2006-366: NATURAL FREQUENCY METHOD (IMPACT ACOUSTIC METHOD) FOR CRACK DEFECT EVALUATION IN STEEL PARTS

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“Natural Frequency Method (Impact Acoustic Method) for crack defect evaluation in steel parts”

Abstract: The effect of natural frequency shift due to crack propagation through a rectangular ¼ in thick specimen was investigated. The experimental measurements of the natural frequency distribution were carried out using impact acoustic method and a simple to use software able to extract the frequency domain from the recorded acoustic response. A FEA dynamic analysis was conducted in order to gain more insight of the phenomenon. By employing modal analysis in ANSYS the analytical and experimental results showed very good agreement, proving the potential for further investigation of the use of the method on more complex geometry.

Introduction.

In recent years, a large number of studies have been carried out on conventional (visual examination, dye penetrant, magnetic particle induction, ultrasonic, radiographic, et cetera,) and modern damage detection techniques for inspecting structures exposed to fluctuating loads, such as aircraft structures, automotive parts, structures used in ocean environment, buildings, bridges, pipelines and other industrial equipment. Cracks can be introduced in the structure during the manufacturing process or due to the limited fatigue strength of the material in the course of exploitation. During the work cycle the cracks open and close, and as the load reversals continue the cracks may develop to such extend that there is a significant threat for the integrity of the structure. Therefore, structures like these must be monitored for the existence and the development of cracks, by using non-destructive crack detection techniques, and also by implementing fatigue analysis to acquire the remaining life expectancy before a costly repair is needed to be made.

The current conventional damage detection methods are either visual or localized experimental procedures that require that the vicinity of the damage is known and that the site of inspection is easily accessible. Due to these limitations, it is believed that monitoring the global vibration characteristics of the structure is a promising alternative for damage detection and quantification.

The basic idea of vibration-based damage detection is that that damage will modify the stiffness and may also affect its mass distribution and its damping properties, which will result in change of the dynamic response of the system. There are different modal parameters that can be utilized for detecting and evaluating the damage (Farrar et al. 2000). The most common of them are resonant frequencies and mode-shape vectors (Obolabi et al. 2003, Narayana & Jebaraj 1999, Chondros et al. 2001). Parameters such as change in mode-shape curvature, dynamically measured flexibility, change in compliance (Choi et al. 2005), and the change of energy of dynamic response (Yan et al. 2004) have also been used as damage detection indexes. In recent years, the phenomenon of the non-linearity in the dynamic response of damaged systems has been heavily studied, giving promising results for the development and application of nonlinear damage evaluation techniques (Johnson 2005, Kin et al. 2005).

The initiation and propagation of micro- and macro-cracks as a result of fatigue loading represents a major part of the total fatigue life, and the ability to monitor the evolution of these stages of damage is essential for the prediction of the residual life in fatigue ageing structures. Also, some of them may contain crack-like defects that are either introduced by the manufacturing process or form early during service. Virtually the whole life of such structures may be represented by fatigue crack growth.

There are many formulations that are used to describe the crack growth rate vs. stress intensity range curve, but the first and most widely used is the Paris formulation, with its modifications. He demonstrated the possibility of using the stress intensity concept for characterizing the fatigue crack growth.

The purpose of this study was:

- To investigate the effect of the change of natural frequencies due to crack propagation through a rectangular steel plate.
- Make comparison of the experimental and Finite Element Analysis results for the vibration behavior of cracked plate.
- Verify the possibility to predict the residual fatigue life of the component by using the crack propagation history.

1. Specimens

Geometry of the steel specimens tested is given in Figures 1 and 2.

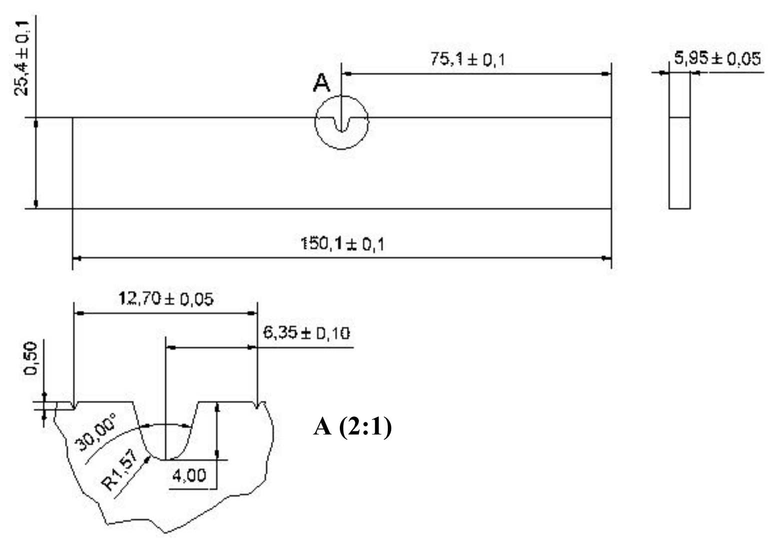

Figure 1 Specimen Geometry – Centered Notch

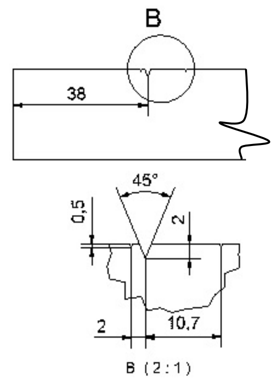

Figure 2. Specimen Geometry – Offset Notch

In order to initiate a crack at the desired location during the cyclic loading a notch with dimensions given in Figure 1 (view A) for the center-crack specimen, and Figure 2 (view B) for the offset-crack specimen was machined.

Also, as seen in the detailed views of the figures above, in the vicinity of the major crack initiation notch two smaller notches were produced to enable the reliable coupling of an extensometer. These notches were not symmetrically situated around the offset notch due to some loading frame fixture limitations.

2. Acoustical experimental procedures

The conceptual set up for the Impulse Resonant Acoustic Spectroscopy (IRAS) experiments (Polytec theory, Kin et al. 2004, Zahariev & Kin 2005) is depicted in Figure 3 and a photo of the actual setup is given in Figure 4.

Facilities used for IRAS experiments included personal computer, laser vibrometer - Polytec, PDV 100, Polytec vibrometer software-VibSoft4.2, striker, and foam support.

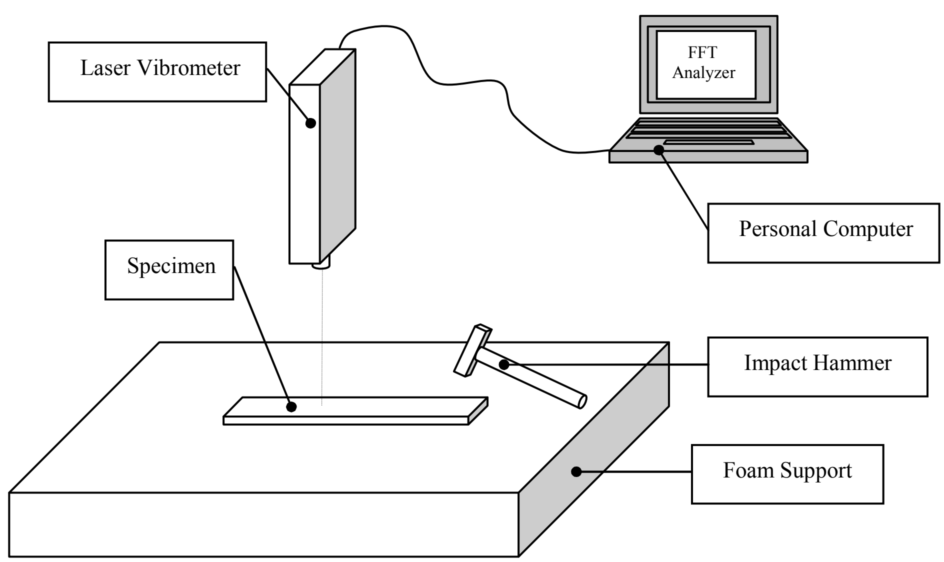

Figure 3. IRAS Setup

Figure 4. Actual IRAS Setup

The specimen is laid on the foam support and excited by a manual hammer blow. The vibration response of the plate is picked at a single point with a laser vibrometer, making sure that it is not on one of the nodes of the vibration modes of interest, which would allow a certain mode to remain hidden. This is achieved by making two or three dry runs to ensure that all the mode frequencies needed appear in the frequency response graph. In order to achieve reliable results it is recommended that the operation instructions for installation, preheating, focusing, et cetera, of the vibrometer be followed (Polytec user). The signal from the laser vibrometer is transferred to the computer where through fast Fourier transformation (FFT) the frequency spectrum of vibration of the part is obtained. In order to diminish the effect of frequency shift from the non-linear response of the cracked specimen, provoked by the non-controlled excitation force, the spectrum is averaged for six runs of the experiment.

3. Fatigue crack growth

A notched specimen was tested under cycling loading at MTS fatigue machine
(Max. load = 22 kN; Min load = 0.5 kN; Frequency = 20 Hz). The image from video camera positioned and focused around the notch area was used to monitor crack growth and permitted measurement of very small crack increments. For verification purposes an extensometer, MTS 632.13, with ± 0.15 strain limits, was attached to the specimen and monitored the change of the local stiffness of the specimen, as an early indicator for crack initiation.

The loading was being stopped at certain intervals, and the crack length was measured on both sides of the specimen taking the average value as the actual crack length. Also, IRAS tests were performed to determine resonant frequency for each stage of damage. The results were tabulated, and plots of the crack length vs. the number of cycles were created to be used in the remaining life analysis for building the crack growth rate vs. the stress intensity range graph.

4. Vibration analysis and IRAS test results

The results from the vibration analysis and the impulse resonant spectroscopy test are given here. They are presented in a comparative manner, so that direct observation of the correlation between them can be made. Figures 5-7 show the flexural modal shapes of vibration and their relative displacement fields for the center-cracked specimen, acquired by the FEA free vibration analysis (ANSYS structural 8.1).

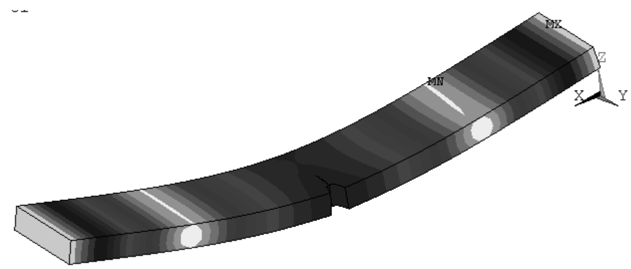

Figure 5. Flexural Vibration Mode Shape 1 – Centered Crack

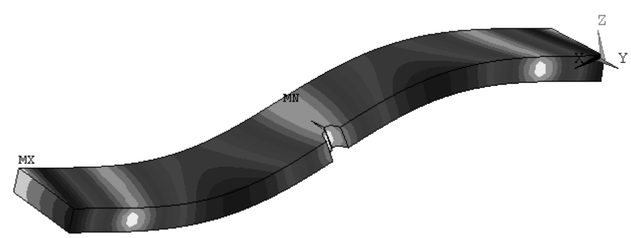

Figure 6. Flexural Vibration Mode Shape 2 – Centered Crack

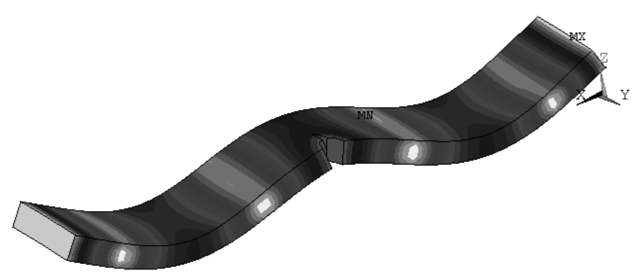

Figure 7. Flexural Vibration Mode Shape 3 – Centered Crack

Frequency shift versus crack length depicted from FEA and IRAS tests for all three modes is shown in Figure 8.

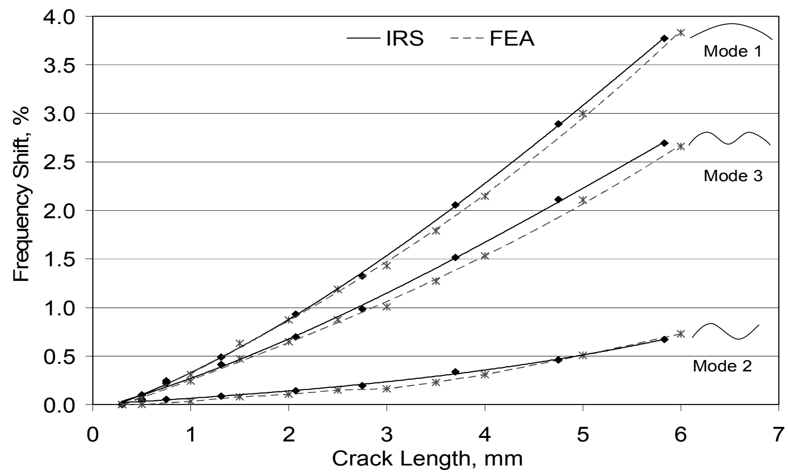

Figure 8. Frequency shift versus crack length- centered crack

From the test results, we may conclude that Mode 2 is the least sensitive mode for the center-cracked plate. The reason for that is that the crack location in the specimen coincides with one of the nodes of Mode 2, where the displacement is close to zero. At the same time experiments showed that for the offset crack plate Mode 1 appears to be the least sensitive mode, Because of the change of the sensitivity of each mode with the change of the location of the crack the method might be extended to crack localization technique. Measuring the natural frequencies of the first three flexural modes will be sufficient to determine the crack length and location for a plate with a single crack.

5. Remaining life prediction results

The life prediction is based on the Paris formulation (Eq. 1). The full crack growth rate curve is plotted in Figure 9 and the results of the remaining life prediction are given in Table 1. The two vertical dashed lines approximately separate the crack growth curve into Region I, Region II, and Region III. The upper bound of Region II is determined from the requirement for predominantly elastic behavior of the specimen (Eq. 2). Also, this is confirmed by visually inspecting the crack growth curve and finding the region where the crack growth rate becomes unstable.

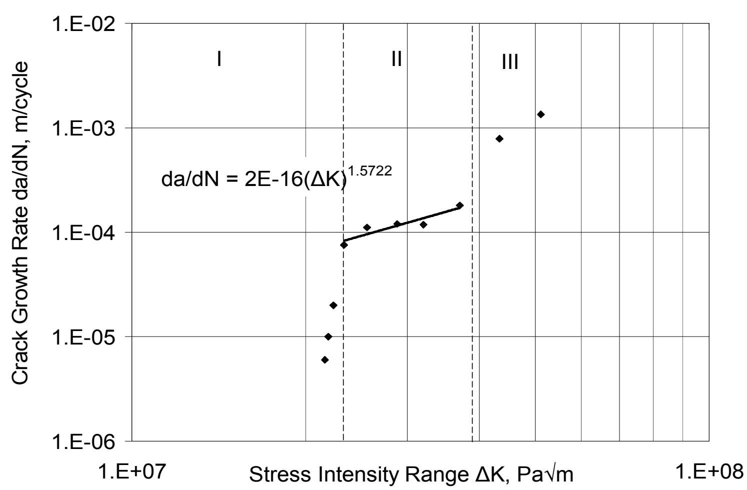

Figure 9. Crack Growth Rate vs. Stress Intensity Range – Centered Crack

The lower bound is determined only by visually identifying the region where a significant drop in the crack growth rate occurs. Having determined Region II a power low fitting of the data in it gives the result for the coefficients, *C* and *m*, of the Paris formulation:

$$\frac{da}{dN} = C(\Delta K)^{m} \qquad \text{Eq. 1}$$

$$C = 2 \times 10^{-16}$$

$$m = 1.5722$$

$$a_c \le W - \frac{4}{\pi}\left(\frac{K_{max}}{\sigma_y}\right)^2 \qquad \text{Eq. 2}$$

a_c – Critical crack length
W – Width of specimen
K_{max} – Maximum stress intensity factor at a_c

A critical crack length is set according to the requirement set by Eq. 2. In our case this is the end of Region II. Here the last experimental data point in Region II, corresponding to $a_c = 7.70\ \text{mm}$, is taken as a critical crack length, because the actual life at this point is known.

The results from the remaining life prediction are given in tables 1 and 2.

Table 1. Life Prediction for the Center Cracked Specimen

Current Crack Length, mm	Critical crack length, mm	*C*	*m*	Predicted Life, cycles	Real Life, cycles	Difference %
5.31	7.70	1×10^{-42}	5.1397	8770	17,500	- 50
6.07	7.70	2×10^{-28}	3.1996	7487	11,000	- 32
6.75	7.70	2×10^{-17}	1.7132	5794	5500	+ 5

Table 2. Life Prediction for the Offset Crack Specimen

Current Crack Length, mm	Critical crack length, mm	*C*	*m*	Predicted Life, cycles	Real Life, cycles	Difference %
3.00	7.22	2.00E-21	2.2296	77,982	62,800	24
4.07	7.22	2.00E-18	1.8289	42,147	36,000	17
6.16	7.22	8.00E-20	2.0184	9626	9400	2

6. Conclusion

6.1. Vibration-based Assessment of Damage

The results from the IRS test and the mode-frequency analysis are good evidence for the applicability of the method for indirectly measuring the crack length in the plate. Also, it was confirmed that the change of the dynamic behavior of a cracked plate can be predicted by conducting vibration modal analysis. The modal shape results from the Finite Element Analysis can give us visual perspective of the distribution of the "sensitive" zones in the specimen for each mode. An attempt to acquire these results experimentally would be much more time and equipment costly. This knowledge can help us determine, for a known location of the damage or the crack, the most sensitive vibration mode, for which the frequency should be monitored.

6.2 Prediction of Remaining Life

As seen from the remaining life prediction results the Paris formulation gives very good results. It has to be noted that the accuracy of the prediction will be improved if more history data points are available. This is confirmed by the results of the remaining life analysis shown in Tables 1 and 2. The closer the crack length gets to the critical crack length, the more data points take part in the calculation of the *C* and *m* constants, thus the more accurate the prediction.

The main advantage of coupling the fatigue analysis with the vibration-based measurement of the crack length is that the propagation of the crack can be monitored almost continuously, which will provide more information for the remaining life estimation. Figure 10 illustrates the possibility of direct use of the relative frequency shift to predict the residual life. As it can be seen, the behavior of both the crack propagation and the frequency shift curves are similar.

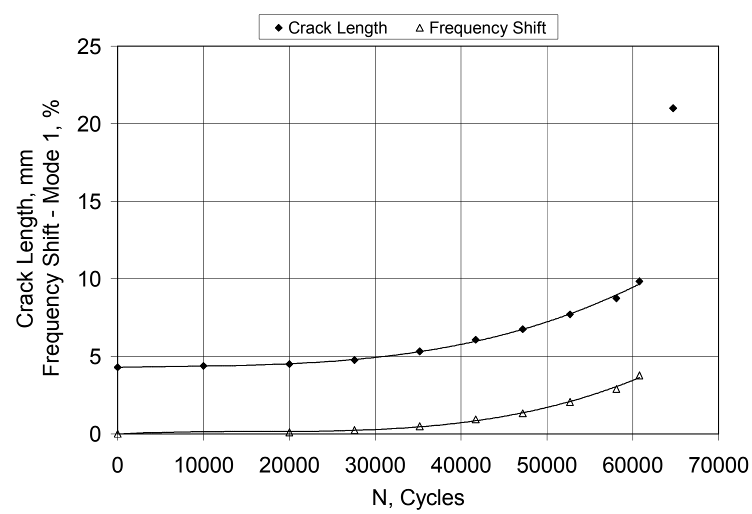

Figure 10. Crack Length and Frequency Shift vs. Life Cycles – Centered Crack

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