follows. First, the possible damage elements are identified using the hypothesis testing algorithm. Second, the severity of damage is estimated using the damage indices for the possible damaged element using Eq. (12).

The percentage of false positives predictions(Type I error) and the percentage of false negatives predictions(Type II error) are used to evaluate the performance of the methodology. A false positive means that the damage is reported where there is no damage exists and a false negative means that damage is not reported where damage exists. The percentage of false positives is calculated by dividing the number of false positive predictions by the number of undamaged elements, and the percentage of false negatives is calculated by dividing the number of false negative predictions by the number of damaged elements. The resulting percentage of false negatives and positives are summarized in Tables 2 and 3, respectively.

Table 2 Number of False Negatives

Damage case	0% noise		1% noise		5% noise	
	#*	%**	#	%	#	%
1	0	0	0	0	0	0
2	1	50	1	50	1	50
3	0	0	0	0	0	0
Average	1	(17)	1	(17)	1	(17)

* Number of false negatives
** Percentage of false negatives

Table 3 Number of False Positives

Damage case	0% noise		1% noise		5% noise	
	#*	%**	#	%	#	%
1	1	0.33	2	0.67	3	1.00
2	0	0.00	1	0.34	2	0.67
3	1	0.34	1	0.34	1	0.34
Average	2	(0.22)	4	(0.45)	6	(0.67)

* Number of false positives
** Percentage of false positives

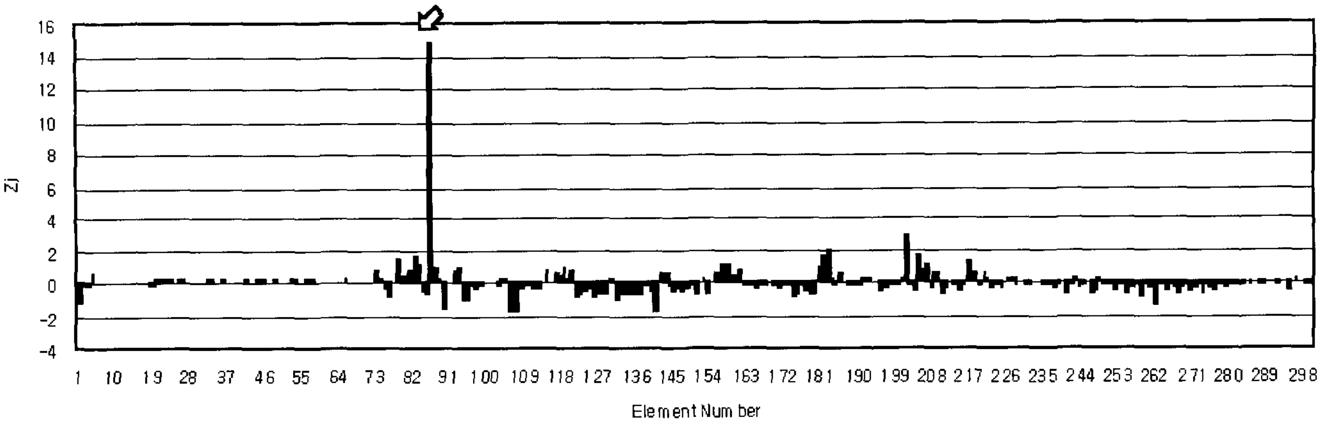
The damage localization results are shown in Figs. 3 to 5. In all of the figures, note that the inflicted locations of damage are indicated by the tilted arrows. The vertical axis is in the non-dimensional unit of the standardized damage index for that particular location. Throughout single and multiple damage location cases, the proposed localization methodology performed quite satisfactorily. With noise free data, the proposed methodology successfully identifies all simulated damage locations except one location in Damage Case 2(see Table 2). A few false positives are observed but all the false positive predictions arise in the neighborhood of the simulated damage locations. When noise added, the percentage of false positive shows a tendency to increase as the NS ratio increases. From Table 2, the percentage of false negatives seems not to be influenced significantly by increasing the number of damage locations and the noise level. However, it can be inferred from the figures that the number of false positives will increase as NS ratio increases.

The severity estimation results using the proposed methodology are presented in Table 4. For all damage cases, the proposed methodology consistently yields lower damage severity estimates than the simulated values. The fact that damage is smeared into the neighboring elements, as shown in Figs. 3 to 5, may explain this systematic error. In the table, it is also observed that the accuracy of the estimated severities decreases as the NS ratio increases.

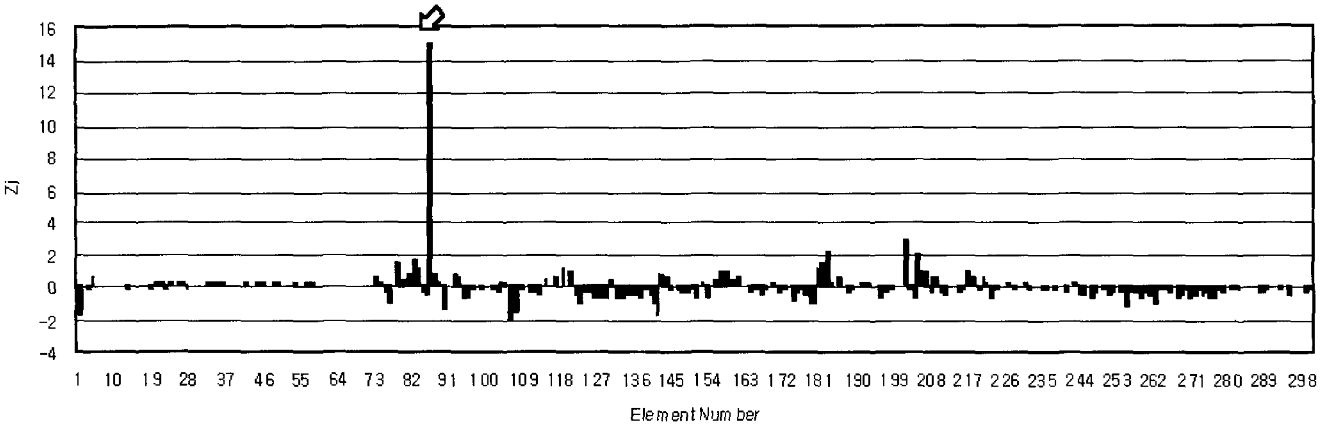
4. Conclusions

The damage detection algorithms proposed herein are verified through a space truss structure. From the numerical study, the following conclusions are drawn:

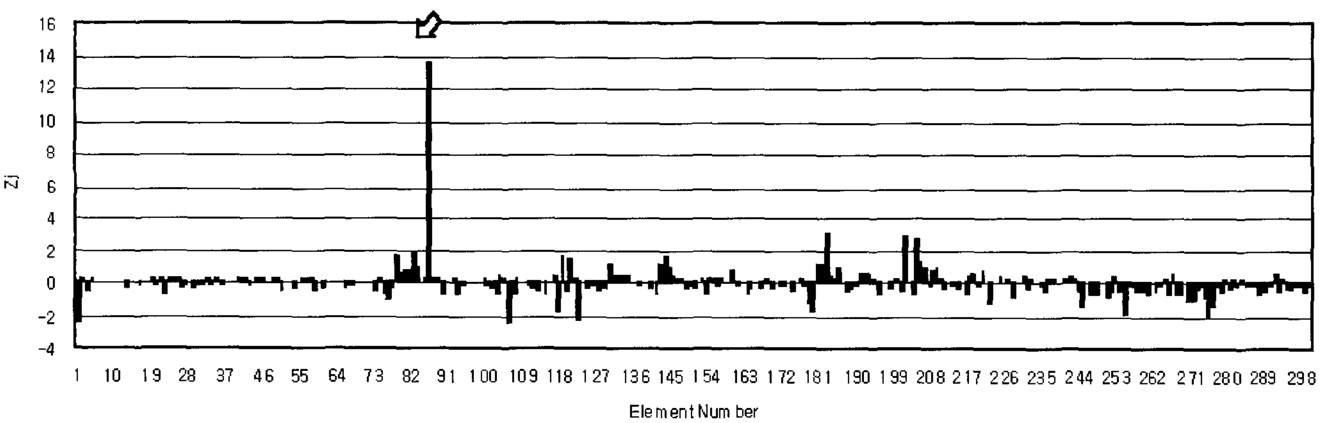
(1) The NDD algorithms presented here can be used for damage localization and severity estimation of truss structure.
(2) The numerical simulation of a space truss structure revealed that the proposed algorithms can identify



(a) 0% Noise



(b) 1% Noise



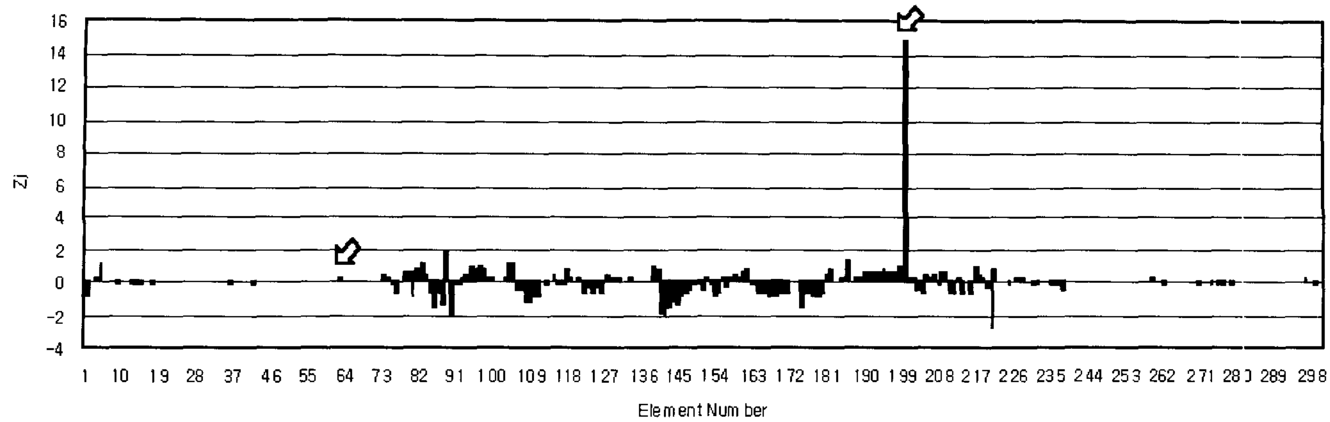
(c) 5% Noise

Inflicted damage location

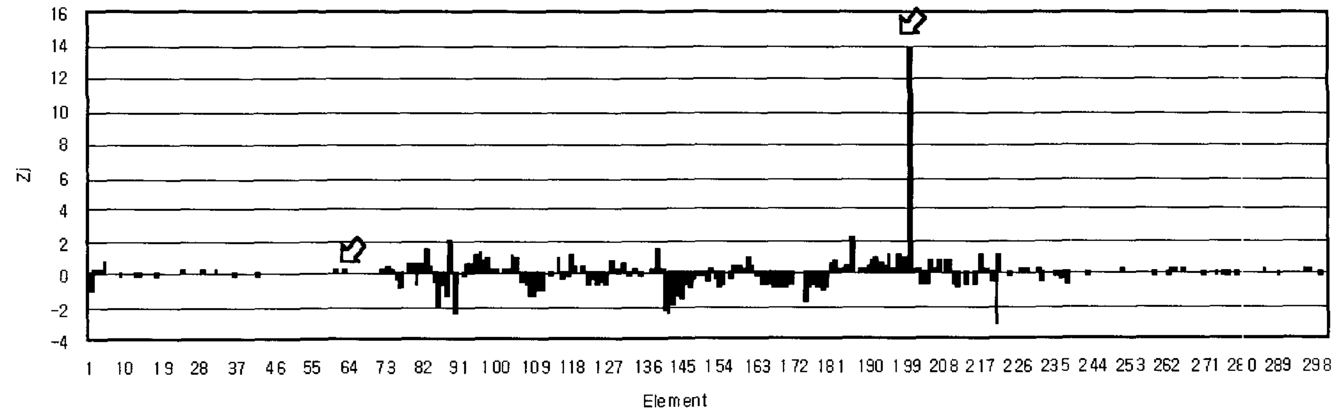
Fig. 3 Damage Localization Results for Damage Case 1

Table 4 Severity Estimation Results

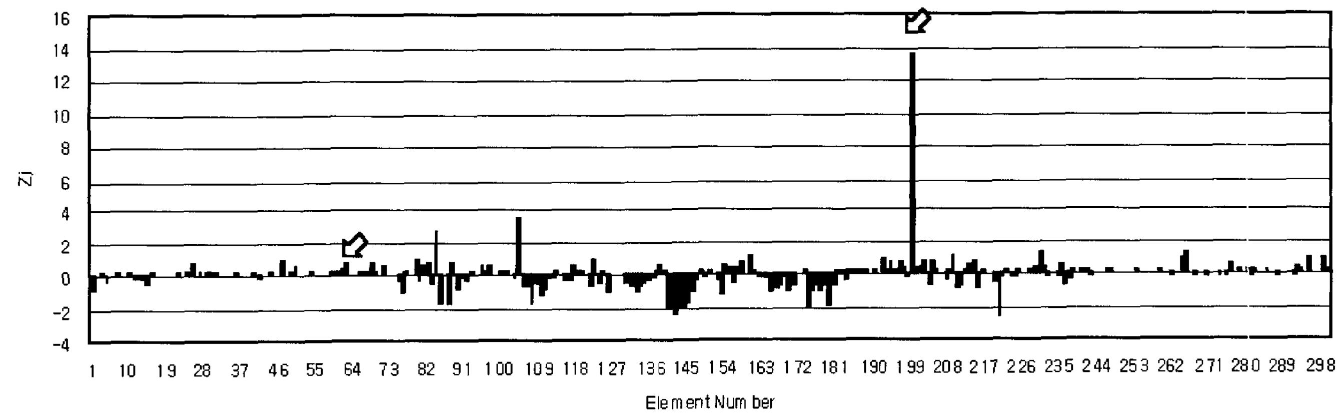
Damage case (Simulated damage)		0% noise		1% noise		5% noise	
		Estimated	Error(%)	Estimated	Error(%)	Estimated	Error(%)
1	87(0.10)	0.083	17.0	0.076	24.0	0.059	41.0
2	63(0.05)	-	-	-	-	-	-
	200(0.03)	0.025	16.7	0.029	3.33	0.018	40.0
3	81(0.02)	0.017	15.0	0.015	25.0	0.012	40.0
	128(0.05)	0.040	20.0	0.036	28.0	0.027	46.0
	210(0.03)	0.022	26.7	0.014	53.3	0.006	80.0
Average			19.1		26.7		49.4



(a) 0% Noise



(b) 1% Noise



(c) 5% Noise

⇗ Inflicted damage location

Fig. 4 Damage Localization Results for Damage Case 2

single and multiple damage locations consistently and accurately.

(3) The proposed methodologies consistently produced a lower damage severity estimations.

(4) When noise were introduced to response data, the results showed that the damage localization scheme proposed herein was not influenced. However, the severity estimation error increased from 19.1% to as much as 49.4%.

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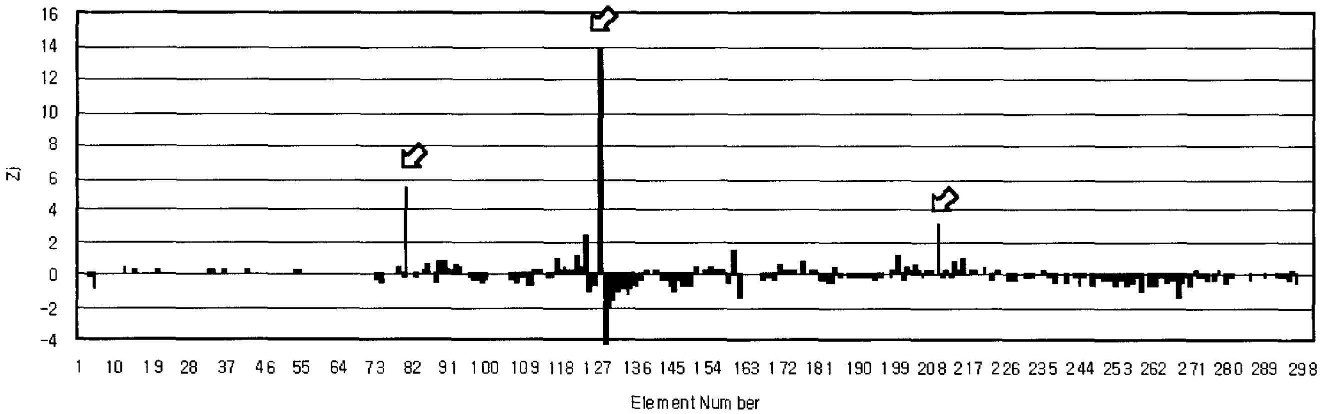
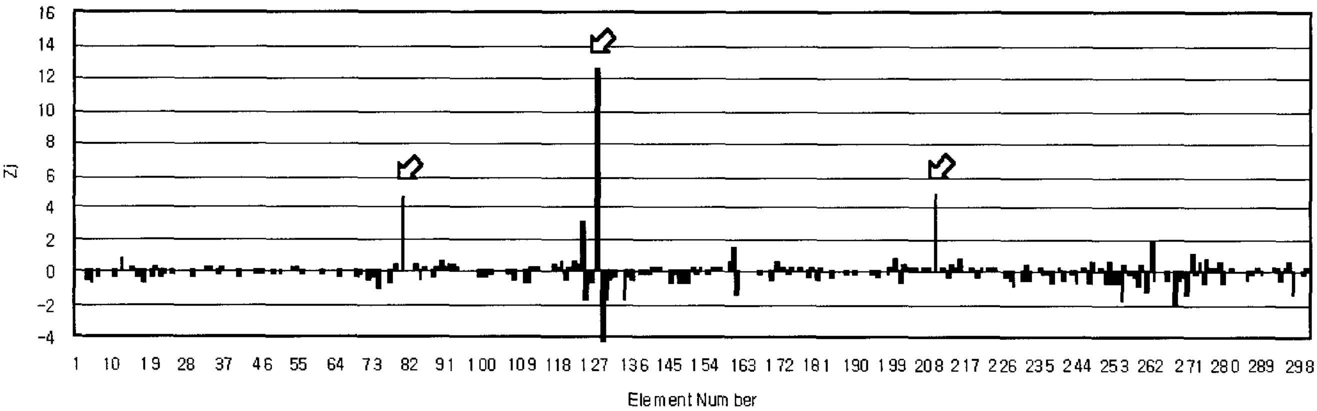
(a) 0% Noise



(b) 1% Noise



(c) 5% Noise

⇗ Inflicted damage location

Fig. 5 Damage Localization Results for Damage Case 3

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