Damage assessment using fracture mechanics and NDT approaches

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Abstract

Assessment of damage in materials and structures can be carried out by applying elements of both fracture mechanics and nondestructive testing. This is particularly important for determining the remaining life of structures subjected to cyclic or fatigue loading. In fatigue, the relationship defining the rate of crack growth $dA / dN$ is given by the Paris law as $dA / dN = a(\Delta K)^b$ where A is the crack length, N is the number of cycles, a is a constant, K is the stress intensity factor and b is an exponent which has a value of about 3 for pearlitic steels and 4 for aluminum alloys.

In the present research, we establish a similar relationship between elements of signals obtained from monitoring using nondestructive testing techniques, such as ultrasonics and acoustic emission. Signal characteristics include features of pattern recognition which are then related to $\Delta K$ by equations similar to the Paris law given earlier. The application of these relationships using custom software allows obtaining in real time the extent of crack growth and hence the accumulated damage incurred during the normal operation of a critical structure or component to be attained in real time. Examples of applications of these algorithms for specific structures are presented.

1 Introduction

The use of nondestructive testing methods (NDT), particularly acoustic emission and ultrasonics to provide a quantitative assessment of damage in structures and components has remained an important objective. However, more recently, acoustic emission has been mostly used for flaw location during hydrostatic and proof testing. Evolution of computer systems with software targeted for specific
applications has helped NDT gain acceptance as a technique for nondestructive evaluation.

Some of the early research was focused on establishing phenomenological relations between observable parameters of acoustic signals and damage parameters. Thus Dunegan et al. [1,2] and others [3-5] developed theoretically a relationship between acoustic emission count rate and the stress intensity factor. These relationships were extended to materials exhibiting elastic plastic behavior at the crack tip [6] and Blanchette et al. [7-8] correlated acoustic emission with the J-integral for steels and 7075-T651 aluminum alloys.

In fatigue, the early work dealt with relating acoustic signal parameters to crack growth rate and to the stress intensity factor using equations resembling Paris equation [9]

\[ \frac{da}{dN} = A(\Delta K)^m \]  \hspace{1cm} (1)

where \( \Delta K \) is the applied stress intensity factor and is given as [10]

\[ \Delta K = \Delta \sigma (\pi a_{av})^{1/2} \]  \hspace{1cm} (2)

where \( \Delta \sigma \) is the magnitude of the alternating stress, \( \sigma_{max} - \sigma_{min} \), and \( a_{av} \) is the average crack length. \( N \) is the number of fatigue cycles and \( A \) and \( m \) are constants for a given material (e.g. steels, aluminums … etc). The exponent \( m \) is 3 for steels and 4 for aluminums [11].

Some particular approaches stemming from techniques of pattern recognition of acoustic signals have also been studied. Two aspects are underlined:

Firstly, the dynamic character of the patterns. It should be stressed here that the recordings of the acoustic signals are to be treated as a sequence of patterns that in sequel would lead to the analysis of a set of features as well as their changes in time intervals. Thus the problem refers to dynamic pattern recognition and requires such methods which are able to cope with dynamics of the process itself. It is worthwhile to underline that most of the methods of pattern recognition are applicable to the recognition problem of static patterns, while now we are faced with dynamical patterns created in time. Secondly, the problem formulated here refers to continuous labeling of classes. In fact, contrary to classic recognition problems where discrete classes are distinguished, we deal here with any value of the physical parameter, e.g. stress \( \sigma \), denoting a particular class. Thus the number of classes is very large.

In the current research, a quantitative approach relating acoustic signal characteristics to fatigue crack extension is developed. This approach is embodied in a second generation acoustic emission equipment dedicated specifically to damage assessment, which was developed, patented and subsequently commercialized by the author of this paper. This technology allows for a stand-alone automated, continuous monitoring of large structures including bridges, aircraft, laboratory specimens, turbines and rotors as well as other metallic structures such as transmission towers [12].
2 Theoretical considerations

A number of studies, including Hamel et al [13-15], showed that there is a relationship similar to Paris equation (Equation (1)) between acoustic signal parameters, most notably but not restricted to [16] the count rate and $\Delta K$.

This equation is as follows [17,18]

$$N' = B(\Delta K)^n$$

(3)

Where $B$ and $n$ are constants. It was further established that $n$ and $m$ are related such that $n$ can be equal to $m$ or to mostly $m + 2$, depending on the loading ratio $R$ ($R = \sigma_{\text{min}} / \sigma_{\text{max}}$). As $R$ increases, $n$ tends to be equal to $m$. Thus, for constrained structures such as bridges, turbines … etc. with a large mean stress (and a high value of $R$), $n = m$.

Using Equations 2 and 3, it is possible to relate $N'$ to $\Delta K$ and $da/dN$. A graphical procedure developed by Scheffey [19] is shown in Fig. 1.

![Graphical procedure for using A.E. to determine crack growth.](image)

Figure 1: Graphical procedure for using A.E. to determine crack growth.

To obtain the “AE count rate” line, the relevant AE parameters are obtained versus time, as defined by the equation

$$P_N [\text{AE parameters}] = B'(\Delta K)^n$$

Which is represented in Fig. 2. The parameter $P_N$ increases with the time interval indicating fatigue crack growth and may fall within a band of limits depending upon the random nature of AE and the application of variable loading. Once this line is established, the procedure in Fig. 1 is applied and $da/dN$ is obtained. This is further integrated to determine the life of the structure under consideration.
This technique was found to be very sensitive to detection of early onset of crack growth, when $\Delta K$ is very near the $\Delta J_{\text{threshold}}$. Thus, in a specific study [20], A.E. was able to study crack initiation at inclusions in rail steels subjected to fatigue. A typical result of the initiation of A.E., once a crack starts growing, is shown in Fig. 3. This was substantiated by observations, using optical and scanning electron microscopy, of cracks as small as 0.01 mm starting at sulphide inclusions in the stressed tensile side of the specimens.

Furthermore, such an approach is also valid for the case of low cycle fatigue [21, 22] and has been used to evaluate damage assessment in strain controlled fatigue testing.
3 System for fatigue monitoring

A new technology, based on the theory presented earlier was patented by M.N. Bassim [23]. The configuration of the system is shown in Fig. 4. It consists of surveillance units (SU) which, in effect, are smart sensors equipped with a microprocessor and which are software operated. These surveillance units are positioned on the structure and perform the analysis described earlier.

The surveillance units are linked to a Central Control Unit (CU) which is a dedicated computer capable of monitoring the performance of each of the surveillance units, programming each individual surveillance unit, provide trend analysis and diagnostic checking of the performance of the surveillance units. It also provides communication and networking of all the surveillance units. The system handles the data on a stand-alone and continuous basis and provides continuous damage assessment of the structures being monitored.

Figure 4: Tiered system for continuous monitoring with A.E.

4 Examples of applications

The approach described earlier was used to continuously monitor and assess a number of industrial structures. These include bridges and bridge members, aircraft fuselage and tail sections, electrical transmission towers, transformers and reactors used in the electrical industry, pipelines for corrosion and leaks and in turbines and rotor equipment.

The transmission tower application was reported earlier [12] while monitoring of reactors was presented. A typical example of a reactor undergoing fatigue damage is shown in Fig. 5. The extent of damage in the reactor was confirmed independently by the owners of the equipment.
Figure 5: A.E. from monitoring electrical transformers.

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References


