

PZT 소자의 정압전 응답을 이용한 보 구조물의 모드 변형에너지기반 손상 모니터링

Modal Strain Energy-based Damage Monitoring in Beam Structures using PZT's Direct Piezoelectric Response

호 득 유이* 이 포 영** 김 정 태†
Ho, Duc-Duy Lee, Po-Young Kim, Jeong-Tae

요 지

본 연구에서는 PZT 소자의 정압전 효과에 의한 동적 응답신호를 이용하는 보 구조물 손상 모니터링 기법을 제안하였다. 특히, 모드 변형에너지기반 보 구조물 손상 모니터링에 PZT 정압전 응답신호를 입력자료로 활용하는 방안에 대한 연구에 주안점이 있다. 먼저, PZT 소자의 정압전 효과 및 동적 변형률 응답의 이론적 배경을 요약하였다. 다음으로, 모드 변형에너지기반 보 구조물 손상위치 모니터링 기법을 제시하였다. 제시된 기법의 적합성을 검증하기 위해, 캔틸레버 보 모형을 대상으로 강제진동 실험을 수행하였으며, 세 종류의 센서(가속도계, PZT 센서, 변형률계)를 통해 동적 응답신호가 계측되었다. 손상 진후에 계측된 이들 진동신호들을 사용하여 모드 변형에너지기반의 손상위치 모니터링이 수행되었다.

핵심용어 : 모드 변형에너지, 손상검색, 캔틸레버보, PZT, 정압전응답

Abstract

The main objective of this study is to examine the feasibility of using lead zirconate titanate (PZT)'s direct piezoelectric response as vibrational feature for damage monitoring in beam structures. For the purpose, modal strain energy (MSE)-based damage monitoring in beam structures using dynamic strain response based on the direct piezoelectric effect of PZT sensor is proposed in this paper. The following approaches are used to achieve the objective. First, the theoretical background of PZT's direct piezoelectric effect for dynamic strain response is presented. Next, the damage monitoring method that utilizes the change in MSE to locate of damage in beam structures is outlined. For validation, forced vibration tests are carried out on lab-scale cantilever beam. For several damage scenarios, dynamic responses are measured by three different sensor types (accelerometer, PZT sensor and electrical strain gage) and damage monitoring tasks are performed thereafter. The performance of PZT's direct piezoelectric response for MSE-based damage monitoring is evaluated by comparing the damage localization results from the three sensor types.

Keywords : modal strain energy, damage detection, cantilever beam, PZT, direct piezoelectric response

1. Introduction

A significant amount of research has been conducted in the area of damage monitoring in structures. Many research studies for monitoring damage location and severity in a structure via changes in vibration responses have been performed by many researchers.

For example for beams, attempts have been made to relate changes in natural frequencies to such influences as cracks and local geometrical changes (Gudmunson, 1982; Cristides and Barrs, 1990) and to identify the damage location and magnitude from the measured vibrational modes (Kim and Stubbs, 1995).

Vibration-based structural health monitoring (SHM)

† 책임저자, 정회원·부경대학교 해양공학과 교수
Tel: 051-629-6585 ; Fax: 051-629-6590
E-mail: idis@pknu.ac.kr

* 학생회원·부경대학교 해양공학과 박사과정

** 학생회원·부경대학교 해양공학과 석사과정

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has become increasingly important for many fields such as aerospace engineering and civil engineering in recent years. For example, changes in natural frequencies and mode-shape features extracted from acceleration signals have been used to identify damage location and damage severity (Kim *et al.*, 2003). At the same time, there has been many efforts on developing new sensors and devices for monitoring the integrity of structures. So many kind of smart sensors and damage detection techniques have been employed (Liang *et al.*, 1996; Sirohi and Chopra, 2000; Farrar, 2001; Kim *et al.*, 2003). Consequently, there exists an issue that how to select the cost-effective and reliable system for SHM purpose. Up-to-dated sensing techniques for vibration-based SHM have the following problems. First, the cost associated with acceleration measurement system is very high due to the high-cost of accelerometers. Second, the wired measurement system is very bulky and inconvenient for field test.

In order to reduce the cost of acceleration-based SHM system, recently, a method of measuring dynamic strain using piezoelectric sensors has been developed (Sirohi and Chopra, 2000). This method is promising since the lead zirconate titanate (PZT)'s direct piezoelectric effect can be easily transformed into dynamic strain response and the cost of PZT sensor is very cheap. Moreover, wireless sensor technology developed by many researchers (*e.g.*, Lynch *et al.*, 2006; Mascarenas *et al.*, 2007; Rice *et al.*, 2010; Kim *et al.*, 2011) can be incorporated with the PZT sensor as the feasible smart sensor system. By using this smart sensor system, therefore, the costs are greatly reduced and the data management and processing is more effective via on-board computation.

The main objective of this study is to examine the feasibility of using PZT's direct piezoelectric response as vibrational feature for damage monitoring in beam structures. For the purpose, modal strain energy (MSE)-based damage monitoring in beam structure using dynamic strain response based on the direct piezoelectric effect of PZT sensor is proposed in this paper. The following approaches are used to achieve

the objective. First, the theoretical background of PZT's direct piezoelectric effect for dynamic strain response is presented. Next, the damage monitoring method that utilizes the change in MSE to locate of damage in beam structures is outlined. For validation, forced vibration tests are carried out on lab-scale cantilever beam. For several damage scenarios, dynamic responses are measured by three different sensor types (accelerometer, PZT sensor and electrical strain gage) and damage monitoring tasks are performed thereafter. The performance of PZT's direct piezoelectric response for MSE-based damage monitoring is evaluated by comparing the damage localization results from the three sensor types.

2. Theoretical Backgrounds

2.1 Dynamic Strain Response from PZT's Direct Piezoelectric Effect

Piezoelectric materials are commonly used as both sensors (direct effect) and actuators (inverse effect) for SHM applications (Liang *et al.*, 1996; Sirohi and Chopra, 2000). A key characteristic of these materials is the utilization of the direct effect to sense structural deformation in addition to the inverse piezoelectric effect to actuate the structure. The constitutive equations in strain-charge relation for a piezoelectric material can be expressed by tensor form as (Sirohi and Chopra, 2000):

$$D_i = e_{ij}^\sigma E_j + d_{im}^d \sigma_m \quad (1)$$

$$\epsilon_k = d_{jk}^c E_j + s_{km}^E \sigma_m \quad (2)$$

where D_i is the electrical displacement; e_{ij}^σ is the dielectric permittivity at zero mechanical stress ($\sigma_{ij} = 0$); E_j is the electric field vector; d_{im}^d and d_{jk}^c are the piezoelectric coefficients; σ_m is the stress vector; ϵ_k is the strain vector; s_{km}^E is the elastic compliance of the piezoelectric material at zero electric field ($E_j = 0$).

Equation (2) shows that when an electric field

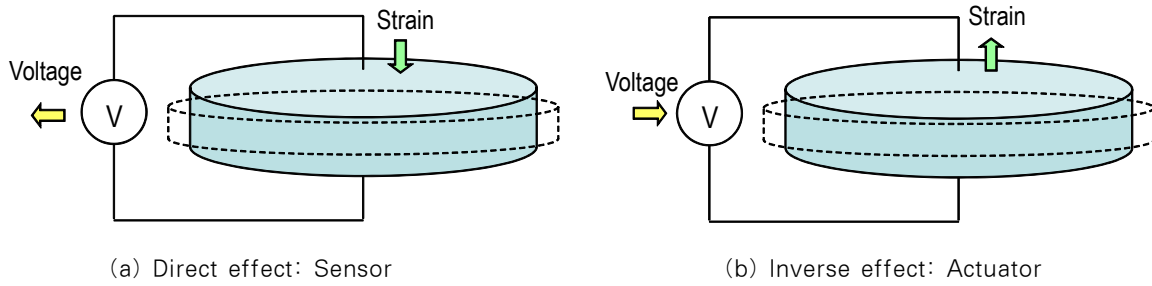


Fig. 1 Piezoelectric sensor: Direct and inverse effects

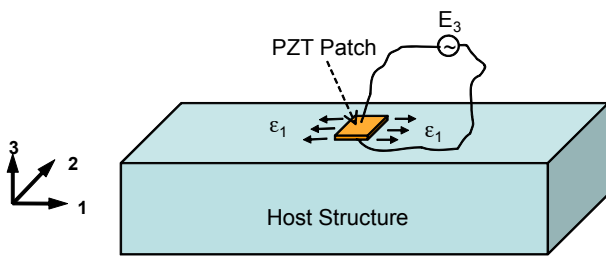


Fig. 2 1-D PZT-structure interaction in direct piezoelectric effect

(directly related to electrical voltage) is applied to two surfaces of a PZT sensor, a strain field is induced. As the inverse effect given in Eq. (1), the electrical displacement (directly related to electrical current) is induced since a mechanical stress field (or mechanical strain field) is applied to a PZT sensor. These effects are conceptually explained in Fig. 1. According to the direct effect and the inverse effect, a PZT sensor can be used as both a sensor and an actuator.

As shown in Fig. 2, the PZT material can be employed as a sensor for dynamic strain measurement. Strain is measured in terms of the charge generated by PZT sensor as a result of direct effect. When a PZT sensor is mechanically strained, an electrical field is produced. The constitutive relations of the PZT strain for 1-D interaction:

$$D_3 = \overline{e_{33}^\sigma} E_3 + d_{31} \sigma_1 \quad (3)$$

$$\epsilon_1 = \frac{\sigma_1}{Y^E} + d_{31} E_3 \quad (4)$$

where D_3 is the electric displacement; $\overline{e_{33}^\sigma}$ is the dielectric constant of piezoelectric wafer; E_3 is the applied external electric field in direction 3; d_{31} is

the piezoelectric coupling constant; σ_1 is the stress in direction 1; ϵ_1 is the strain in direction 1; $\overline{Y^E}$ is the complex Young's modulus of the zero-electric field.

If the PZT sensor bonded on surface of host structure is desired to be used as sensor only, without external electric field across its terminals, the strain in the PZT sensor can be expressed in terms of the voltage measured across its terminals as (Sirohi and Chopra, 2000):

$$\epsilon_1 = \left(\frac{\overline{e_{33}^\sigma}}{d_{31} t_p Y^E} \right) V = K_p V \quad (5)$$

where V is the output voltage across the terminals of the PZT sensor; t_p is the thickness of PZT sensor. From Eq. (5), the dynamic strain is determined from the output voltage which is easily measured directly.

By using Eq. (5), the dynamic strain is calculated from the dynamic output voltage. However, in order to improve measurement accuracy, the output voltage of PZT sensor should be passed through some signal conditioning circuits (Sirohi and Chopra, 2000). It should be noted that the derivation of Eq. (5) was based on the assumption that only strain in 1-D contributed to the charge generated, the effect of other strain components was negligible, and that there is no loss of strain in the bond layer. In reality, however, a transverse component of strain exists and there are some losses in finite thickness bond layer (Bhalla *et al.*, 2009). As a result, the value of strain as calculated by Eq. (5) is not the actual strain

measured by the strain gage. For this reason, some correction factors should be required to account for transverse strain and shear lag losses in the bond layer. Moreover, the effect of temperature on sensor characteristics should be considered for accuracy measurement of dynamic strain using PZT sensor. The properties of PZT sensor are very sensitive to temperature (Kim *et al.*, 2011). Therefore, the dynamic strain should be measured at known temperature conditions, then, it should be modified by using appropriate values of the constants for calibration.

2.2 MSE-based Damage Monitoring Method

Modal strain energy (MSE) is one of damage sensitive features using mode shape curvature. Kim *et al.* (2003) proposed an MSE-based damage monitoring method by measuring the fractional change in MSE. For a beam structure, damage in the j^{th} member is defined as the relative change between undamaged flexural stiffness, k_j , and damaged one, k_j^* , of the same element. For M available vibration modes, the MSE-based damage index is for j^{th} location, β_j , is given by

$$\beta_j = \frac{k_j}{k_j^*} = \frac{\sum_{i=1}^M \gamma_{ji}^*}{\sum_{i=1}^M (\gamma_i g_i + \gamma_{ji})} \quad (6)$$

where γ_i and γ_{ji} are the i^{th} modal stiffness and the contribution of the j^{th} element to the i^{th} modal stiffness, respectively. The asterisk (*) denotes the damaged state. γ_{ji} , γ_{ji}^* and γ_i are formulated as follows (Kim *et al.*, 2003): $\gamma_{ji} = \int_j [\Phi_i''(x)]^2 dx$, $\gamma_{ji}^* = \int_j [\Phi_i''^*(x)]^2 dx$ and $\gamma_i = \int_0^L [\Phi_i''(x)]^2 dx$. The term $\Phi_i''(x)$ is the i^{th} mode shape curvature determined from the i^{th} mode shape vector $\Phi_i(x)$. The term g_i is a dimensionless factor representing the fractional changes in the i^{th} natural frequencies ($g_i = \delta\omega_i^2/\omega_i^2$).

For the damage localization, the damage indices are normalized according to the standard rule as

$$Z_j = (\beta_j - \mu_\beta) / \sigma_\beta \quad (7)$$

where μ_β and σ_β are the mean and standard deviation of the collection of β_j values, respectively. Then, the damage is localized from the statistical hypothesis tests. The null hypothesis (*i.e.*, H_0) is taken to be the structure undamaged at the j^{th} element and the alternate hypothesis (*i.e.*, H_1) is taken to be the structure damages at the j^{th} element. In assigning damage to a particular location, the following decision rule is utilized: first, choose H_1 if $Z_j \geq Z_o$; or choose H_0 if $Z_j < Z_o$, where Z_o is the statistical criterion depending upon the confidence level of the localization test. As a result, the damage is assigned to the j^{th} location if Z_j exceeds the confidence level.

The MSE-based damage monitoring is performed in the following four steps: firstly, vibration signals (*e.g.*, acceleration or dynamic strain) are measured at distributed locations; secondly, vibration features such as natural frequency and mode shape for entire structure are extracted by using modal identification methods such as frequency domain decomposition (FDD) method or stochastic subspace identification (SSI) method (Brincker *et al.*, 2001; Yi and Yun, 2004); and the MSE-based damage index and also normalized damage index are computed from Eqs. (6) and (7) and post-processed modal data; and finally, the location of damage is estimated by the statistical hypothesis tests stated above.

3. Experimental Validation

3.1 Experiments on Lab-scale Beam

Dynamic tests were performed on a lab-scale 600×60×10-mm aluminum cantilever beam as shown in Fig. 3. Five sensor locations were arranged along the beam with a constant interval 150mm and the

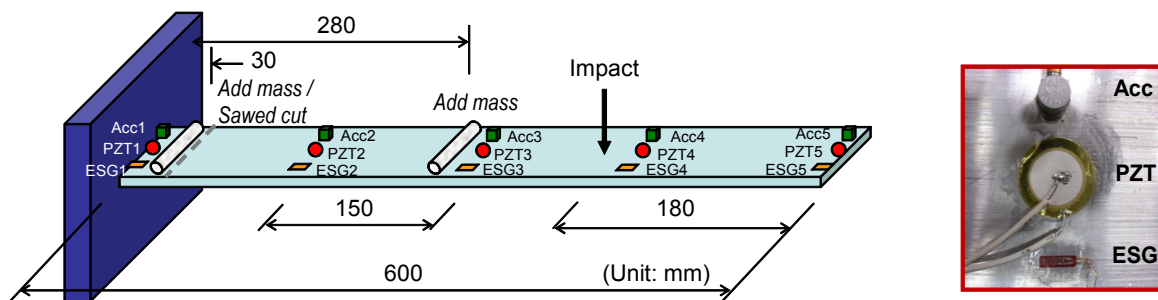
impact force was applied at a location 180mm distanced from the free end. At one sensor location, three different sensor types (*i.e.*, accelerometer, PZT sensor, electrical strain gage) were installed. As a result, three responses were measured from accelerometers, PZT sensors and electrical strain gages. For acceleration measurement, Dytran 3101BG accelerometers, with the nominal sensitivity of 100 mV/g, were used. The data acquisition system consists of 16-channel PCB signal conditional, DAQ card, terminal block and Laptop with MATLAB software. For dynamic strain measurement from PZT sensor, FT-20T-3.6A1 PZT sensors were used. The data acquisition system consists of DAQ card, terminal block and Laptop with MATLAB software. For dynamic strain measurement from electrical strain gage, TML FLA-5-11-1L strain gages were used. The data acquisition system consists of TML SB120B bridge boxes, Kyowa EDX-100A universal recorder and Laptop with DCS-100A software.

Table 1 gives the information about three measurement system for acceleration from accelerometer, dynamic strain from PZT sensor and dynamic strain from electrical strain gage. The cost for measuring dynamic strain from PZT sensors is lowest (*i.e.*, about 10% cost for acceleration measurement). However, PZT sensor has the following weak points in comparison to electrical strain gage. First, the quality of PZT sensor much depends on the time. Second, it is not easy to make the same PZT sensors which are necessary for SHM applications.

3.2 Vibration Responses of Test Beam

Dynamic responses were measured in vertical direction with sampling frequency of 1 kHz. Frequency domain decomposition (FDD) method (Brincker *et al.*, 2001) was employed to extract frequency responses and modal parameters. Three damage cases were inflicted on test beam as given in Table 2. A 2.4 N mass was added on the beam at 30mm (*i.e.*, damage case 1) or 280mm (*i.e.*, damage case 2) from the fixed end. For damage case 3, a cut was sawed along the width of beam at a location 30mm from fixed end, as shown in Fig. 3(a). The crack-size was considered with ratio of crack depth (a) and beam thickness (t) of 0.2.

Fig. 4 shows the time history responses at sensor location 3 for three different sensor types. Fig. 5 and Fig. 6 show frequency responses and mode shape curvatures for first three bending modes, respectively. The natural frequencies measured by three sensor types are also given in Table 3. It is observed that the responses show good agreement for three sensor types. Frequency response from electrical strain gages contains high noise level in comparison with those from accelerometers and PZT sensors. It should be noted that mode shape curvatures used for MSE-based damage monitoring method described in section 3 are extracted directly in case of using PZT sensors and electrical strain gages. Meanwhile, for accelerometers, one more step is required to determine mode shape curvatures from mode shapes.



(a) Test beam

(b) Three sensor types

Fig. 3 Experimental setup for lab-scale beam

Table 1 Three-types of vibration measurement systems

Specification	Acceleration	Dynamic strain (PZT sensor)	Dynamic strain (Strain gage)
Sensor	Dytran 3101BG Accelerometer	FT-20T-3.6A1 PZT sensor	TML FLA-5-11-1L Strain gage
DAQ	1) NI-6036E DAQ card 2) BNC-2090 terminal block 3) PCB-481A03 conditional 4) Laptop PC	1) NI-6036E DAQ card 2) BNC-2090 terminal block 3) Laptop PC	1) TML SB120B bridge box 2) Kyowa EDX-100A logger 3) Laptop PC
Total cost	US\$ 20,000	US\$ 5,000	US\$ 25,000

Table 2 Damage scenarios on test beam

Case	Damage-type	Damage-size	Location (x/L)	Note
Damage 1	Add mass	Add-mass 2.4N	30mm (0.05)	Add mass equivalent to 26% of beam weight
Damage 2	Add mass	Add-mass 2.4N	280mm (0.47)	Add mass equivalent to 26% of beam weight
Damage 3	Sawed cut	a/t=0.2	30mm (0.05)	a is crack depth; t is beam thickness

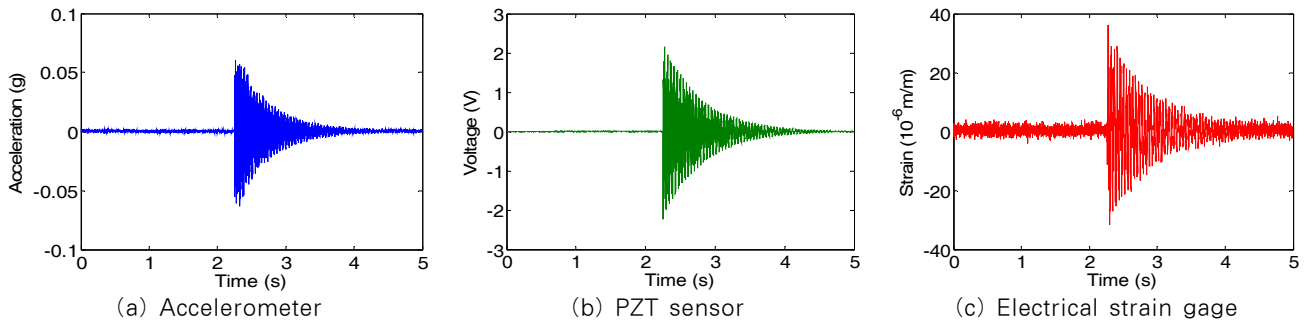


Fig. 4 Time history responses of test beam

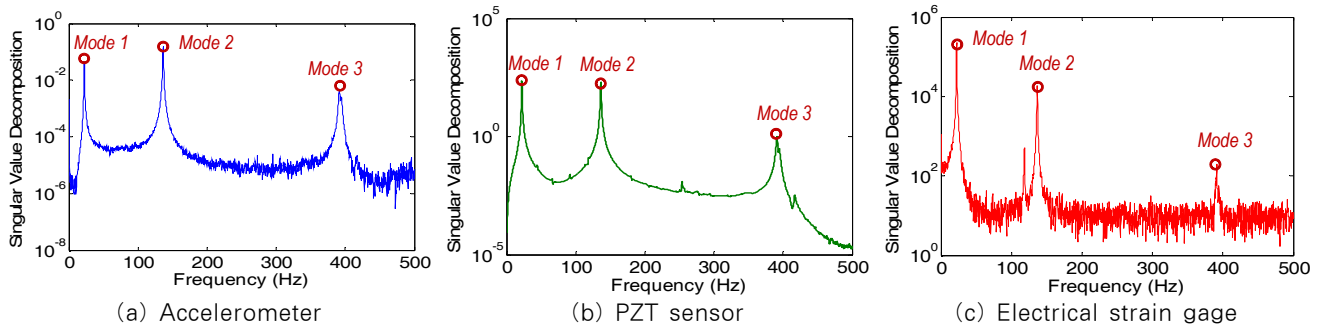


Fig. 5 Frequency responses of test beam

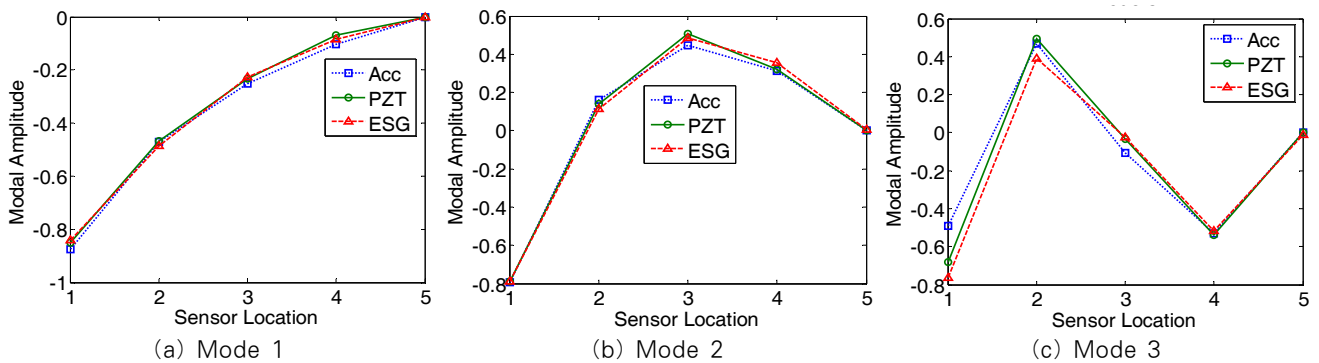


Fig. 6 Mode shape curvatures of test beam

Table 3 Natural frequency (Hz) of test beam measured by three sensor types

Damage case	Acceleration			PZT sensor			Electrical strain gage		
	Mode 1	Mode 2	Mode 3	Mode 1	Mode 2	Mode 3	Mode 1	Mode 2	Mode 3
Undamage	22.46	140.87	392.09	22.46	140.87	392.09	22.46	140.87	392.09
Damage 1	22.46	140.87	391.36	22.46	140.87	390.63	22.46	140.87	390.14
Damage 2	21.48	114.01	388.18	21.48	114.01	388.18	21.48	114.01	387.7
Damage 3	21.97	135.5	390.63	21.97	135.5	390.63	21.97	135.5	390.87

3.3 MSE-based Damage Localization Results

As described in section 2.2, MSE-based damage monitoring method proposed by Kim *et al.* (2003) was employed to estimate the damage localization. The damage localization index, as described in Eqs. (6)

and (7), is calculated from the fractional change in MSE between undamage and damage cases. Fig. 7~9 show MSE-based damage localization results for three damage cases, respectively, by using three sensor types (*i.e.*, accelerometer, PZT sensor and electric strain gage). It is observed that the damage locations

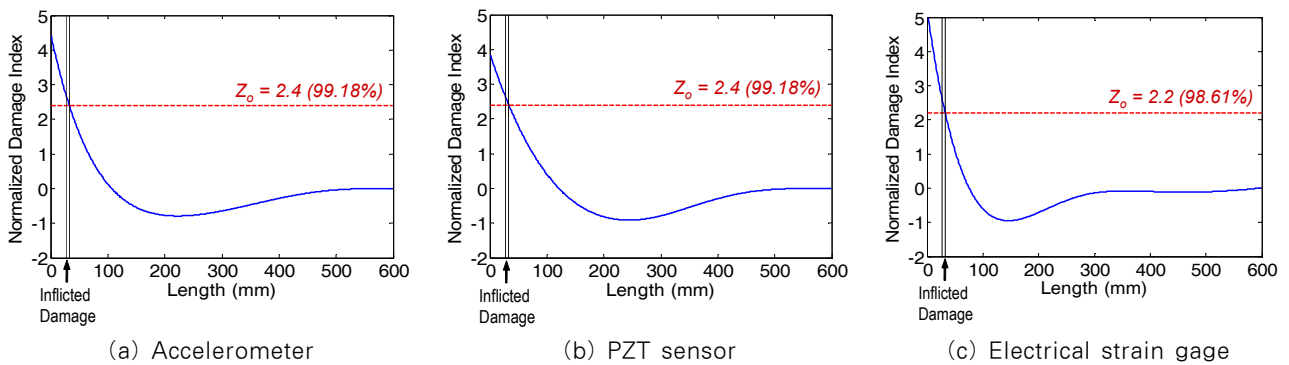


Fig. 7 MSE-based damage localization results: Damage 1

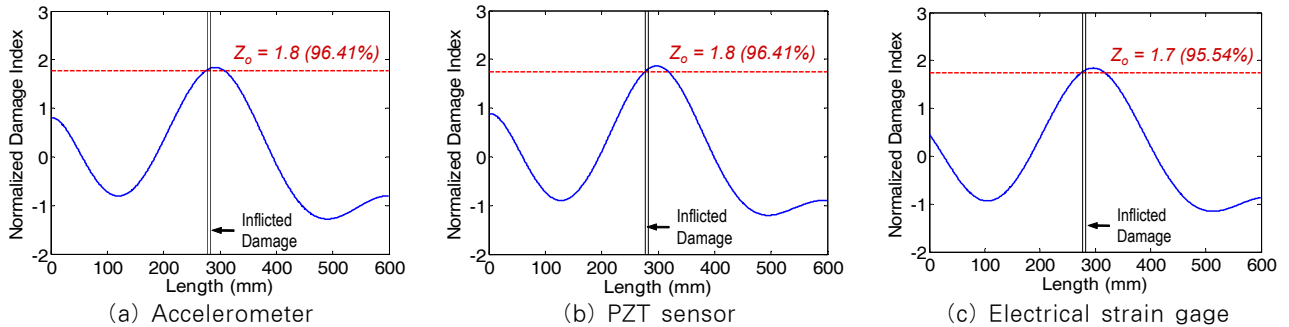


Fig. 8 MSE-based damage localization results: Damage 2

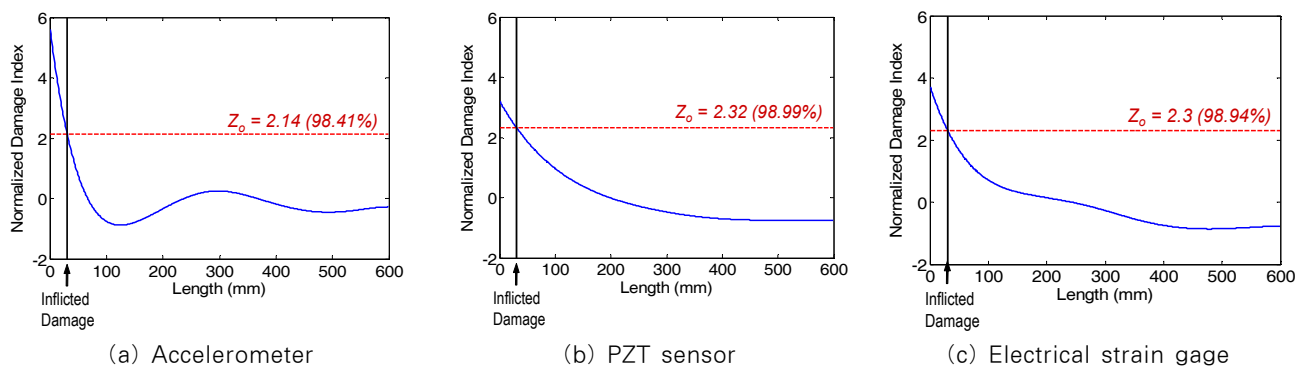


Fig. 9 MSE-based damage localization results: Damage 3

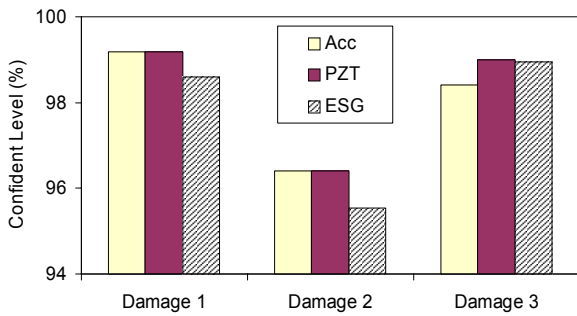


Fig. 10 MSE-based damage detectability for three sensor types

are well localized as shown in Fig. 7~9. The confidence levels were up to 96%. As shown in Fig. 10, for damage cases 1 and 2, the confidence levels in case of using electrical strain gage are relative lower than those in case of using accelerometer and PZT sensor. As also shown in Fig. 10, for cantilever beam, it is easier to detect the damage near fix-end location than mid-span location. As a result, the fix-end location is more critical than mid-span location for cantilever beam. Compared to the results by the accelerometer and the electrical strain gage, the damage localization results by the PZT sensor were accurate with high confidence level for all damage cases.

4. Conclusions

In this paper, the feasibility of using lead zirconate titanate (PZT)'s direct piezoelectric response as vibrational feature for damage monitoring in beam structures was examined. First, the theoretical background of PZT's direct piezoelectric effect for dynamic strain response was presented. Next, the damage monitoring method that utilizes the change in modal strain energy (MSE) to locate the severity of damage in beam structures was outlined. For validation, experiments were carried out on lab-scale aluminum cantilever beam. For several damage scenarios, dynamic responses were measured by three different sensor types (i.e., accelerometer, PZT sensor and electrical strain gage) and damage monitoring tasks were performed thereafter. The vibration responses showed good agreement for three sensor

types. The performance of PZT's direct piezoelectric response for MSE-based damage monitoring was successfully evaluated by comparing the damage localization results from the three sensor types. The damage locations were well localized with high confidence level.

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