**46th Annual Review of Progress
in Quantitative Nondestructive Evaluation
QNDE2019
July 14-19, 2019, Portland, OR, USA**

QNDE2019-1234

THE SIZING OF FATIGUE CRACKS USING NON-LINEAR SHEAR WAVE MIXING METHOD

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ABSTRACT

In this paper, the immersion non-collinear shear wave mixing technique is applied to experimentally detect and size vertical fatigue cracks. In the experimental measurements, the amplitude of the generated longitudinal wave from a vertical fatigue crack was first measured over a range of interaction angle of two incident shear waves and ratio of their frequencies. The resulting amplitude parameter space is termed the nonlinear fingerprint of the crack. It is shown that an interaction angle of 110° and frequency ratio of 0.8 lead to the maximum amplitude in the fingerprint. These optimal parameters were used to measure the nonlinear amplitude from various crack positions along its length direction. Finally, an approximate method combining the measured nonlinear amplitudes with the predicated interaction areas of two incident waves was proposed to measure crack length. As expected, the measured crack lengths are around 2~3 mm greater than those measured using the conventional linear ultrasonic phased array images due to the closed fatigue cracks being undetectable with linear arrays.

Keywords: fatigue crack, wave mixing, crack sizing

1. INTRODUCTION

The effective detection of fatigue crack at its early stage is important in a range of industrial sectors to provide warning of damage and ensure the structural integrity [1]. Due to its flexibility in selection of wave mode, frequency and spatial location and reduced sensitivity to system nonlinearity [2-5], the use of a non-collinear wave mixing technique to detect early damage has been developed in recent years. Theoretical investigations of bulk wave mixing have been conducted by several researchers [6-8]. Based on this theoretical understanding, the nonlinear wave mixing techniques has been used for detecting and evaluating different damages (sources of material nonlinearity or contact acoustic nonlinearity, CAN) in early development stages [2-5].

Recently, Alston et al. [5] used the parameter space, namely the amplitudes of generated longitudinal wave as a function of the interaction angle and the frequency ratio of two incident shear waves, to detect and characterize horizontal kissing bonds. The experimental results indicate that the resonant conditions required for measuring material nonlinearity may not be the same as for CAN from an interface feature. Further investigation of this on real fatigue cracks is the main motivation of this paper. Specifically, can the approach of measuring the parameter space of the non-collinear shear wave mixing technique be used to detect and characterize fatigue cracks?

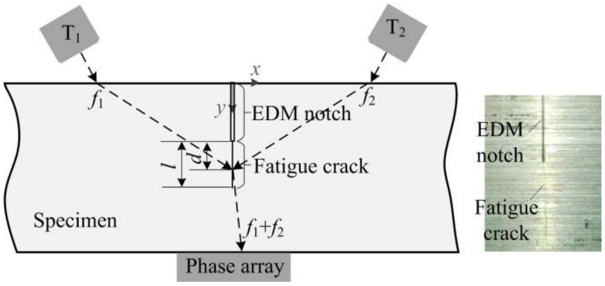

FIGURE 1: SCHEMATIC DIAGRAM OF THE NON-COLLINEAR SHEAR WAVE MIXING EXPERIMENTAL SYSTEM

2. EXPERIMENTAL METHOD

Figure 1 shows the schematic diagram of the non-collinear shear wave mixing immersion experimental system. Here, two signals are generated from two arbitrary waveform generators and amplified respectively, and finally transmitted by two transducers (T_1 and T_2) to generate two longitudinal waves. Two shear waves were generated through mode conversion at the water-specimen interface. The incident angles and the lateral separation distance of these transducers were controlled by motors. The ultrasonic array probe with 128 elements was placed on the bottom surface of the specimen to receive the signals. The polarity flipping method [4] was used to extract the amplitude of the generated longitudinal wave. The experimental

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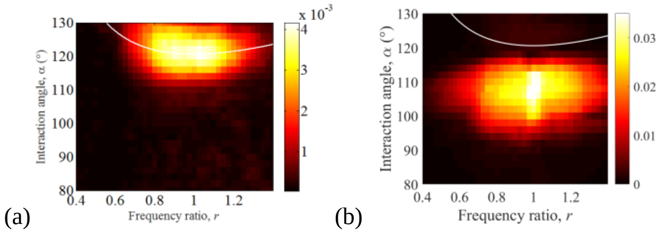
measurements were conducted on a number of aluminum specimens with different features. The crack lengths were measured using both the TFM image-based method [9,10] and the proposed nonlinear technique and they are defined as l_{m1} and l_{m2} respectively.

3. RESULTS AND DISCUSSION

3.1 Experimentally measured fingerprints

Figures 2 (a-b) compare the measured fingerprints from a reference specimen without starter notch or fatigue crack and one with the EDM starter notch and a long fatigue crack, when the interaction depth is y = 29 mm. As shown, for the reference specimen, the interaction angle at the peak nonlinear amplitude is $\alpha_p = 120°$, while α_p is around 110° for the specimen with a fatigue crack. Comparing Figures 2(a-b), it is also shown that the amplitude from crack nonlinearity is around one-order magnitude higher than these from material nonlinearity. The results show the potential of using the location of α_p and nonlinearity amplitude to identify the source of nonlinearity and detect cracks.



(a) (b)

FIGURE 2: THE EXPERIMENTALLY MEASURED FINGERPRINT AT AN INTERACTION LOCATION OF y = 29 mm FROM; (a) THE SPECIMEN WITHOUT ANY INSIDE FEATURE AND (b) THE SPECIMEN WITH A FATIGUE CRACK (l_{m1} = 7.8 mm).

3.2 The interaction area of two incident shear waves

FE models were developed to investigate the effect of crack length on the nonlinear amplitude. In these models, the center of the cracks is fixed at y = 23 mm and their sizes vary from 0.2 mm to 18 mm. The interaction angle is 110° and frequency ratio is 0.8. Figure 3 (a) shows the measured nonlinear amplitude as a function of crack length obtained from FE simulation. As shown, the location with the peak amplitude, i.e., l = 10 mm, should indicate the case when the crack is fully contained by the interaction region of the two incident shear waves. Restricted by this interaction region, even for the large cracks (l > 10 mm), the resulting nonlinear amplitudes do not further increase.

Using Huygens principle, Figure 4(a) shows the acoustic pressure from the inspection configuration used in the FE models along crack length direction. It can be calculated that the amplitude is -6.5 dB relative to the peak when the width of the intersection area is a = 10 mm, suggesting this is the area activated by the interacting waves. This threshold can then be used to calculate the interaction area from the acoustic pressure at various interaction locations. As an example, Figure 4(b) shows the acoustic pressure from the inspection configuration used in the experimental measurements when the interaction location is y=23mm. At the amplitude threshold of -6.5 dB, the intersection area can be calculated as a=7.35mm.

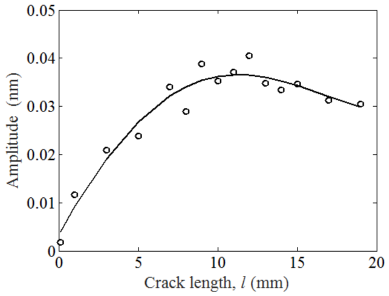


FIGURE 3: (a) AMPLITUDE OF THE NONLINEAR SIGNAL AS FUNCTION OF VERTICAL CRACK LENGTH FROM FE MODELS.

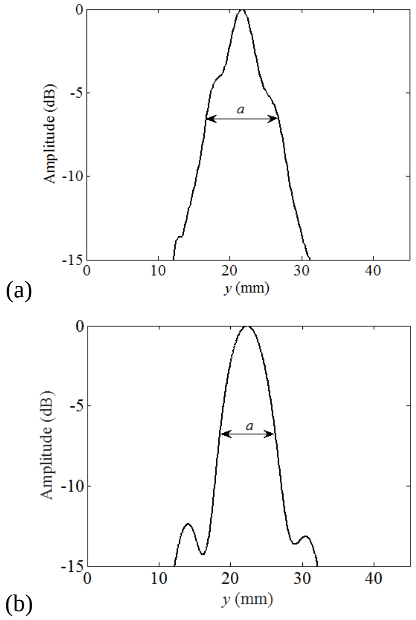


FIGURE 4: SIMULATED ACOUSTIC PRESSURE DISTRIBUTION AT AN INTERACTION LOCATION OF (b) CRACK CENTRE IN A CONFIGURATION USED IN THE FE SIMULATIONS; (c) OF y = 23 mm IN A CONFIGURATION USED IN AN EXPERIMENTAL MEASUREMENT.

3.3 Sizing fatigue cracks

Figure 5 shows a few examples of the measured nonlinear amplitudes as the interaction location is moved along fatigue cracks of various lengths. As shown in Figure 5, the interaction location with the peak amplitude, d_p, should correspond to the case when the closed part of the crack tip aligns with the highest amplitude area in the incident waves, while the interaction location with a convergent amplitude close to zero after the peak, d_e, should correspond to the case when the high energy area of the incident waves is away from the crack tip.

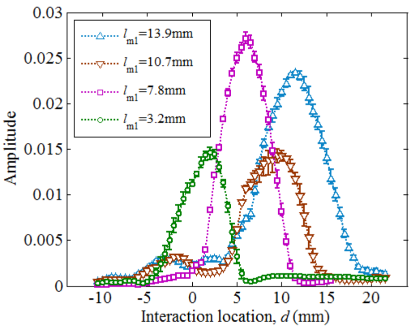


FIGURE 5: THE EXPERIMENTALLY MEASURED NONLINEAR AMPLITUDES FROM THE FATIGUE CRACKS WITH VARIOUS SIZES AS A FUNCTION OF THE INTERACTION LOCATION.

Figure 6 compares the measured crack size from a group of predominantly vertical fatigue cracks. It is noted that d_e is the largest and l_{m1} is greater than d_p for all cases. This is because the crack tips are partially closed hence have some visibility in the TFM images and can also lead to the nonlinear signals. The end of the crack tips should be between d_p and d_e. Conservatively, the measured crack length can be d_e. Less conservatively, we can assume that the peak nonlinear amplitude happens when a partially closed crack is fully activated within the effective incident wave interaction area, and the measured crack length can therefore be defined as,

$$l_{m2} = d_p + a/2 \tag{1}$$

where, a can be calculated from the simulated acoustic pressure fields of -6.5 dB amplitude threshold, as described in Section 3.2. Comparing l_{m1} and l_{m2} in Figure 5, the measured crack lengths using the proposed method are 2-3 mm longer than those using the TFM image-based method. The difference is due to the closure condition of the cracks making their linear detection impossible and the incident wave energy distribution around the cracks.

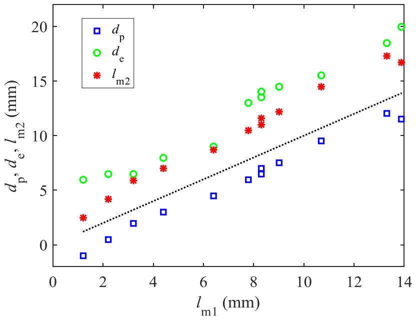


FIGURE 6: THE COMPARISON OF l_{m1}, d_p, d_e AND l_{m2} MEASURED FROM THE FATIGUE CRACKS WITH VARIOUS SIZES.

4. CONCLUSION

In this paper, the non-collinear shear wave mixing approach was used to size real fatigue cracks. The interaction angle leading to the peak nonlinear amplitude was used as an indicator to distinguish between material nonlinearity and that from fatigue cracks. Measured crack lengths using the proposed method are around 2~3 mm greater than those measured using the TFM image-based sizing technique. This could be caused by the partial closure of the cracks and the incident wave energy distribution around the cracks.

ACKNOWLEDGEMENTS

This work was supported by the National Key Research and Development Program of China (Grant No. 2016YFF0203002), National Natural Foundation of China (Grant No. 11572010, 11572011), and China Scholarship Council (Grant No. 201706540035). This work was also supported through the core research programme within the UK Research Centre in NDE (RCNDE) funded by EPSRC EPS (Grant No. EP/L022125/1).

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