Looseness Estimation of Bolts on Truss Structure with PZT Patches

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Abstract: This work presents a study on development of a practical and quantitative technique for assessment of the healthy state of a structure by piezoelectric impedance-based technique associated with longitudinal wave propagation measuring method. A truss structure embedded with piezoelectric patches is investigated for a fundamental study on estimation of the looseness of bolts in the joint. In order to evaluate the minute mechanical impedance change due to loosening bolt, a harmonic longitudinal elastic wave is applied to the structure by a pair of PZT patches and their electric impedance is measured simultaneously. According to the experimental results, the change of the electric impedance of PZT is affected significantly by the elastic wave dissipation or the disturbance occurred in or through the bolts at the joint. In this paper, a technique for estimation of the bolt looseness is investigated in detail. With a plenty of experiments, the resonant frequency shift DF, the peak amplitude ratio d and quality factor ratio g, calculated from the electric impedance response, are proposed as the bolt looseness indices. The estimation of the fastening state in bolts at the truss structure is obtained in a high accuracy by the aid of the bolt looseness indices.

Keywords: Keywords: Structural Health Monitoring, Truss Structure, PZT Patches, Piezoelectric Impedance Response, Fastening State of Bolts, Looseness Indices.

1. Introduction

A lot of large structures built almost more than 20 years, such as high buildings, large bridges, tunnels, high-level roads and so on, become superannuated and the accidents, such as the fall of tunnel concrete walls, the damage on buildings and the broken of bridges, are happening frequently. Development of in-service and on-line health monitoring techniques are strongly required and a lot of trials are made for civil infrastructure, high speed train, military and commercial aircraft.

There have been also a lot of fundamental studies on this area. Modal analysis has been one of the most popular approaches in NDE and a lot of useful techniques have been developed for the last few decades [1-2]. The techniques based on the modal analysis are efficient only when the damage is relatively large which makes the resonant frequency change significant enough to be detected in usual way. The typical experimental results in the literature showed that the modal analysis has good accuracy usually at low frequency region, but the accuracy could be decreased significantly at high frequency. It might to say, the traditional modal analysis method is not suitable for detection of a relative small damage occurred in a large structure because it usually gives a very small resonant variation at low frequency region.

Several structural health monitoring techniques or non-destructive damage detection methods have been developed for the smart structures embedded with piezoelectric materials because it could sever as both oscillator and sensor and be easily treated in various conditions. The impedance-based technique with PZT sensor/actuator is one of the simple high frequency domain methods [3-6] for structural health monitoring. This technique is very sensitive for assessment of incipient-type damage such as small cracks or loose connections. However, it is hard to estimate the damage state quantitatively because the impedance change due to damages would be affected strongly by the frequency regions for measuring.

The objective of this research is to develop a practical and quantitative technique for assessment of the healthy state of a structure by longitudinal wave propagation measuring method. Since the piezoelectric actuator can be driven at very high frequency and the piezoelectric sensor is very sensitive to the rate of strain variation, the piezoceramic patches are utilized to embed in structures working as both oscillators and receivers. As an example, the evaluation of the looseness of bolts at the joint is investigated in detail. With a plenty of experiments, the impedance resonant frequency shift, the peak amplitude ratio and quality factor ratio are proposed as the bolt looseness indices and they are validated experimentally for monitoring the bolt fastening condition at the joint.

2. Impedance Measuring System

Figure 1 shows the PZT electro-mechanical impedance measuring system, which is consisted of an impedance analyzer and a computer. In this fundamental study, a pair of PZT patches is bonded on two sides of a beam element of the structure in order to generate a longitudinal wave in the beam due to the way that the PZT patches are undergoing axial vibration in response to an applied alternating voltage. Since the PZT is embedded in the structure, the PZT electric impedance is subjected to the mechanical impedance of the structure. Usually, a tiny mechanical impedance change on the structure is not easy to be measured, but it can be monitored very sensitively by measuring the electric impedance of the embedded PZTs. The basic concept of the PZT impedance-based measuring technique is that the infancy or small damage happening in the structure is assessed through monitoring the PZT's electric impedance.

In the experiment, the coupled electromechanical impedance measurement is performed as follows: The impedance analyzer (HP4192) provides a constant alternating voltage signal (1 Vrms), at a selected frequency region, to a pair of PZT patches in order to apply a longitudinal wave in the structure. The magnitude and phase of the steady state current (after transient behavior has decayed) from the PZT is recorded and converted into real and imaginary electric impedance. The damage in the structure, leading a mechanical impedance change, can be detected by comparing the variation of the obtained electrical impedance of its healthy state to that of the structure in the current or damaged state. The excitation frequency has to be selected high enough, in other word, the wavelength should to be significantly smaller than the damage size.

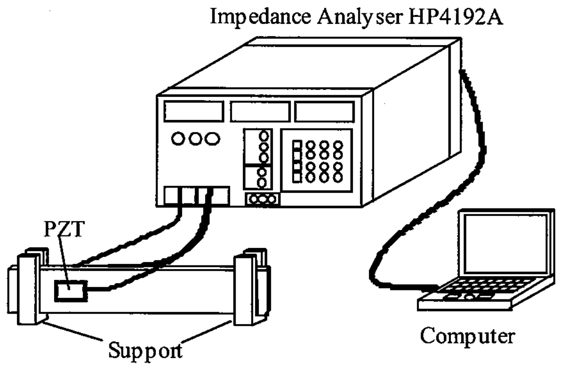

Fig. 1. Impedance measuring system and experimental setup

The material properties of the PZT patch and the beam element in the truss structure used in this study are listed in Table 1. The schematic of PZT patches embedded beam, which is used as the basic element in the truss structure, is shown in Fig.2.

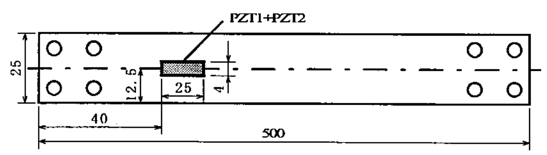

Fig.2. Schematic of beam element embedded with PZT patches.

The electric impedance response of the beam in Fig.2 measured in free supported condition is plotted in Fig.3. The impedance output is a complex data. Its real part is used in the following analysis because its imagery part contains a large DC component due to its dielectric property.

Figure 4 is the truss structure for investigating how to evaluate the fastening state of the bolts at the joint quantitatively. The PZT embedded beam shown in Fig.2 is installed in the center of the structure. All the bolts in the structure were tighten initially by a torque wrench to 2Nm, which is supposed as the healthy or inertial condition of the structure. The piezoelectric impedance in this condition were measured first and stored to a database file as a reference source.

Table 1 Material properties of beam element and PZT patch.

Aluminum beam element in truss structure	
Length l_s (mm)	500
Width w_s (mm)	25
Thickness h_s (mm)	2
Density ρ_s ($\times 10^3$kg/m^3)	2.70
Young's modulus E_s ($\times 10^{10}$N/m^2)	7.06
Piezo-electric element (C-6)	
Length l_a (mm)	25
Width w_a (mm)	4
Thickness h_a (mm)	0.3
Density ρ_a ($\times 10^3$ kg/m^3)	7.4
Relative dielectric constant ε_{33}^T	2000 $\pm$300
Piezo-electricity constant d_{31} ($\times 10^{-12}$m/V)	-195
Young's modulus Y_{11}^E ($\times 10^{10}$ N/m^2)	5.8
Induced loss tanδ	2.1
Frequency constant N_{31} (Hz・m)	1400

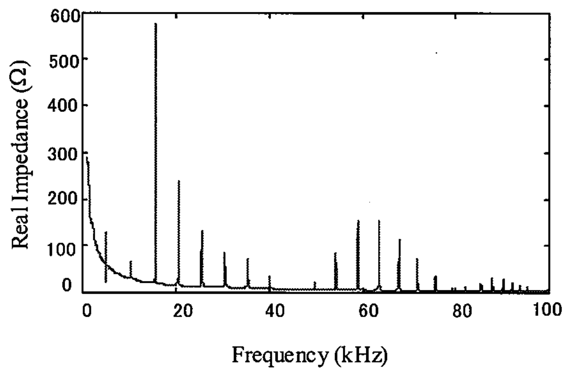

Fig. 3. Impedance response of element beam used for the truss structure.

As the PZT embedded element beam of Fig.2 is constructed into the truss structure as shown inFig.4, its piezoelectric impedance responses are usually affected by the fastening boundary condition at the joint. Figure 5 shows the comparisons of the real part impedance responses obtained from the free beam and the beam built in the truss structure. The results are plotted separately in two frequency regions [1-30] kHz and [45-80] kHz. The impedance responses between the free beam and the built-in beam in low frequency region, say at [1-30] kHz, have a significant change in their magnitude, but they have small change at the high frequency region [45-85] kHz. It indicates that the impedance response at low frequency region is affected much by the boundary conditions, i.e. the way to fasten the beam on the structure.

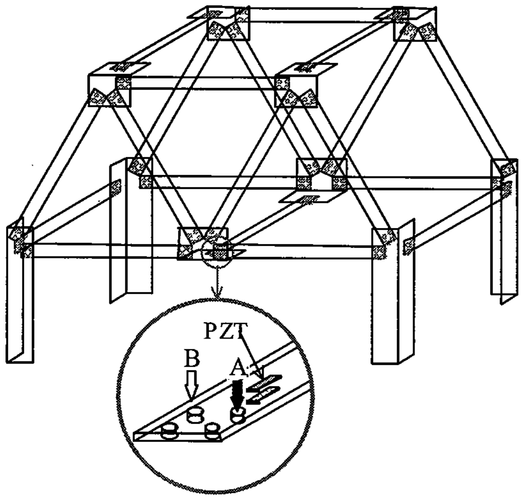

Fig. 4 Sketch of the truss structure and the positions where the bolts and PZTs are taken into account in experiment.

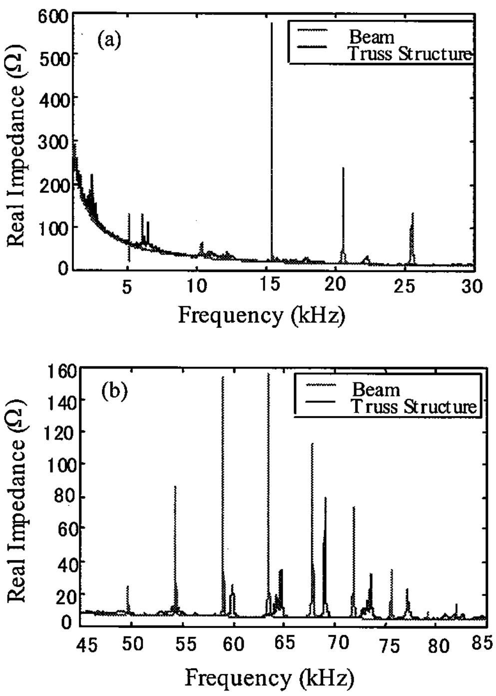

Fig. 5. Comparisons of the impedance responses obtained from the beam in free case and fixed on truss structure.

Considering a single beam with a pair of PZT patches on its both sides as shown in Fig.6, the longitudinal wave generated in the beam can be estimated simply by the motion of equation as follows.

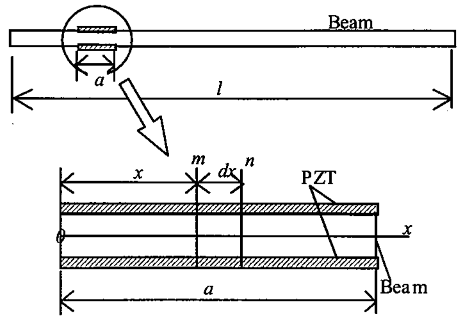

Fig. 6. Analytic model of the sandwich structure consisted of a beam and two PZT patches.

$$\frac{\partial^2 u}{\partial t^2} = \frac{E_s}{\rho_s}\frac{\partial^2 u}{\partial x^2} = c_s^2 \frac{\partial^2 u}{\partial x^2} \tag{1}$$

where, E_s is Young's modulus and ρ_s is density of the beam. The resonant frequency for a free-free or fixed-fixed beam can be calculated numerically by substituting the material parameters in Table 1 to

$$f_n = \frac{c}{2l}n = \frac{n}{2l}\sqrt{\frac{E_s}{\rho_s}} \approx 5.11n \text{ (kHz)}, \quad n = 1, 2, 3..... \tag{2}$$

As for a free-fixed beam the resonance frequency is then obtained by

$$f_n = \frac{(2n-1)c}{4l} = \frac{(2n-1)}{4l}\sqrt{\frac{E_s}{\rho_s}} \approx 2.55\times\frac{2n-1}{4} \text{ (kHz)}, \quad n = 1, 2, 3..... \tag{3}$$

On the other hand, if the length of longitudinal wave is very short, which is equal to or less than the length of the PZT Patch, the motion of longitudinal wave propagating in the PZT's sandwiched part as shown in Fig.6 will be generated and can be expressed by

$$\frac{\partial^2 u}{\partial t^2} = \frac{\left(A_s E_s + 2A_a Y^E\right)}{\left(\rho_s A_s + 2\rho_a A_a\right)}\frac{\partial^2 u}{\partial x^2} = c^2 \frac{\partial^2 u}{\partial x^2} \tag{4}$$

where Y^E is Young's modulus and ρ_a is density of the PZT patches. A_s and A_a are the cross section areas of the beam and PZT patches. Therefore, one sensitive resonant frequency region to the PZT will be between

$$f_b = \frac{1}{4a}\sqrt{\frac{A_s E_s + 2A_a Y^E}{A_s \rho_s + 2A_a \rho_a}} \tag{5}$$

and

$$f_e = \frac{1}{2a}\sqrt{\frac{A_s E_s + 2A_a Y^E}{A_s \rho_s + 2A_a \rho_a}} \tag{6}$$

Substituting the material parameters to the Eq.5 and Eq.6, it gives f_b = 42.29 kHz and f_e = 84.58 kHz. Comparing with the Fig.5(b) it is very clear that the impedance response at the frequency region $[f_b, f_e]$ is not affected much by the boundary conditions of the beam but sensitive to the length of PZT. So it might be a suitable frequency region for assessment of structural damage. Furthermore, the frequency region $[f_b, f_e]$ can be easily estimated by Eq.5 and Eq.6 if the material parameters of the structure and PZT patch are fixed. The following results are obtained and analyzed mainly in this frequency region.

3. Results And Discussions

Now considering a requirement to monitor a bolt looseness at a joint such as the case in Fig.4 with the impedance-based measuring technique, the procedure in this study is proposed as follows, (1) acquire the piezoelectric impedance response coarsely at frequency region $[f_b, f_e]$ in its initial or healthy condition; (2) select the detail frequency regions corresponding to the most sensitive peaks in the region $[f_b, f_e]$; (3) measure the impedance responses finely in these regions selected by step 2. For example, one can easily find out the frequency region with the most sensitive peaks from Fig.5, say around 60kHz to 80kHz with 5 peaks. Then, one could measure these peaks' changes in detail for analysis of the bolt looseness. In the following, Bolt A(see Fig.7) loosened by the torque wrench was investigated and three bolt looseness indices are proposed for estimation its fastening condition.

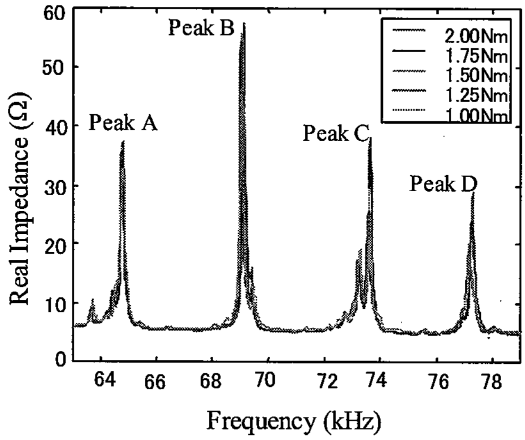

Fig. 7. Impedance variations at the selected frequency region as Bolt A is loosened by a torque wrench.

Figure 7 shows the impedance responses measured at the frequency region [64, 78]kHz and the details of the impedance changes at each peak are plotted respectively in Figs.8(a-d). It is clear that the frequency and amplitude of each peak are varied monotonously with the decrease of the torque. So it is easily coming to a conclusion that the fastening condition of bolts could be estimated by evaluation of the variation of these peaks.

Now, the problem is how to evaluate these peaks in numerical, in another word, what kind of parameters could be valid for the evaluation.

Considering a longitudinal wave propagating on a structure, some wave energy might be dispersed at the place where damage occurred, such as at a joint where a bolt is loosened or at a welded connection where a crack appears. Also the longitudinal wave will reflect at the damage place, which makes a change in wavelength or generates a new wave with new wavelength. In following, three indices are introduced for evaluation of the looseness of a bolt in the structure.

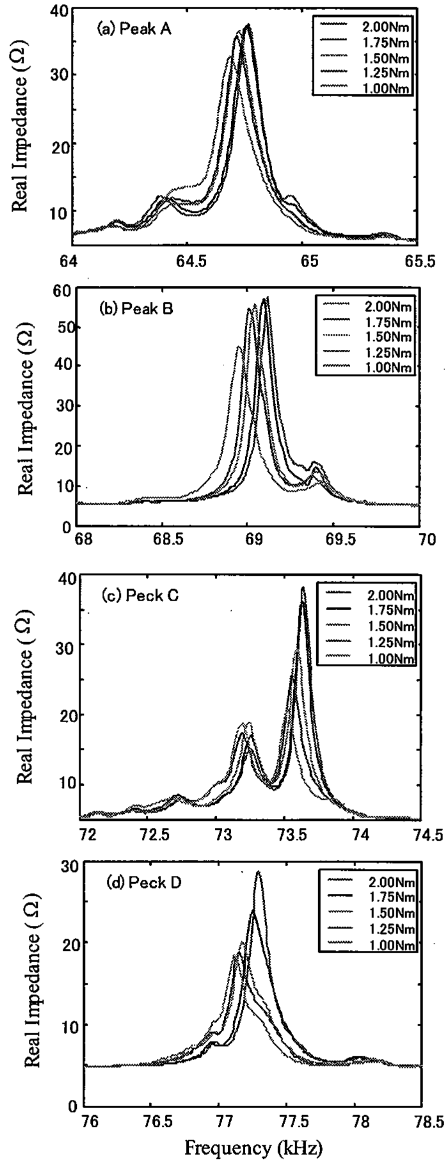

Fig. 8. Detail plots of the impedance responses at (a) Peak A, (b) Peak B, (c) Peak C, (d) Peak D of Fig.7.

3.1. Index I: Peak Frequency Shift ΔF

The wavelength will be varied due to the reflection at or between the damage, so one can monitor the damage condition or size by observing the frequency variation with comparison to its healthy condition. Suppose the peak frequency at a considering region in the healthy condition is measured as f_h and the one at the same region in damaged structure is f_d as shown in Fig.9, the peak frequency shift ΔF could be then defined as the damage index by

$$\Delta F = \left| f_h - f_d \right| . \tag{7}$$

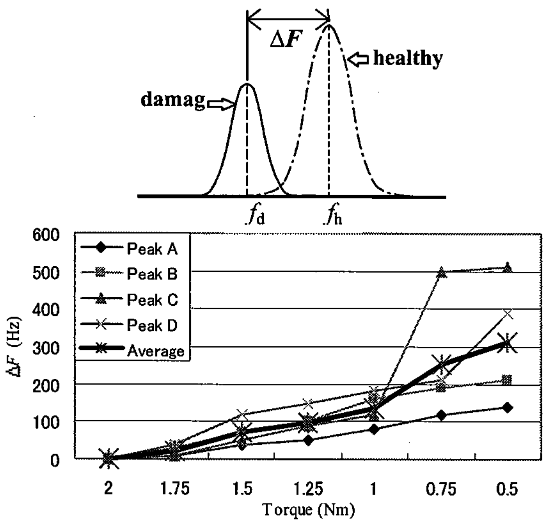

Fig. 9. Definition of Peak Frequency Shift ΔF and its variation at each peak to the fastening torque.

The peak frequency variations in Fig.8 are calculated by Eq.7 and the results are plotted in Fig.9. The frequency shifts ΔF at the four peaks have different values, but they are increased monotonously with decrease of the torque in the bolt. It is evidence that the peak frequency shift can be used to estimate the looseness of the bolts in the structure. Furthermore, frequency shift at Peak C has a significantly change after the torque reduced less than 1Nm. It means that this torque could be considered as a critical torque.

In order to increase the accuracy of estimation, an average of the frequency shifts at four peaks is taken and plotted in heavy line in Fig.9. Therefore, the current torque on the bolt could be estimated by Eq.8 which is obtained by the least square method.

$$\tilde{T} = 1.966 - 0.00718\overline{\Delta F} \tag{8}$$

3.2. Index II: Peak Amplitude Ratio δ

The mechanical impedance of the structure will be varied due to the presence of damages. Suppose the peak amplitude measured at a selected frequency region in the healthy condition is given by A_h and the one obtained in damage condition is A_d, the second damage index, named by Peak Amplitude Ratio, is then defined as (Ref. Fig.10)

$$\delta = \left| \frac{A_h - A_d}{A_h} \right| \times 100 \ (\%) \tag{9}$$

The peak amplitude at each resonant frequency is usually reduced as the damage becomes serious because of the energy dispersion. On the other hand, if the exciting wavelength is related to the size of the damage or the resonant frequency, a new peak might appear or the amplitude might be increased at this frequency. Figure 10 shows the results of the peak amplitude ratios in percentage obtained from the four selected regions(Fig.8). The loosening condition of the bolt can be also qualitatively evaluated by value δ.

With same consideration, the estimation equation using Index δ, is obtained in Eq.10.

$$\tilde{T} = 1.979 - 0.03467\overline{\delta} \tag{10}$$

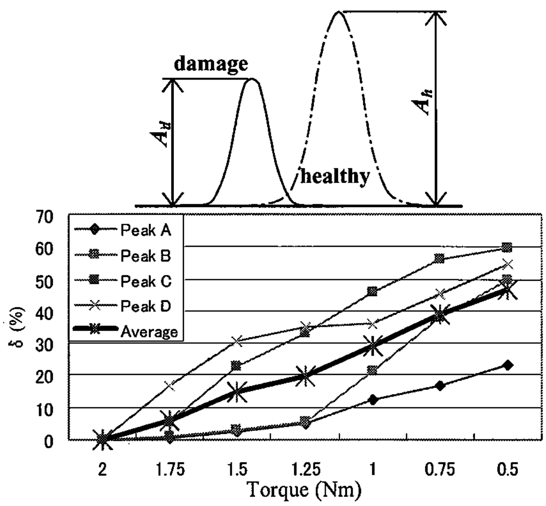

Fig. 10. Definition of Peak Amplitude Ratio δ and its variations at each peak to the fastening torque.

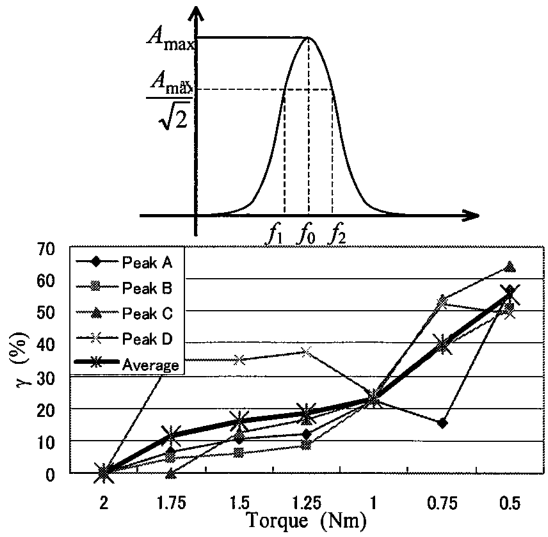

Fig. 11. Definition of Quality Factor Ratio γ and its variations at each peak to the fastening torque.

3.3. Index III: Quality Factor Ratio γ

As the third damage index, the quality factor Q is introduced for evaluation of the damping effect of damage. Considering a damped single-degree-of- freedom system the quality factor Q defined in Fig.11 can be expressed by the damping ratio ζ when it is relative small.

$$Q = \frac{f_0}{f_2 - f_1} \approx \frac{1}{2\varsigma} \tag{11}$$

Imitating the expression of the peak amplitude ratio, the third damage index γ is then defined in percentage as

$$\gamma = \frac{Q_h - Q_d}{Q_h} \times 100 \quad (\%) \qquad (12)$$

Figure 11 describes the variations of the quality factor ratio at the selected region shown in Fig.8 as the bolt is loosened to 0.5Nm step by step. In contrast with the results of Fig.10 the variation of the quality factor ratio has same tendency as the peak amplitude ratio but the value γ is varied some unstable comparing to the values ΔF and δ. However, the index γ could estimate the viscous characteristics of a damage, and it might be a powerful parameter in our future study on assessment of more characteristics of the damage happened in the structure.

The qualitative estimation based on the average index γ of the four peaks is then given by

$$\tilde{T} = 2.095 - 0.04314\bar{\gamma} \qquad (13)$$

4. Conclusions

A damage assessment technique based on the piezoelectric impedance measurement is described for monitoring the fastening state of bolts at the joint. Three estimation indices, Peak Frequency Shift DF, Peak Amplitude Ratio d and Quality Factor Ratio g, are proposed for estimation of the bolt looseness. The experimental results validated that the fastening condition of the bolt at the joint can be evaluated accurately by using these three estimation indices.

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