Fatigue damage diagnosis and prognosis using EMI technique

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Fatigue damage diagnosis and prognosis using electromechanical impedance technique

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15.1 Introduction

Structures and structural components in service are often subjected to repeated fluctuating stresses of magnitude lower than that of their strength limit. However, after enduring a large number of loading cycles, the structures or some components start to develop progressive localized damage. This phenomenon is often known as fatigue crack and the cyclic load applied is known as fatigue load.

The number of loading cycles a structural member or component can sustain before fracture occurs is referred to as its fatigue life. The exact number of cycles, in turn, is dependent on several factors including the nature of load, the load displacement curve, the frequency of repetition, load history, the size of member, the flaw that is initially present, the temperature, and other environmental conditions. Therefore, in practice, it is difficult to accurately estimate the fatigue life of a member. The designer usually relies on either a full-scale test or more often, a laboratory test. In the conventional structural design, conservative estimation of fatigue life is adopted to ensure safety.

However, it is often noticed that the structure or structural member remains functional despite the design life having been reached, resulting in earlier-than-required replacement. On the other hand, premature failure could also occur when the actual loading exceeds the estimated loading significantly. Therefore, it is of general interest to develop a reliable technique which could accurately access the status of the structure in service and thus predict the remaining useful life (RUL) of the structure.

In real-life application, it is essential to detect fatigue crack at the earliest possible stage of the process. In terms of metal fatigue, nondestructive inspection (NDI) is expected to detect the presence of crack as well as to characterize its size. Visual
inspection, magnetic particle inspection, radiography, and ultrasonic and electromagnetic fields (Pook, 2007) are some of the most commonly used NDI techniques. Although some of these techniques are effective in sizing fatigue cracks, major drawbacks exist such as the location of crack has to be known a priori, difficulty in automation, interruption of service, disassembly of device, as well as cost and being labor-intensive.

The emergence of smart material such as the piezoelectric transducer-based electromechanical impedance (EMI) technique could possibly provide an alternative to its conventional counterparts, meanwhile overcoming some of the drawbacks. The EMI technique, employing piezoelectric transducer as a collocated actuator and sensor, is potentially applicable in this aspect with its widely known capability to detect and characterize various forms of damages (Park et al., 2003). It offers advantages such as being nonintrusive to host structure, capable of providing autonomous, and real-time and remote damage monitoring, including the detection and characterization of incipient cracks (Lim and Soh, 2010).

This chapter presents a series of investigative studies to evaluate the feasibility of fatigue crack monitoring and estimation of RUL using the EMI technique. Experimental test was conducted to study the ability of EMI technique in monitoring fatigue crack in one-dimensional (1-D) laboratory-sized aluminum beams subjected to mode I fatigue loading. The experimental results prove that the EMI technique is very sensitive to monitoring fatigue crack propagation in all three stages of fatigue crack. In the crack initiation stage (stage I), a microcrack invisible to the naked eye can be detected by the technique especially when employing the higher frequency range. Sensitivity of the EMI technique at different frequency ranges is discussed. In the crack propagation stage (stage II), a proof-of-concept semianalytical damage model for fatigue life estimation has been developed by incorporating the linear elastic fracture mechanics (LEFM) theory into the finite element (FE) model. At critical crack condition (stage III), a quick and handy qualitative-based critical crack identification method is suggested by visually inspecting the admittance frequency spectrum. The prediction of the model matches closely with the experiment, suggesting the possibility of replacing costly experiment in future.

15.2 Electromechanical impedance technique and fatigue crack monitoring

15.2.1 Physical principles of electromechanical impedance technique

Piezoelectric material (PZT) is capable of converting electrical energy into mechanical energy and vice versa. With the PZT transducer affixed to the host structure, an alternating voltage of varying frequency is applied across the poling direction of the transducer. The transducer can thus be excited (converse effect of piezoelectricity) and correspondingly actuates the host structure. On the other hand, the structural response affects the vibration of the PZT transducer, thus modulating the current passing through the transducer (direct effect of piezoelectricity). The modulated current is usually expressed in terms of complex electrical admittance, and can be measured by an
impedance analyzer. The admittance signatures contain information related to the vibrational behavior of the host structure. Any changes in the host structure affecting vibration such as degradation, disintegration, damage, etc. would be reflected in the admittance signatures.

A 1-D EMI model was introduced by Liang et al. (1994), shown in Fig. 15.1, where a vibrating PZT patch is simplified as a thin bar undergoing axial vibrations. Its interaction with the host structure is confined to both end points. Assuming ideal strain transfer between the PZT patch and the host structure, the entire structure is represented by its driving point mechanical impedance. Incorporating the dynamic force equilibrium and the piezoelectric constitutive relations, the complex electrical admittance expression is derived for the electromechanical admittance based on 1-D modeling (Liang et al., 1994):

\[
Y = 2\frac{\omega w_{la}}{u} \left( \frac{Z_a}{Z + Z_d} d_{31}^E \frac{\tan \kappa l_a}{\kappa l_a} d_{31}^E \right) \tag{15.1}
\]

where \(\omega\) is the angular frequency of the driving voltage, \(i\) is the imaginary number, and \(w_{la}, l_a, h_a\) are the width, length, and thickness of the PZT patch, respectively. \(Y_{11}^E\) is the complex Young’s modulus, \(\varepsilon_{33}^T\) is the complex electric permittivity, \(d_{31}\) is the piezoelectric strain coefficient, and \(\kappa\) is the wave number. \(Z_a\) and \(Z\) are the mechanical impedance of the PZT patch and the structure, respectively. Furthermore, the mechanical impedance of the PZT patch, \(Z_a\) can be derived as:

\[
Z_a = \frac{\kappa w_{la} h_a \varepsilon_{33}^T}{(io)\tan(\kappa l_a)} \tag{15.2}
\]

The working principles of the EMI technique are similar to the conventional global dynamic response techniques but with a higher frequency range (30–1000 kHz), rendering it to be very effective in detecting local and small damages. Park et al. (2000) demonstrated the applicability of the EMI technique in laboratory-sized civil
structures such as reinforced concrete (RC) wall, steel bridge, and pipe joint. Naidu and Bhalla (2002) showed the robustness of the EMI technique in characterizing damages induced in concrete structures. Lim et al. (2006) presented some parametric-based damage detection using equivalent structural parameters in characterizing the severity of damage in different structures. Park et al. (2008a) adopted principal component analysis, a data compression technique as a preprocessing module to reduce the data dimensionality and eliminate unwanted noise. Park et al. (2009) proposed an impedance model incorporating the effects of sensor and bonding defects for sensor self-diagnosis.


Giurgiutiu et al. (2006) showed that both EMI and Lamb wave propagation techniques are able to detect the presence and propagation of a crack under mixed-mode fatigue loading. Sevostianov et al. (2010) studied the relationship between strength reduction caused by accumulated damage in elastic electrically conductive material, its corresponding resistance across the damaged specimen, and EMI response.

Soh and Lim (2009) conducted an experimental study to detect fatigue damage on aluminum beam with a preinduced circular notch using the EMI technique. Lim and Soh (2011, 2014a) proposed a damage prognosis model for beam structures subjected to mode I fatigue loading.

Comprehensive reviews on the EMI technique can be found in Park et al. (2003, 2008b) and Annamdas and Soh (2010).

### 15.2.2 Finite element modeling of electromechanical impedance technique

Fairweather (1998) developed an FE-based impedance model for the prediction of structural response to induced-strain actuation. The simplicity of this model lies in the fact that modeling of the PZT patch is omitted by replacing it with a force or moment. However, the accuracy of the model is drastically reduced at higher frequency ranges, such as those employed in the EMI technique. The problem was later circumvented by researchers such as Liu and Giurgiutiu (2007) and Yang et al. (2008b), where the PZT patch and bonding layers were incorporated in the model using coupled field element. The coupled field FE model is found to exhibit closer agreement to the experimental results. Lim and Soh (2014b) conducted an in-depth parametric study into various parameters affecting the admittance signatures using the FE model. The accuracy of the FE model was significantly enhanced through model updating.
15.3 Fatigue crack growth

LEFM is by far one of the most expedient theories for predicting fracture failure based on the remaining uncracked section for a structural component under fatigue loading. Stress intensity factor is the parameter used for characterizing the initiation and propagation of cracks. Generally the stress intensity factor, $K$, can be expressed as (Stephens et al., 2001):

$$K = \sigma \sqrt{\pi a Y}$$  \[15.3\]

where $a$ denotes half length of the crack size, $\sigma$ is the stress applied, and $Y$ is the dimensionless shape factor, dependent on the specimen geometry and crack length.

Critical value of stress intensity factor is a state where a crack will propagate rapidly or unstably without further increase in loading. It is often denoted with a subscript $c$:

$$K_c = \sigma \sqrt{\pi a_c f \left( \frac{a_c}{w} \right)}$$  \[15.4\]

where $a_c$ is the crack length at instability (critical crack length) and $w$ is the width.

The relationship between different fatigue crack growth rates can be related to the applied stress intensity factor range, as shown in Fig. 15.2. Three distinct regions exist. Region I is the threshold region as indicated by a threshold value, $\Delta K_{th}$, below which fatigue cracks are characterized as nonpropagating.

Figure 15.2 Sigmoidal behavior of fatigue crack growth rate ($da/dN$) versus stress intensity factor range ($\Delta K$) for metals.
Region II is also known as the Paris region and is characterized by a linear relationship between crack growth rate, $da/dN$, and stress intensity factor range, $\Delta K$, in a logarithmic scale. This linear zone can be mathematically represented by the Paris equation (Paris et al., 1961):

$$\frac{da}{dN} = C(\Delta K)^m$$  \[15.5\]

where $C$ and $m$ are material-dependent constants. The Paris region represents the fatigue crack growth that corresponds to stable macroscopic crack growth. The presence of mean stress can be incorporated with the empirical correction factor, known as the Walker equation (Stephens et al., 2001):

$$\frac{da}{dN} = C'(\Delta K)^m$$  \[15.6\]

where $C' = \frac{C}{(1 - R)^{\lambda - 2}}$, $R = K_{\text{min}}/K_{\text{max}}$, $K_{\text{min}}$, and $K_{\text{max}}$ are the minimum and maximum stress intensity factors applied, respectively. $\lambda$ is the material constant which ranges from 0.3—1 for metals.

In region III the fatigue crack growth rate is very high. Propagation of cracks in this region is rapid and unstable, fracture failure is impending. In real-life engineering design, region II is often adopted as it covers the largest range of intensity. Extrapolation into both regions I and III are also acceptable as it provides conservative fatigue life prediction.

With the crack growth rate, stress state, and crack length determined, the remaining life of a cracked component can be estimated by integrating the sigmoidal curve between the limits of the initial crack size and final crack size. Within the Paris region the number of cycles to failure, $N$, can be expressed as:

$$N = \frac{1}{C'(\Delta \sigma)^m} \int_{a_0}^{a_f} \frac{da}{\left(\sqrt{\pi\alpha f(a/w)}\right)^m}$$  \[15.7\]

in which $a_0$ is the initial crack length.

In this study, a rectangular aluminum beam with a single edge crack loaded in tension was used. For a beam with finite width ($0 < a/w < 0.95$), $\Delta K$ can be modified as (Stephens et al., 2001):

$$\Delta K_f = \Delta \sigma \sqrt{\pi} \left[1.99 - 0.41 \left(\frac{a}{w}\right) + 18.7 \left(\frac{a}{w}\right)^2 - 38.48 \left(\frac{a}{w}\right)^3 + 53.85 \left(\frac{a}{w}\right)^4\right]$$  \[15.8\]

Thus, substituting Eq. [15.8] into Eq. [15.6] and integrating yields the predicted number of cycles for a crack to propagate from $a_0$ to $a_f$ (final crack length):

$$N = \frac{1}{C'(\Delta \sigma)^m} \int_{a_0}^{a_f} \frac{da}{\left(1.99 a^{1/2} - 0.41 \frac{a^{3/2}}{w} + 18.7 \frac{a^2}{w^2} - 38.48 \frac{a^{3/2}}{w^2} + 53.85 \frac{a^2}{w^4}\right)^m}$$  \[15.9\]
15.4 Experimental study

Three identical aluminum (Al 6061-T6) beam specimens with dimensions $300 \times 50 \times 6$ mm, namely S1, S2, and S3, were prepared in this experiment. One piece of PIC 151 PZT patch ($10 \times 10 \times 0.3$ mm) was attached to the surface of each specimen using high-strength epoxy (Fig. 15.3). To protect the PZT patch from wear and tear during the process of handling and testing, a thin layer of silicone rubber was applied.

As shown in Fig. 15.3, a single edge notch (measuring 4.75 mm) was created at the center of the specimen using electric discharge machining. With this stress concentration point, fatigue cracks will initiate at the tip of the edge notch and propagate inward.

A 25-ton dynamic test machine (Fig. 15.4a) was used to apply uniaxial cyclic tensile stress (mode I fatigue load). Nominal stress level was controlled between 40 and 50% of the yield stress of the aluminum beam, which was equivalent to a mean stress of 134.6 MPa and an alternating stress of 15.0 MPa. The frequency of cyclic loading was fixed at 30 Hz at the initial stage, and reduced to 15 Hz when a crack can be clearly identified.

A Wayne Kerr precision impedance analyzer 6420 (Fig. 15.4b) was used to actuate the PZT patch and to measure the admittance signatures required. Propagation of the

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**Figure 15.3** Aluminum beam specimen with a piece of PZT patch and a preinduced single edge notch.
Baseline admittance signatures of the PZT patch bonded on the beam specimen was first recorded at the healthy stage from 0–200 kHz. A cyclic tensile load was then applied at stages with predetermined numbers of cycles. The specimen was removed from the machine after each stage for acquisition of admittance signatures in free-ended condition.

All specimens were loaded to fracture. Specimens S1, S2, and S3 failed at 240,000, 225,000, and 220,000 cycles, respectively. The corresponding critical crack lengths were measured to be 18, 17, and 17 mm, respectively, inclusive of the machined notch.

It is worth mentioning that in this study, all three phases of fatigue crack were closely monitored. According to observation, it is expedient to define the “first crack” in this case as a 1-mm crack, which occurred at approximately 160,000 cycles for all specimens. Thus, the period before 160,000 cycles is considered as “crack initiation” (phase I), whereas the period after 160,000 cycles is the “crack propagation” (phase II). Upon reaching critical crack (phase III) the remaining fatigue life of a specimen is found to be negligible as fracture is fast approaching (often within a few thousand cycles or 1–2% of the entire life span).

According to the recommendation of Sun et al. (1995) the conductance (real component of admittance) signature is preferred as a damage quantifier due to its higher sensitivity toward damage than the imaginary component. Leftward horizontal movement of the structural resonance peak (reduction in resonance frequency) serves as a useful guideline for fatigue damage characterization (Lim and Soh, 2010). In this study the frequency range selected for damage detection was set between 40 and 150 kHz to minimize contamination due to effects of bonding and temperature at higher frequency ranges (Yang et al., 2008a), while maximizing sensitivity (Lim and Soh, 2014a).

The following sections present the monitoring of all three phases of fatigue crack using the EMI technique. A damage prognosis model is also presented.
15.4.1 Crack initiation process (phase I)

Fig. 15.5 presents two diagrams illustrating typical resonance peaks selected from two distinct frequency ranges of specimen S2 from 0 cycles (baseline) to 160,000 cycles (first crack). The four peaks represent the health conditions of the specimen in the crack initiation process. The first crack (1 mm) occurs at 160,000 cycles while a 0.2-mm surface crack occurs at 120,000 cycles.

A series of peaks representing the 100 kHz range is shown in Fig. 15.5(a). It is shown that the leftward movement of the resonance peak is highly sensitive to fatigue-induced cracks, even in its initiation period. A 0.2-mm crack occurring after 120,000 cycles could only be noticed using a crack detector and is invisible to the

![Diagram of Conductance signatures acquired from a PZT patch surface bonded on specimen S2 subjected to cyclic load from 0–160,000 cycles.](image)

**Figure 15.5** Conductance signatures acquired from a PZT patch surface bonded on specimen S2 subjected to cyclic load from 0–160,000 cycles. (a) 106.4–107 kHz and (b) 14.5–15.2 kHz.
naked eye. An incipient crack at 55,000 cycles is undetectable even with the assistance of crack detector, but both could be effectively picked up by the EMI technique in this frequency range.

However, the sensitivity could become much lower when employing the lower frequency range, as depicted in Fig. 15.5(b). In the 10–20 kHz range, a first crack at 160,000 cycles could be picked up but the detection of microcrack is inefficient, as reflected from the overlapping of the first three peaks.

Generically the sensitivity of EMI technique increases with frequency, and higher frequency ranges are more sensitive to microcracks. A sensitivity study was conducted by Lim and Soh (2014a). They found that the sensitivity of the EMI technique in the 200 kHz range is approximately seven to eight times higher than that in the 20 kHz range. However, they recommended that the sensing frequency should not be increased indefinitely to achieve higher sensitivity because various external factors such as the presence of densely spaced local resonance peaks, the effect of bonding and temperature, etc. would reduce the practicality of the method. Thus, frequency range should be limited to 200 kHz for real-life application.

15.4.2 Crack propagation process (phase II)
15.4.2.1 Fatigue crack characterization

Fig. 15.6 plots a selected structural resonance peak of specimen S1, recorded at different health conditions, against frequency. The corresponding crack length and shift in frequency at different loading cycles for all three specimens are shown in Fig. 15.7. The peak of baseline signature occurs at 41.4 kHz. Gradual and progressive horizontal leftward movements of the resonance peak at different loading stages could be observed.

Figure 15.6 Conductance signatures versus frequency (39.8–41.5 kHz) acquired from PZT patch surface bonded on specimen S1 after different number of loading cycles.
The shift in resonance peak could also reflect the severity of cracking encountered by the specimen. As described earlier, the first three peaks (baseline, 120,000 cycles, and 160,000 cycles), indicate the crack initiation process, which consisted of up to 70% of its entire life span. Above 160,000 cycles, the rate of movement of peaks increases significantly denoting a higher rate of crack propagation.

Upon loading from 235,000 to 240,000 cycles, which indicated the occurrence of critical crack, a sudden reduction in 0.5 kHz of its resonance frequency is observed, implying that very serious damage has been inflicted throughout these 5000 cycles of loading. After the critical crack was reached the specimen failed shortly, in less than a thousand cycles.

In Fig. 15.7 the crack length and the reduction in resonance frequency are plotted against the life cycles (%), exhibiting similar trend. The slopes of the curves from 0–70% of life cycles are mild, indicating that the crack increment is at its initiation stage. Beyond that the slope increases drastically up to failure. One could therefore use the frequency reduction as an indication of crack length for structural health monitoring.

15.4.2.2 Finite element simulation

A three-dimensional model of the aluminum beam of dimensions 300 × 50 × 6 mm was simulated using eight-noded, Solid 45 brick element in ANSYS 12.1 workspace (ANSYS, 2010). The PZT patch (10 × 10 × 0.3 mm) was modeled using eight-noded, Solid 5 coupled field element as shown in Fig. 15.8. Details of simulation such as material properties and convergence test can be found in Lim and Soh (2011) and Yang et al. (2008b).

The propagating crack under fatigue loading was also simulated. For the sake of simplicity the crack was assumed to be through-the-thickness and propagate perpendicularly to the direction of loading. Nodal displacements along the crack were...
Figure 15.8 Aluminum beam (300 × 50 × 6 mm) surface bonded with PZT patch (10 × 10 × 0.3 mm) modeled in ANSYS 12.1 workspace (ANSYS, 2010).

Figure 15.9 Reduction in resonance frequency against crack length (beyond the preinduced edge crack) acquired from FE simulation and test specimens S1, S2, and S3.
uncoupled so that the interfacial nodes could move freely relative to each other. In this simulation the cyclic loading, stress intensity factor, and crack propagation were not included to simplify the problem. Results of the FE simulation agreed reasonably well in terms of resonance peaks with the experimental counterparts at various health conditions \(\text{(Lim and Soh, 2011)}\).

Reductions in resonance frequency at different crack lengths (beyond preinduced edge crack) acquired from both FE simulation and experimental test are plotted in Fig. 15.9. The outcome from the FE simulation agreed closely with the experimental results, exhibiting an approximate linear relationship.

15.4.2.3 Electromechanical impedance technique-based damage model for fatigue life prediction

As shown earlier, the conductance signatures acquired from the EMI technique through the finite element method (FEM) can be used to quantify the crack length of the aluminum beam specimens. On the other hand, if the crack length in the specimens can be evaluated at any instance during the monitoring process, the remaining life could be predicted using Eq. [15.9].

The fatigue-related parameters for aluminum (T6061-T6) beam specimen required for solving Eq. [15.9] are tabulated in Table 15.1. Values of \(m\) and \(c\) in the Paris equation are proposed by Kapp and Duquette (1986).

With all the relevant parameters determined the number of loading cycles, \(N\), at various crack length, \(a\), can be calculated. The relationship between reduction in

### Table 15.1 Physical and fatigue-related properties of aluminum (Al6061-T6) beam specimen

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<th>Parameters</th>
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<td>Yield stress</td>
<td>(\sigma_y)</td>
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<td>MPa</td>
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<td>Critical fracture toughness (plane strain)</td>
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<td>MPa(m)(^{1/2})</td>
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<tr>
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<td>Gradient, Paris equation (log scale)</td>
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<td></td>
</tr>
<tr>
<td>Intercept, Paris equation (log scale)</td>
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<td></td>
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<td>Maximum stress</td>
<td>(\sigma_{max})</td>
<td>149.5</td>
<td>MPa</td>
</tr>
<tr>
<td>Minimum stress</td>
<td>(\sigma_{min})</td>
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<td>MPa</td>
</tr>
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<td>Range of stress</td>
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<td>0.805</td>
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</tr>
<tr>
<td>Initial crack length</td>
<td>(a_0)</td>
<td>4.75</td>
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resonance frequency versus crack length (as simulated by FEM and shown in Fig. 15.9) is incorporated in the relationship of crack length versus loading cycles (derived from Eq. [15.9]) to form a semianalytical solution. The predicted and actual number of loading cycles measured experimentally are compared and plotted in Fig. 15.10. A relatively close agreement between the semianalytical damage model’s prediction and experimental results could be observed.

The proof-of-concept semianalytical damage model presented above could provide useful information for monitoring the fatigue crack length and estimating its remaining life. Although the model is developed based on the Paris equation, it can easily be extended to take into account the other two phases. This model could serve as an alternative to experimentation to acquire baseline data for damage detection and damage prognosis.

15.4.3 Critical crack identification (phase III)

The third phase of the fatigue crack is the occurrence of critical crack. At this stage, failure is impending and the structural component concerned could only sustain limited number of cycles. An EMI-based, proof-of-concept qualitative visual examination method is proposed (Lim and Soh, 2014a) for identifying the critical crack. This method requires the visual examination over a range of frequency, such as that presented in Fig. 15.11.

From Fig. 15.11a the outlook of the frequency spectrum remains generally the same compared with the healthy stage when the number of cycles is less than 190,000, with a 5-mm crack. Movement of the peaks is generally small. Almost all peaks shifted slightly to the left, only a few minor peaks disappeared, and a few new minor peaks emerged.
However, after 225,000 cycles (where critical crack occurred) the appearance of the frequency spectrum is clearly quite different from the baseline (Fig. 15.11b). At this stage, identification of original peaks is extremely difficult, if not impossible. Some major peaks in the healthy stage disappeared and some new major peaks emerged, altering the outlook of the entire spectrum.

According to Lim and Soh (2014a) the abrupt changes in outlook of the frequency spectrum at critical crack length is described as a fundamental change in the vibrational behavior of the host structure. This phenomenon can be physically explained by the fact that the resonance frequencies in the admittance signature spectrum represent the modes of vibration of the host structure. The presence of a relatively small crack
would slightly reduce the stiffness of the structure but may not be significantly enough to alter its vibrational behavior. However, at critical crack lengths, the modes of vibration of the beam have been significantly altered, which can be reflected by the emergence of new resonance peaks or disappearance of the existing resonance peaks. The new resonance peaks resulted from nonlinear ultrasonic phenomenon due to the friction between crack surfaces.

Thus, an inspection of the frequency spectrum can provide a quick way of identifying the status of fatigue cracks. This qualitative method can be summarized in table form for ease of application (Lim and Soh, 2014a).

15.5 Conclusions

This chapter presents a series of laboratory-scale experimental tests to investigate the feasibility of fatigue crack detection, characterization, and prognosis employing the EMI technique.

A proof-of-concept semianalytical fatigue damage model is proposed for estimating the remaining fatigue life of 1-D beam structures. The model is developed based on the crack propagation phase of a fatigue crack but could be conservatively extended to the other two phases. The damage model is experimentally verified using a laboratory-sized aluminum beam.

The sensitivity and effectiveness of the EMI technique in detecting fatigue-induced cracking, even in its incipient stage, is demonstrated. Peaks from a higher frequency range (100–200 kHz) are recommended for characterizing microcracks due to their higher sensitivity. On the other hand, a handy qualitative-based critical crack identification method by visually inspecting the admittance frequency spectrum is suggested.

At this stage the technique is proven workable for laboratory-sized structures but extension to real-life structures or structural components requires further study.

References


Yang, Y., Lim, Y.Y., Soh, C.K., 2008a. Practical issues related to the application of the electromechanical impedance technique in the structural health monitoring of civil structures: I. Experiment. Smart Mat. Struct. 17, 035008.

Abstract
Engineering structures are often subjected to fatigue loads. Monitoring the process of fatigue crack propagation as well as estimating the remaining useful life (RUL) of a structure is thus essential to prevent catastrophic failure while minimizing earlier-than-required replacement.

Autonomous, real-time, remote monitoring becomes possible with the use of smart piezoelectric transducers, alleviating the shortcomings of conventional nondestructive inspection techniques. For instance the electromechanical impedance (EMI) technique is known for its ability in damage detection and characterization.

This chapter presents a series of investigative studies to evaluate the feasibility of fatigue crack monitoring and estimation of RUL using the EMI technique. Experimental tests were conducted to study the ability of EMI technique in monitoring fatigue crack in one-dimensional laboratory-sized aluminum beams subjected to mode I fatigue loading. The experimental results demonstrated that the EMI technique is very sensitive to monitoring fatigue crack propagation in all three stages. A proof-of-concept semianalytical damage model for fatigue life estimation has been developed by incorporating the linear elastic fracture mechanics theory into the finite element model. The prediction of the model matches closely with the experiment, suggesting the possibility of replacing costly experiment in future.

Keywords:
Damage prognosis, Electromechanical impedance (EMI) technique, Fatigue, Finite element method (FEM), Linear elastic fracture mechanics (LEFM), Piezoelectric material (PZT), Structural health monitoring.