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Nonlinear Ultrasonic Characteristics due to an Evolution of Micro-crack During a Fatigue Process

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1. Introduction

Early detection of cracking is an important issue for the extension of structural life and increases of material reliability. Because of the limitation of current nondestructive evaluation methods, fatigue cracks are detected after a half of the structural life has passed.

Recently a nonlinear stress-strain relationship is investigated for the early diagnosis of micro-cracks or damages. The nonlinearity can be determined by a ratio of ultrasonic amplitudes of fundamental frequency and harmonic frequency. This technique is relatively simple and direct in a viewpoint of theory and experimental device. However, it is not easy to get a consistent data with a direct coupling harmonic measurement.

Nonlinear effect in the resonant measurement can be a potential tool for an early diagnosis of micro-cracks. The nonlinearity can be measured by increasing the dynamic strain i.e. excitation amplitude in a Nonlinear Resonant Ultrasound Spectroscopy (NRUS) method. The more damage, the larger the level of nonlinearity and it can be used for the diagnosis of micro-cracks [1]. NRUS has been applied for micro-damage assessment in the human bone [2]. On the contrary, undamaged or intact material shows essentially linear behavior in their resonance response.

This study conducted an investigation of a NRUS (NRUS) method for an early diagnosis of fatigue cracks. A shift of resonance frequency and a normalized resonance pattern as a function of driving voltage or strain reflect the nonlinearity.

2. Methods and Results

2.1 Experimental Method

A fully digitized resonant ultrasound spectroscopy system was used to control the power amplifier for the excitation of the required ultrasound with a sweep function, signal processing of the received signal. The frequency vs. normalized amplitude is measured at the different driving voltage levels.

Standard 1/2T-1CT specimen with dimension of 63.5 mm x 61 mm x 12.72 mm was fabricated with SA508-Gr.3 material, which is used for a nuclear reactor pressure vessel. In order to fabricate a natural close crack, a fatigue test was carried out with an Instron universal test machine. The number of cycles of each step are N = 1000, 5000, 10000, 20000, 40000, 60000 and 120000 cycles with 10 Hz.

In order to shield it from vibration, temperature change, and even air flow, the sample is suspended with loops of synthetic fibre such as dental floss inside a double-wall chamber. The temperature inside the chamber was monitored with a thermocouple with a dummy specimen, shown in Fig. 1. The temperature variation was kept within 0.10℃ during data acquisition. Considering the variation of the elastic constants or acoustic wave velocity with temperature, all measured ultrasonic resonance data were compensated to the temperature of 25℃.

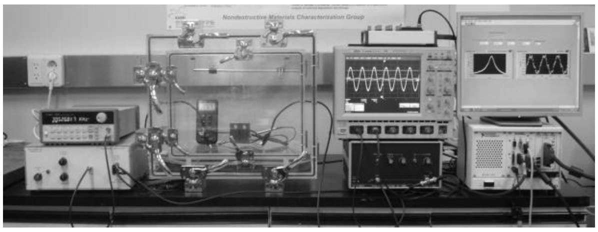

Fig. 1 A chamber to maintain constant temperature and free of vibration and experimental setup.

2.2 Results and Discussion

The shift of the resonance frequency is strongly dependent on the driving amplitude and the nonlinear hysteretic behavior proportional to dominates and the first order approximation gives

$$\frac{f_0 - f}{f_0} = \alpha \Delta \varepsilon$$

, where f_0 is the linear resonant frequency and f the resonant frequency for an increasing driving amplitude [2].

The fatigue cracks were fabricated progressively at the different fatigue cycles. An intact material shows no variation with the different driving voltage, which can show a linear elastic response, shown in previous study [3].

In order to shield it from vibration, temperature change, and even air flow, the sample is suspended with loops of synthetic fibre such as dental floss inside a double-wall chamber. The temperature inside the chamber was monitored with a thermocouple with a dummy specimen, shown in Fig. 1. The temperature variation was kept within $\pm 0.10^\circ$ C during data acquisition. Considering the variation of the elastic constants or acoustic wave velocity with temperature, all measured ultrasonic resonance data were compensated to the temperature of 25° C. The temperature compensation was established based on the temperature dependence of SA 508 Gr. 3 materials give by: [4]

$$(E = 214.54 - 0.0787T)(Gpa, T = °C)$$

The resonance frequency can be compensated as,

$$f_r^{\ 2} = K(214.54 - 0.0787\ T)$$

,where $K = L\ /\ \rho = const.$ and L dimension, ρ. density.

The amount of dynamic strain at the resonance was estimated and verified by a measurement by a laser vibrometry. When the excitations were 2 ~ 10 volt, the dynamic displacement, $\Delta l = 200 \sim 600\ nm$, can be correlated to the dynamic strain of $\varepsilon = 3.3 \sim 10.0 \times 10^{-6}$.

Fig. 2 shows a normalized resonance pattern of a cracked CT specimen with increasing excitation amplitude from 2 volt to 160 volt. At the very early stage of cracking, such as fatigue cycles of 1000 shown in Fig. 2(a), the normalized resonance pattern shows a small change as increasing excitation voltage. As the fatigue crack increases, a resonance frequency shift can be observed with an increase of excitation amplitudes, shown in Fig. 2(b) and (c). A meaningful frequency shift is observed at the fatigue cycle of 5000, which corresponds to an estimated crack length of 0.1 mm.

Comparing the resonance patterns of the fatigue cycle of 2000 (crack length < 50 μ m) and fatigue cycle of 5000 (crack length ≈ 0.1 mm), it can be concluded the NRUS technique can be effective to detect very early stage of cracking.

3. Conclusions

A nonlinear ultrasonic effect is applied for an early detection of micro-crack. Resonance frequency shift of normalized resonance patterns were measured by the NRUS technique. At the very early stage of cracking, such as crack length < 15 μ m, the normalized resonance pattern shows a small change as increasing excitation voltage.

A meaningful frequency shift can be observed at the stage of an estimated crack length of 30 μ m. The nonlinear characteristics of resonance frequency shift and normalized amplitude can be an useful tool for early detection of micro-cracks in a fatigue process.

Acknowledgement

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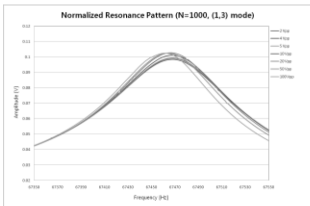
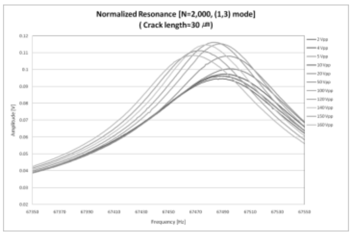
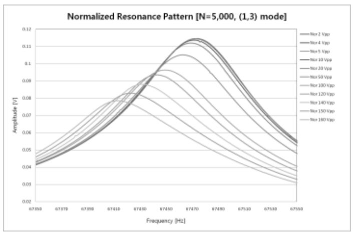


(a)N=1000 ($a \approx 15\mu m$)



(b) N=2000 ($a \approx 30\mu m$)



(c) N=5000 ($a \approx 80\mu m$)

Fig. 2 Normalized resonance pattern of CT specimen with a number of cycle (a) N = 1000, (b) N = 5000, (c) N = 10000.

REFERENCES

[1] Yong-Moo Cheong and Mohammad Khurshed Alam, Feasibility of a Nonlinear Resonant Ultrasound Spectroscopy (NRUS) for Diagnosis of Micro-cracks, Trans. Korean Nuclear Society Spring Meeting, Jeju, Korea, 2009.

[2] M. Muller, J. A. TenCate, T. W. Darling, A. Sutin, R. A. Guyer, M. Talmant, P. Laugier, P. A. Johnson, Bone micro-damage assessment using non-linear resonant ultrasound spectroscopy (NRUS) techniques: A feasibility study, Ultrasonics, Vol. 44, p. 245, 2006.

[3] Yong Moo Cheong, M. K. Alam, and Cheol Ki Kim, Nonlinear parameters for a diagnosis of micro-scale cracks using a nonlinear ultrasound spectroscopy (NRUS), Review of Quantitative Nondestructive Evaluation, AIP CP1211, Vol. 29, p.1439, 2010.

[4] Yong Moo Cheong, Joo-Hak Kim, Hyun-Kyu Jung and Jun-wha Hong, Temperature Dependency of Elastic Properties of RPV Steel Using Resonant Ultrasound Spectroscopy, Trans. 2001 Spring Conf., Korean Soc. Nondestructive Testing, 2001.