Generation of Harmonics at a Real Fatigue Crack Interface

Khalid CHOUGRANI¹, Leo SCHRÖDER²

¹ Applus RTD Technological Center; Rotterdam, The Netherlands
Phone: +31 1071 66146, Fax: +31 1071 66206; e-mail: khalid.chougrani@applusrtd.com
² Applus RTD Application Center; Rotterdam, The Netherlands
e-mail: leo.schroder@applusrtd.com

Abstract

Detection of cracks using conventional ultrasound in assets operating under severe conditions and undergoing a cyclic load is a major challenge in non-destructive testing (NDT). Due to the nature of the cracks initiated during the fatigue process, and as a result of compressive stresses surrounding the cracked area, crack closure may occur leading to acoustical transparency of such cracks. To increase detection capabilities of the existing inspection approach, different NDT techniques can be applied and combined to provide more insight into crack behavior. Although these techniques are combined, difficulties in terms of detection of such cracks still remain. To face this challenge and to enhance crack detection, a new approach is introduced, where second harmonics generated at the crack interface are exploited. Results obtained from this study provide vital information on the crack response and reveal essential nonlinear features generated at the crack interface when higher ultrasonic amplitudes are used.

Keywords: ultrasonic testing, non-linear ultrasound, harmonic generation, fatigue mechanism, crack closure

1. Introduction

Despite new technological developments in non-destructive testing (NDT), the inspection of assets operating under severe conditions and undergoing a cyclic load, e.g., steel catenary risers (SCRs), is still challenging due to the nature of cracks that might grow during the fatigue process of these assets. As a result of compressive stresses surrounding cracked areas in fatigued components, bridging between crack asperities may occur. A crack of this type may become acoustically transparent, the so-called closed crack, and will act as a transmitting layer for incident waves. Consequently, the ultrasonic inspection performance of the current NDT approach is negatively affected.

To overcome this limitation, non-linear acoustics can be applied as it showed a great potential in different applications, such as material characterization and medical imaging. In this approach, non-linear effects resulting from the interaction of ultrasonic waves with the object under inspection are exploited. For material characterization and evaluation, non-linear acoustics has proven to be a sensitive method for material damages [3], [4]. In medical diagnostics, harmonics arising from the wave propagation in the medium are recorded and used for the so-called harmonic imaging [1], [2]. In NDT applications, a defect with a contacting interface shows non-linear features when interacting with an intense acoustic wave, and behaves as a source of harmonics [5], [6], [7], [8], [9], [10], [11]. The key element in NDT is to excite the crack at one frequency with high ultrasonic amplitudes and extract harmonics generated at the crack interface for crack detection. It is expected that these generated harmonics are found in the reflected, as well as in the transmitted wave fields.

This paper describes fatigue tests performed for producing a fatigue crack that was used for the investigation of crack closure and harmonic generation (second harmonics) at the crack interface. It also shows the benefits of using second harmonic generation for the crack detection when using higher ultrasonic amplitudes.
2. Experiments

2.1 Fatigue testing

Fatiguing of a test specimen requires precautionary measures in terms of notch preparation, applied load, crack initiation and crack growth. For this purpose, a block of carbon steel with dimensions 400 x 200 x 200 mm was fatigued using the three-point bending method (Figure 1a). To ensure a controlled crack initiation at one position, a sharp V-notch was introduced at the center of the block and extended along the width of the block (normal to the drawing plane). To avoid crack initiation in the vicinity of the notch, the corners of the slit area were finished with a radius. Furthermore, the block was equipped with two openings machined at 100 mm from the notch centerline, in which ultrasonic probes were placed for monitoring crack growth during fatiguing (3 and 4 in Figure 1a). The same probes were used, after completion of fatigue tests, for scanning along the crack length by sliding the probe holders for- and backward through the openings.

To accurately register crack initiation and crack growth, a two-dimensional optical tracking method, the so-called digital image correlation (DIC), was applied [12]. In this method, deformation of the object is tracked through changes in images (grey levels) at successive time steps, as shown in Figure 1b. Based on correlation algorithms, strain is deduced from differences in displacement between a deformed subset at time \( t_1 \) and a reference subset at earlier time \( t_0 \).

During fatigue tests, the block was initially loaded at 290 kN with a testing frequency of 10 Hz. Once the crack was initiated (at approx. 90,000 cycles), snapshots of the crack, at intervals of 10,000 cycles, were made. By monitoring the speed of crack propagation, the applied load was gradually adapted and reduced down to 180 kN for the remainder of the fatiguing test (approx. 700,000 cycles), ultimately resulting in a crack length of 53 mm. Figure 2 depicts a section of the initiated crack with a typical DIC image. In this image, the red color code corresponds to regions with high strain values, whereas the blue-violet color code represents regions of minimum strain values. Near the crack tip, a greenish area is visible, which represents the plastic region resulting from high stress concentration near the tip.

![Figure 1: Schematic setup for fatigue testing (a), numbers 1 through 4 indicate V-notch, bending points, probe, probe holder, respectively; DIC method showing a reference image at \( t_0 \) and a deformed image at time \( t_1 \) (b).](image-url)
2.2 Crack closure and harmonic generation

To investigate crack closure when applying a compressive load, the fatigued block of Figure 1a was turned vertically and loaded under an electro-hydraulic testing machine with a maximum load of 3500 kN (Figure 3a). For this purpose, reflection and transmission of ultrasonic waves at the crack asperities were monitored by two compressional wave probes labeled C1 and C2, placed on both sides of the crack interface. In this setup, at zero load, the probe arrangement was fixed at a position at which reflection from the crack area showed a maximum. By gradually applying the load, the contact area between crack asperities becomes larger leading to a significant decrease of the reflection amplitude and, therefore, increasing the transmission of ultrasonic waves through the crack interface. Figure 3b depicts reflection amplitudes as a function of the applied load at different peak-to-peak probe excitation voltages ($V_{pp}$) with a sinusoidal signal of 24 cycles. The reflection curves in this figure can be divided in two sections: the first part (< 200 kN) exhibits a fast decay of the reflected amplitudes, while the second part (>200 kN) shows a flat behavior in terms of amplitude decay. The latter can be explained by the fact that at high compressive loads, the crack opening is very small, at which repulsive forces between crack asperities are very strong and, therefore, prevent further crack closure. It can be noticed that the severity of crack closure can directly be linked to the amount of reflection and transmission through the crack interface.

To examine the non-linear response of the crack interface when intense excitation amplitudes are applied, dedicated high voltage compressional wave probes were designed for pulsing at one frequency (fundamental) and receiving at higher frequencies (harmonics). In these experiments, the compressional wave probes consist of two elements, incorporated in one housing, with the transmitting element exhibiting a narrowband spectrum with a center frequency of 4 MHz, and the receiving element having a wideband spectrum with a center frequency of 8 MHz. The bandwidths of both crystal elements were chosen in such a way that possible harmonics carried in the excitation spectrum are reduced, whereas harmonics that may result from the vibration of the crack interface are well recorded by the receiving element. Using this probe arrangement (Figure 3a) with a motor-driven mechanism, scanning along the crack length (from region 1 towards region 3) was achieved. Different data sets from these regions were collected both in reflection and transmission modes. A typical example of a data set collected from region 2 (cracked region) is depicted in Figure 4, where the x-, y- and z-axis represent frequency, crack position and signal amplitude in reflection (Figure 4a) and transmission (Figure 4b) modes, respectively. For this case, the load was fixed at 10 kN while scanning along the crack length.
Figure 3: Front view of the experimental setup (a), where regions 1 through 3 indicate uncracked, cracked and block-end regions, respectively, and reflected amplitudes at increased load and increased excitation voltages (b).

Figure 4: Measured waveforms and the related frequency spectra in reflection (a) and transmission mode (b) between crack positions 30 and 40 mm at 1200 \( V_{pp} \) for 24 cycles; the second harmonics are highlighted in red.
It can be seen that in both modes, second harmonics are generated at different crack positions. Clearly, the amplitudes of the transmitted fundamental frequency are significantly distorted between signal traces 34 and 40 and become comparable to the magnitudes of the second harmonic. This illustrates the fact that the crack response strongly depends on a local crack closure and, hence, on the contact area between crack asperities at a specific location.

To extend our analysis of the crack response when the load is applied in combination with the use of different voltages for probe excitation, a thorough analysis of harmonics (fundamental frequency and second harmonic) is required. To this end, the magnitudes of the fundamental frequency and the second harmonic of the reflected and transmitted waves at each crack position were selected and normalized to the amplitudes of the harmonics extracted from the reference trace (without load), respectively. In this manner, an easier comparison between magnitudes of harmonics, along the crack length, can be made. Figures 5 and 6 illustrate the magnitude evolution of the reflected and transmitted harmonics at 1200 V

As illustrated in these figures, the cracked area is located between positions 20 mm and 90 mm. Within this area, the crack response strongly depends on the applied load. For instance, in the case of reflection, the crack region between 20 mm and 50 mm is more influenced by increasing load, especially when looking at the magnitude of the fundamental frequency. For instance, by applying a load of 10 kN, the magnitude of the fundamental frequency of signal trace 38 decreases by approximately 6 dB, while the magnitude of the second harmonic drops by about 2 dB only. However, by further increasing the load, new contact areas between crack asperities may be introduced along the crack length and, therefore, the magnitudes of the harmonics change again. This observation can be illustrated, e.g., at signal trace 82, where the magnitudes of the fundamental and the second harmonic increase by approximately 6 dB when raising the load from 10 kN to 50 kN.

Figure 5: Normalized reflected amplitudes of fundamental en second harmonic of various traces at 1200 V

cycles at increased load.
Figure 6: Normalized transmitted amplitudes of fundamental en second harmonic of various traces at 1200 V_{pp} - 24 cycles at increased load.

In the case of transmission, however, it can be seen that other areas along the crack length are more influenced than in the case of reflection. For instance, at 10 kN the magnitude of the second harmonic increases between position 30 mm and 50 mm, while at 50 kN it increases between position 50 mm and 70 mm. It should be noticed that a change in applied load means a change in contact area between crack asperities and, hence, the realization of a new crack shape. This explains why the magnitude of harmonic generation changes as a function of applied loads. Other parameters that can influence harmonic generation are the input frequency and the excitation amplitude driving the contact.

3. Conclusion

Fatiguing of a test specimen was performed by using the three-point bending method. Crack initiation and crack growth were successfully monitored by means of a digital image correlation method. Crack closure and harmonic generation were achieved by gradually applying a compressive load and using higher excitation voltages. On one hand, the severity of the crack closure was measured by comparing magnitudes of reflection and transmission of ultrasonic waves through the crack interface. On the other hand, the magnitude of second harmonic generation was investigated for different crack contacts as the load was applied.

Information gained from the experiments on harmonic generation has shown the potential of this technique for the inspection of fatigued components. The non-linear signature of closed cracks revealed in these experiments is an essential feature for the improvement of methods for the detection of closed cracks. This is the first step towards harmonic imaging, by which closed cracks can be imaged using second harmonics.
References