Fatigue Life Assessment of Structures Using Electro-Mechanical Impedance Technique

S Bhalla
Associate Professor, Department of Civil Engineering, Indian Institute of Technology (IIT) Delhi, Hauz Khas, New Delhi 110 016 (India)
E-mail: sbhalla@civil.iitd.ac.in

Abstract. This paper describes a new experimental approach for fatigue life assessment of structures based on the equivalent stiffness determined by surface bonded piezo-impedance transducers through the electro-mechanical impedance (EMI) technique. The remaining life of the component (in terms of the cycles of loading that can be sustained) is non-dimensionally correlated with the equivalent identified stiffness. The proposed approach circumvents the determination of the absolute stiffness of the joint and employs the admittance signature of the surface-bonded piezo-transducers directly. The second part of the paper briefly describes the recent advances made in the field of impedance based structural health monitoring (SHM) in terms of low-cost hardware system and improved damage diagnosis through the integration of global dynamic and EMI techniques using the same set of piezo-sensors. Other recent applications such as bio-sensors and traffic sensors pioneered at the Smart Structures and Dynamics Laboratory (SSDL) are also briefly covered.

1. Introduction
All real-life structures are in general prone to fatigue, which is the occurrence of localized but progressive damage due to fluctuating stresses. Even if the tensile or the compressive stresses are well within the limits of the field strength of the material, their alternating nature is responsible for fatigue. Several major failures across the world can be traced to be initiated by fatigue, such as the Seongsu Bridge in Seoul [1]. Fatigue damage can be monitored by observing changes in specimen’s stiffness as a function of the number of loading cycles. However, in an actual structural component (say a large bridge joint), it is not possible to determine the residual stiffness while the component is under service. This paper presents an alternative approach, based on the changes in the admittance signatures of surface-bonded piezoelectric ceramic (PZT) patches. The test results of a monitoring study conducted on a steel joint are presented. Further, the recent advances in the EMI technique in terms of low-cost hardware, improved algorithms and new applications in bio-mechanics and traffic monitoring are described.

2. Electro-mechanical impedance (EMI) technique
The PZT patches serve as the transducers in the EMI technique, which has established its potential for cost-effective structural health monitoring (SHM) of a wide variety of engineering structures [2-4]. Several new variants of the technique have also been proposed [5-7]. In principle, this technique is similar to the conventional global vibration techniques, the major difference, however, is with respect to the excitation frequencies employed. The EMI technique typically operates in the frequency range

1 To whom any correspondence should be addressed.
of 30-400 kHz, against typically less than hundred hertz for the global vibration techniques. Such high frequency of vibrations is achieved by electrically exciting a PZT patch surface bonded to the monitored structure by means of an impedance analyzer/ LCR meter. Under an external electric field excitation, the bonded patch induces deformations in the host structure, whose response is transferred back to the patch in the form of admittance, consisting of conductance (the real part) and susceptance (the imaginary part). These electrical ‘signatures’ of the structure in frequency domain contain vital information concerning the phenomenological nature of the structure. Thus, the same PZT patch acts as an actuator as well as a sensor concurrently in the EMI technique.

Bhalla and Soh [8] extended the 1D impedance formulations to 2D structures by introducing the concept of ‘effective impedance and derived an expression for the complex electro-mechanical admittance \( \bar{Y} \) as

\[
\bar{Y} = G + Bj = \frac{4\pi\epsilon_0}{\mu_0} \left[ \frac{2d_{ij} Y^\text{eff}}{(1-v)} \right] + \frac{2d_{ij} Y^\text{eff}}{(1-v)} \left( \frac{Z_{a,\text{eff}}}{Z_{s,\text{eff}} + Z_{a,\text{eff}}} \right) \]

(1)

where \( h \) is the thickness of the PZT patch, \( v \) the Poisson’s ratio and \( \omega \) the angular frequency. \( Z_{s,\text{eff}} \) and \( Z_{a,\text{eff}} \) respectively denote the effective mechanical impedances of the structure and the patch. The term \( \bar{T} \) is complex tangent ratio, ideally equal to \( \frac{\tan(\kappa l)}{\kappa l} \), with \( \kappa = \omega \sqrt{\rho(1-v^2)/Y^\text{eff}} \) the wave number. Correction factors \( C_1 \) and \( C_2 \) were introduced to realistically represent the behaviour of the PZT patch, modifying the expression for \( \bar{T} \) as

\[
\bar{T} = \frac{1}{2} \left( \frac{\tan(C_1 \kappa l)}{C_1 \kappa l} + \frac{\tan(C_2 \kappa l)}{C_2 \kappa l} \right)
\]

(2)

As can be observed from Equation (1), any damage to the structure (i.e. any change in mechanical impedance ‘\( Z_{s,\text{eff}} \)’) will manifest itself as a deviation in the admittance value, thereby providing an indication of the damage. This forms the fundamental premise for damage detection in the EMI technique. The next section covers an experimental study on a steel joint.

3. Fatigue study on Structural joint

Figure 1 shows the fabrication details of the test specimen, a steel bolted joint. Two bolts (of 20mm diameter and grade 10.9) were used to make up the lap joint. The connecting plates were 120x210x3mm in size, with an overlap of 70mm. This arrangement provided equal effective area at the location of the top as well as the bottom rows of bolts in the upper plate. Three PZT patches were bonded to the upper plate as shown in the figure.

The specimen was subjected to a cyclic tensile stress varying from 15.6MPa to 172.9MPa (0.062 \( f_s \) to 0.7 \( f_s \)) at a frequency of 5Hz until 40,000 cycles. Thereafter, the stresses were varied from 15.6MPa to 200MPa (0.0625 \( f_s \) to 0.8 \( f_s \)) until 90,000 cycles. Finally, the stresses were varied from 15.6MPa to 234MPa (0.0625 \( f_s \) to 0.94 \( f_s \)) at 5Hz until failure. After 100,000 cycles, stretch marks were externally visible in the upper plate. Final failure of the specimen occurred at 130,000 cycles, with the failure pattern shown in Figure 2. As can be noted, the failure occurred by tearing of the plate at the location of the bolts. The signatures of the three PZT patches were recorded after every 2500 cycles Figure 3 shows the variation of conductance \( G \) (the real part of admittance) of the PZT patches, bonded to the steel joint specimen, corresponding to different cycle ratios. In general, from Figure 3, the
conductance signature can be observed change with increase in the cycle ratio. However, the variation is random in nature and does not seem to follow any consistent pattern or trend.

![Joint specimen ready for testing.](image1)

**Figure 1.** Joint specimen ready for testing.

![Joint specimen after failure.](image2)

**Figure 2.** Joint specimen after failure.

![Conductance signatures of PZT patches.](image3)

(a) PZT 1 (b) PZT 2 (c) PZT 3

**Figure 3.** Conductance signatures of PZT patches.

Figure 4 presents the variation of the RMSD index with cycle ratio for all the patches, which was computed with reference to the baseline signature. The observations are almost similar to those reported by Giurgiutiu et al. [9]. The RMSD increases abruptly after the first few cycles and then attains more or less constant value or exhibits a weakly linearly increasing trend. The variation of the RMSD index can be studied in light of the degradation of actual stiffness of the specimens with load cycles, determined using the load-deflection data directly measured from the MTS system and shown in Figure 5 as a function of the cycle ratio. It can be observed from the plot that an initial abrupt loss of stiffness occurred first, followed by a gradually increasing loss, finally culminating in failure of the specimen. The initial increment is possibly on account of the slip accompanying the overcoming of the friction forces between the steel plates. In overall, as can be observed from the comparison of
Figures 4 and 5, the RMSD index fails to provide a measure of the degradation on a uniform scale. It does not correlate well with stiffness degradation of the specimen. To gain further insight into the phenomenon, the extracted mechanical impedance, in particular the equivalent stiffness, was explored, the details are covered in the next section.

![Figure 4. RMSD index of PZT patches.](image)

(a) PZT 1 (b) PZT 2 (c) PZT 3

![Figure 5. Variation of specimen stiffness with cycles of loading.](image)

4. Correlation with equivalent stiffness

Figure 6 shows the variation of $x$ and $y$ (the real and the imaginary components respectively) of the effective mechanical impedance of the host structure (here steel joint) in healthy state, extracted out from the admittance signatures of a PZT attached to the specimen. The computational procedure devised earlier [8] was used for this purpose. From the figure, it can be observed that the variation is similar to that of a Kelvin-Vogit system. Within the range of the frequencies shown, $x$ has more or less constant positive value and $y$ has a negative value with magnitude decreasing with frequency, which is the impedance characteristic of Kelvin-Vogit systems.
Figure 6. Variation of extracted mechanical impedance for a PZT patch of specimen. (a) Real component of (b) Imaginary component

Figure 7. Variation of ‘y’ with inverse of frequency for various cycle ratios.

The relevance of this analysis can be further appreciated by the plot of $y$ vs $\omega^{-1}$ in the frequency range of 50 to 200 kHz, as shown in Figure 7, corresponding to various cycle ratios. The slope of the curve (and hence the identified value of $k$) can be observed to decrease consistently with loss of stiffness of the specimen with increasing cycle ratio (see Figure 5 also). This is much more consistent than the trend of the RMSD (see Figure 4) or the variation of the raw conductance signatures (see Figure 3). Although the values of $k$ so determined by the PZT patches differed from the actual measured stiffness of the joint, the loss of the PZT identified $k$ (averaged over all the PZT patches bonded to the specimen) reasonably correlates with the loss of the actual stiffness of the specimen. For purposes of quantification, stiffness loss can be defined in non-dimensional form as
\[ \frac{\delta S}{k} = k_0 - \Delta k \]  

(3)

where \( k_0 \) is the original stiffness of the component and \( \Delta k \) the loss of stiffness. Here, both actual stiffness and the PZT identified stiffness can be substituted. Similarly, the remaining life of the component can be defined in a non-dimensional form as

\[ L = 1 - CR = 1 - \frac{N}{N_o} \]  

(4)

where \( CR \) is the acronym of cycle ratio, \( N \) the number of cycles completed at a given point and \( N_o \) the total number of cycles till failure. Based on the response of all the three PZT patches, following equation can be derived relating the remaining life with the loss of equivalent stiffness identified by the surface-bonded PZT patch.

\[ L = A(\Delta S)^3 + B(\Delta S)^2 + C(\Delta S) \]  

(5)

The approach is more reliable as compared with the RMSD index owing to greater consistency in variation as shown above. The repeatability and consistency of the proposed approach was studied on two more similar specimens, the details of which can be found in the related publication [10]. The next section provides a glimpse of the recent advancements in the field of PZT based SHM at the Smart Structures and Dynamics Lab (SSDL) at the Indian Institute of Technology Delhi.

5. Recent advances in SHM using piezo-transducers

Active research is currently underway to facilitate a widespread use of the piezo sensors in effective SHM in important industries. Bhalla et al. [7] proposed ultra low-cost adaptations of the EMI technique using the set-up illustrated in Figure 8. A combination of function generator and digital multimeter replaced the expensive LCR meter. Together, the cost of the minimum hardware came down to about $2500 only, against over $20,000 for the LCR meter.

![Figure 8. Ultra low-cost adaptation of EMI technique [7]](image-url)
Further, Dr. S. Bhalla’s research team has proposed a new approach to monitor structural health more efficiently by integrating the global dynamic technique with the local EMI technique [11]. The same PZT patches are employed to determine the first few natural frequencies and mode as well as the admittance signature using the EMI technique. Since the PZT patches perform well in low as well as high frequencies ranges, both techniques are integrated meaningfully to monitor the health of structures locally as well as globally. The EMI technique locates incipient damage (which the global dynamic techniques fail to detect) reasonably well. On the other hand, the global dynamic technique locates as well as quantifies moderate to severe damages (which the EMI technique fails to distinguish) quite well. Use of the PZT patches circumvents the need for several tedious numerical computations since they enable obtaining the curvature mode shapes directly for SHM, as illustrated in Figure 9 for a simply supported steel beam with a damage introduced in the form of a crack.

Figure 9. Direct extraction and use of curvature mode shape for SHM [11]

Other recent applications of the piezo-transducers include traffic monitoring, corrosion monitoring in steel rebars and foot pressure monitoring. Figure 10 shows the schematic set-up which can be embedded in carriageway and can provide signals for the traffic passing through the carriageway. Through appropriate calibration, the system can easily classify the passing vehicle in different categories based on the axle loads. Details can be assessed in the related paper [12]. Figure 11 shows one of the steel rebar on which a detailed corrosion monitoring study was performed. The EMI technique exhibited good performance in terms of corrosion detection as well as quantification [13]. Figure 12 shows a customized footwear in which piezo sensors have been embedded to generate signals providing a measure of the foot pressure generated. This can be used for corrective therapy for diabetic patients.
6. Conclusions
This paper has presented a new approach to realistically quantify fatigue induced damage in structures and to predict the remaining useful life of the component using the equivalent stiffness identified by surface bonded PZT patches. The approach, based on the equivalent ‘k’, is an improvement over statistical indicators, such as RMSD, which fail to provide meaningful indication of the loss of stiffness of the component. The specimen showed reasonably good correlation between the absolute specimen stiffness and the PZT identified stiffness, justifying the use of the latter in place of the former for remaining life assessment. The empirical correlation derived from all the PZT patches can be utilized in the real-life bolted joints, where estimation of the absolute stiffness is either impossible, or very difficult. A more detailed coverage of the experimental study can be found in the related publication [10]. The paper also provides a glimpse of other research activities at SSDL laboratory at IIT Delhi focused at the use of piezo sensors for traffic monitoring, corrosion assessment, and foot pressure measurement.

Figure 10. Traffic monitoring using piezo-transducers [12]

Figure 11. Corrosion monitoring in steel rebar [13].

Figure 12. Foot pressure measurement.
References

[1] Park S, Yun C B, Roh Y and Lee J J 2006a. *Smart Mater. & Strs.* **15** 957.

[2] Soh C K, Tseng K K H, Bhalla S and Gupta A 2000. *Smart Mater. & Strs.* **9** 533.

[3] Soh C K and Bhalla S 2005. *Smart Mater. & Strs.* **14** 671.

[4] Lim Y Y, Bhalla S and Soh C K. 2006. *Smart Mater. & Strs.* **15** 987.

[5] Peairs D M, Park G and Inman D J 2004. *J. Intelli. Mater. Sys.& Strs.* **15** 129.

[6] Overly T G, Park G, Farinholt K M and Farrar C R 2008. *Smart Mater. & Strs.* **17** 065011.

[7] Bhalla S, Gupta A, Bansal S and Garg T 2009. *J. Intelli. Mater. Sys.& Strs.* **20** 991.

[8] Bhalla S and Soh C K 2004. *J Aero. Eng.* ASCE. **17**:154.

[9] Giurgiutiu V, Reynolds A and Rogers C A 1999. *J. Intelli. Mater. Sys.& Strs.* **10** 802.

[10] Bhalla S, Vittal A P R and Veljkovic M. 2011. *J. Strl. Health Monitoring*, in press.

[11] Shanker R, Bhalla S and Gupta A 2011. *J. Intelli. Mater. Sys.& Strs.* **22** 1841.

[12] Bhalla S and Deb S K. 2011. *Exp. Tech.* **35** 30.

[13] Visalakshi T, Bhalla S and Bhattacharjee B 2011. *Int. J. Earth Sciences and Engineering* **04** 889.