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Abstract

Nonlinear vibro-acoustic is a highly reliable and sensitive method for damage detection. It is a method based on propagation of high frequency acoustic waves in solid structures with low-frequency excitation. Interaction of the acoustic wave with material or geometry properties changes caused wave distortion effects. The causes called nonlinear acoustic effects are amplified with the low frequency excitation. Nonlinear acoustic-acoustic modulations are investigated for fatigue crack detection. The focus is on vibro-acoustic wave modulations used for crack detection in aluminium. Experimental works are performed to investigate the effect of crack characteristics, i.e. crack lengths and crack modes, on vibro-acoustic effects intensity. Nonlinear acoustic tests are performed for the uncracked and cracked aluminium plates. The analyses results show that there are many nonlinear phenomena (i.e. hysteresis and classical 1st order perturbation) involved in the vibro-acoustic wave modulations. The nonlinear modulations produced by the low-frequency modal excitation and high-frequency ultrasonic excitation can be used effectively for fatigue crack detection.

Keywords — nonlinear vibro-acoustic, wave modulation, modal excitation, fatigue crack detection.

I. EXPERIMENTAL METHOD

The vibro-acoustic test was performed on the uncracked and cracked plate to evaluate the effects of nonlinear acoustic modulation caused by nonlinearities inside the plate's particular crack. Specifically the tests were performed to investigate the relation of crack edge behaviour to nonlinear acoustic modulation.

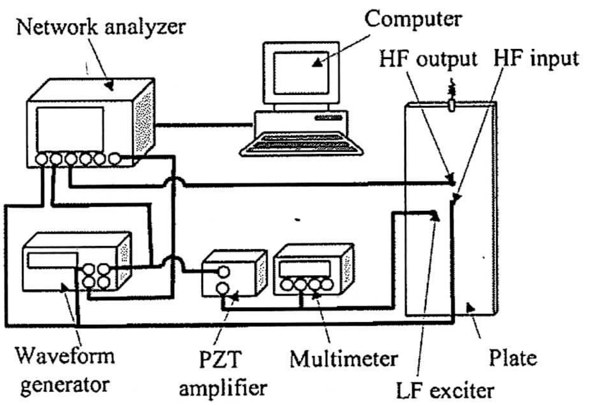


Figure 1: Experimental setup and arrangement for the conventional vibro-acoustic test

The plate was freely suspended using a spring. A PI Ceramics PL-055.31 stack actuator (5 mm × 5 mm × 2 mm) and a PI Ceramics PIC155 transducer (diameter 10 mm; thickness 1 mm) were surface-bonded in the positions as illustrated in Figure 1. Both transducers were bonded using X60 fast-curing, two-component adhesive glue and wired using additionally bonded connectors. The stack actuator was used to excite the plate and the transducer was used to obtain the plate vibration responses. The plate was freely suspended using a spring.

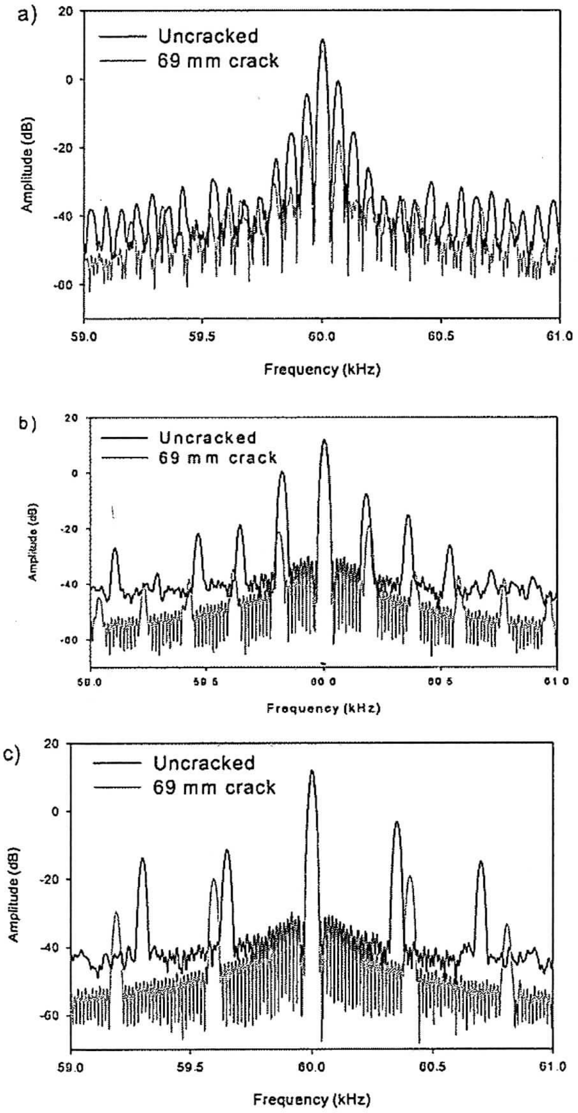
A 60 kHz ultrasonic wave was introduced to the plate using the "HF input" piezoceramic transducer. At the same time the plate was harmonically vibrated using the "LF exciter" piezoceramic stack actuator. The 1st, 3rd and 6th vibration mode frequencies were used for low-frequency vibration excitation. The amplitude of high- and low-frequency excitation was equal to 10 and 100 Vpp, respectively. The "HF output" piezoceramic transducer was used to obtain the responses. The excitation signals were generated using a two-channel TTi-TGA 1242, 40 MHz arbitrary waveform generator. The PI E-505 LVPZT piezo-amplifier was used to amplify the signal introduced to the stack actuator. Vibration responses were acquired using a four-channel LeCroy Waverunner LT264, 350 MHz, 1 GS/s digital oscilloscope. A schematic diagram illustrating the experimental set-up used in nonlinear acoustics tests is given in Figure 1.

The recorded data was converted into power spectral density (PSD) using Welch's method. From the PSD, analysis regarding the sidebands at acoustic frequency, harmonics of low-frequency responses, and the plate responses amplitude dissipation were performed.

II. RESULTS

Based on the above experimental procedure, analyses of power spectral density, particularly the nonlinear modulation intensity effect, were performed. In the vibro-acoustic test, amplitude modulation effect due to weak ultrasonic wave distortion is notoriously used for evaluating the presence of a crack in structures. The R modulation coefficient is used to quantity the modulation intensity. The tests were performed on uncracked and 69 mm cracked plate. The 1st, 3rd and 6th vibration mode frequencies along 60 kHz ultrasonic frequency were used to excite the plates. As expected, sidebands are observed around the fundamental frequency peak for all tests as shown in **Error! Reference source not found.**2.

Error! Reference source not found.2 shows power spectral density for the uncracked and 69 mm cracked plate at 60 kHz fundamental frequency peak. **Error! Reference source not found.**2a, **Error! Reference source not found.**2b and **Error! Reference source not found.**2c show results for the 1st, 3rd and 6th vibration modes excitation respectively. Those figures clearly show that both the uncracked and cracked plates produce significant modulation effects when excited with the analysed vibration modes. It can be said that the effect produced by the uncracked plate is due to the inherent structure nonlinearities such as micro voids or non-uniform density. It also may be affected by the way of attaching the actuator and transducer to the structures, which are known as boundary effects [1, 2].



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Comparing power spectral density between the uncracked and cracked plate, the average response of the cracked plate was slightly less than the uncracked plate. The fundamental frequency and sidebands amplitude for the cracked plate is mostly lower than for the uncracked plate. This means that the presence of the crack had caused energy dissipation against the transmitting waves. From this observation, it is very difficult to distinguish the R value of the uncracked and cracked plates. Therefore the difference of R, ΔR, value between those plate was taken to evaluate the modulation intensity caused by the crack.

Error! Reference source not found.2 also clearly shows that the interval of sidebands depends on low-frequency excitation. It is an effect of the interaction between the weak high-frequency wave and the strong low-frequency excitation. These are familiar findings in most experimental results from previous researches [3, 4, 5].

ΔR values for 15, 30, 38, 48, 58 and 69 mm cracked plates were calculated and plotted against the crack length as shown in Figure3. The plot shows results for the plates excited with the 1st, 3rd and 6th vibration modes. For comparison, the figure also shows the average R value for the corresponding crack length estimated from the FE modelling method. However, the average of R values from FE analysis is not related to any vibration mode excitation because they were estimated values based on the average changes of transfer function parameters, i.e. natural frequency and mode shape, against the crack model. At all vibration modes excitation, the ΔR value increased from crack length 0 to 40 mm. The ΔR values were slightly reduced and attenuated for crack lengths above 40 mm. Compared to the result from the FE modelling method, the average R value suddenly increased from 0 to 40 mm crack length and then increased gradually above the 40 mm length. This finding confirms the experimental results that show the effect of stiffness reduction is proportionate to the crack length. This is because the FE modelling results are solely based on the changes in material stiffness that produced deviation of the extracted natural frequencies between the cracked and uncracked plate models.

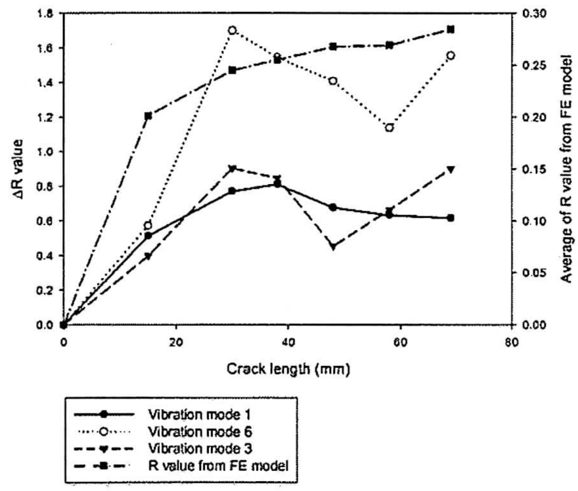

Figure 3: ΔR value from experimental results and average of R value from FE modelling results versus crack length of aluminium plate.

Figure also shows that the 6th vibration mode produces the highest ΔR value at all crack lengths. Results produced by the 1st and 3rd vibration modes are mostly similar.

III. CONCLUSIONS

The nonlinear acoustic modulation is the most prominent effect that could directly relate to the crack behaviours from experimental analysis. From the experimental analysis results, the 6th vibration mode that corresponds to the crack mode-II behaviour shows good correlation with the modulation intensity for both small and large cracked plates.

Although the modal/vibration mode excitation shows significant effects of the nonlinear acoustic modulation, the corresponding strain level that produced the modulation effect is not sufficient enough to trigger crack opening/closing. The maximum strain level produced by the stack actuator is around $10^{-6} - 10^{-7}$. Estimation of CED based from the experimental results is about 10^{-7} mm.

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