Detection of Transparent Cracks Using Nonlinear Acoustics

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Abstract

In conventional ultrasonic testing, where linear acoustics is applied, reliable detection and sizing of cracks in fatigued components can be a major challenge. This is especially the case if defects are acoustically (partially) transparent due to compressive stresses, limiting the performance of linear ultrasonic non-destructive techniques. Tight defects such as fatigue cracks behave as transmitting layers, hence reflection- and diffraction-based ultrasonic techniques suffer from crack transparency.

More information on crack behavior and thus a better probability of detection may be achieved by using nonlinear effects generated by the crack. Such effects are the result of the motion of contacting crack interfaces, when high ultrasonic amplitudes are applied. The key element in this approach is that the crack is excited at one frequency, and that received signals also contain harmonics resulting from crack motion. In this paper, crack transparency is investigated and results obtained from experiments using a nonlinear setup are presented.

Keywords: Nonlinear acoustics, harmonic generation, fatigue cracks, crack transparency, contact interface

1. Introduction

1.1 Background

Detection and sizing of cracks in fatigued components using conventional ultrasound is one of the biggest challenges in non-destructive testing (NDT). Due to compressive stresses and fatigue loading, crack faces can be pressed together and hence tend to become transparent for ultrasonic waves. However, in the microscopic range, a transparent crack might be open although it is not visible to ultrasound. To overcome this limitation, the nonlinear approach can be considered in which nonlinear effects resulting from crack motion are exploited.

Over the last decades, various studies have been conducted for different applications using nonlinear acoustics [1]. Early efforts have revealed the nonlinear behavior of contact boundaries and the generation of harmonics at these interfaces [2], [3], [4], [5], [6]. In medical diagnostics, the nonlinear nature of wave propagation has extensively been exploited for improving the image quality using harmonic imaging [7].

From a material point of view, areas containing a crack behave differently compared to undamaged ones, when intense ultrasonic waves are applied. Besides the linear reflection, the amplitude response exhibits a nonlinear signature in this region [1]. To illustrate this effect, the object under inspection is excited at one frequency while the received signal contains also the harmonics [3].

This paper describes measured reflection and transmission behavior when a crack tends to become acoustically transparent. Furthermore it elaborates on the complexity of using a nonlinear setup for harmonic detection. It also demonstrates the added value of using the nonlinear signature of tight cracks for detection purposes.
1.2 Fatigue and transparency behavior

When material components undergo cyclic loading, fatigue mechanisms can be started that lead to crack initiation, crack growth and, hence, failure of the material structures. Extensive research has been carried out over many years to understand fatigue mechanisms, failure and crack propagation [8], [9], [10]. Remarkably, failure of components can occur when tight cracks suddenly open and extend in a fast way through the specimen. Crack propagation depends on various parameters, such as the failure mode and the nature of the atomic bonds forming the specimen. Figure 1a, 1b and 1c summarize the basic modes by which cracks can propagate and fractures can occur [10], [11]. Time to failure is linked to different factors such as fatigue sensitivity of the structure, cyclic load, environmental effects, crack growth period, etc [10], [11]. As a result of fatigue mechanism, cracks may be tight and, hence, difficult to detect using conventional NDT techniques. A typical fatigue crack with irregular crack faces is shown in Figure 1d, where a contact area of the crack asperities is visible. When additional compressive stress is applied on these asperities, the contact area will increase leading to crack closure.

2. Experiments

2.1 Linear setup: crack transparency

The experimental setup used to bring about the acoustical transparency of a simulated crack interface, is shown in Figure 2a. In this setup, four steel blocks were stacked in series, where the upper and lower blocks 1 and 4 were designed as probe housing while the crack interface was simulated by the contact area (50x50 mm) between blocks 2 and 3. To avoid any plastic deformation of the contact area of the blocks at high values of compressive loading, a smooth surface was chosen for which the roughness value was less than 0.05 Ra. Prior to measurements, the condition of the contact interface in terms of surface deformation was monitored as a function of several loading and unloading cycles.

It should be noted that a real crack has asperities as shown in Figure 1d. This means that the crack faces are not flat on a microscopic level. This observation is also valid for the artificial interface made for this experiment. To monitor crack transparency when applying compressive loading, a multichannel acquisition system was used with eight ultrasonic channels for recording reflected and transmitted signals through the crack interface (Figure 2b, Table 1).
Figure 2: Schematic representation of the stacked blocks: (a) crack interface and probes (compressional wave probes are designated by “C”, angled shear wave probes by “S”); (b) ultrasonic channels required for monitoring crack acoustic transparency as a function of the loading force.

Table 1: Ultrasonic channels for monitoring crack transparency.

<table>
<thead>
<tr>
<th>Wave mode</th>
<th>Reflection</th>
<th>Transmission</th>
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<tbody>
<tr>
<td>Compression</td>
<td>C1-C1</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>C2-C2</td>
<td>x</td>
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<td></td>
<td>x</td>
<td>C2-C1</td>
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<tr>
<td>Shear</td>
<td>S1-S2</td>
<td>x</td>
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<td></td>
<td>S3-S4</td>
<td>x</td>
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<td></td>
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<td>S3-S2</td>
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2.2 Reflection and transmission

To investigate reflection and transmission of ultrasonic waves through the crack interface when applying a loading force (crack closure), dual compressional wave probes labeled C1 and C2 and single shear wave probes labeled S1, S2, S3 and S4 were used. The complete setup was loaded under an MTS electro-hydraulic system with a maximum force of 3500 kN. At zero loading force only reflections from the crack interface were recorded and no transmissions. As soon as the compressive loading increased, ultrasonic energy started to leak through the contact interface and transmissions signals were recorded (Figure 3). Figure 4 shows results recorded with ultrasonic channels for compressional and shear waves simultaneously. Clearly, it can be seen that the curves corresponding to transmitted and reflected signals exhibit different slopes as the applied force increases. This means that transmission through the crack interface starts at very low values of the applied loading force (< 5 kN). For instance, at 53 kN, the transmitted shear signal (Figure 4c, 4d) reaches its maximum value (100 %) while the reflected signal is still visible (18 %). In the case of compressional waves, the reflected signal had a value of 28 % while the transmitted one reached 95 %. This suggests in both modes that reflection-based techniques suffer less from crack transparency than transmission-based techniques [12].
Figure 3: Reflection and transmission signals at 1000\,V_{pp}, 16 cycles. Channel C1-C1 (upper figure) and transmission channel C1-C2 (lower figure).

Figure 4: Reflection and transmission as a function of the loading force: (a), (b) and (c), (d) represents reflection and transmission recorded by dual compressional wave probes and single shear wave probes respectively.
2.3 Setup for harmonic detection

To investigate the response of the crack interface when intense input signals are applied, a setup for harmonic detection has been designed. The same block arrangement as shown in Figure 2, including probes was re-used for these experiments. The previous ultrasonic multichannel setup is used for data collection, while probe excitation and signal amplification are now performed by an Arbitrary Wave Generator (AWG) and a gated RITEC amplifier respectively (Figure 5). The probes are especially designed for harmonic detection. In the case of the dual probe, the transmitting element is 4 MHz narrowband and the receiving element has 8 MHz wideband. In these measurements, the input voltage and the number of cycles are changed from 200 \( V_{pp} \) (peak-to-peak value) up to 1200 \( V_{pp} \) and from 4 cycles up to 24 cycles, respectively. The loading force is applied until the reflected signal completely vanishes. A typical example of data representation in which transparency behavior can be seen is illustrated in Figure 6.

Since the AWG is a two-channel system, compressional and shear wave probes were excited separately. Due to space restrictions, only reflection data of the compressional mode will be presented in this paper.

Figure 7 shows the amplitude response of the crack interface recorded by the reflection channel C1-C1 at different excitation voltages and a fixed number of cycles. It can be seen that the amplitude decay (red dotted rectangle in Figure 7) is comparable for all excitation voltages and exhibits the same slope with increasing loading force. It can be observed that a complete crack closure occurs at 1600 kN.

![Figure 5: Picture of the used function generator and the RITEC gated amplifier.](image)

![Figure 6: Example of crack amplitude response (reflection) at 200 \( V_{pp} \) as a function of applied loading force.](image)
Figure 7: Amplitude recorded by the dual probe C1-C1 at various excitation voltages (peak-to-peak values).

2.4 Harmonic signature

To investigate the nonlinear behavior of crack motion under compressive loading, the excitation voltages and the number of cycles of the incident wave packet were varied. It is well known, that harmonics might arise from the acquisition system, e.g., from the amplifier, when higher excitation voltages are used. To reduce this effect and avoid distortion of the input signal, precautionary measures related to signal amplification and probe design were taken. Furthermore, the properties and sizes of the crystals were chosen in such a way that optimal transformation into sound wave energy could be achieved.

To quantify the contribution of the crack to the harmonics generated, a reference measurement without loading force was performed for which the dual probe was excited at variable voltage levels and number of cycles. In this way, a power spectra footprint of the acquisition system for each excitation voltage level was obtained. Figure 8 illustrates a typical example of the power spectra of the acquisition system at 1000 V_{pp} excitation voltage. In this case, frequencies up to the 4th harmonic are clearly visible. It is remarkable that the fundamental and its odd harmonics (3f and 5f) are dominant compared to its even harmonics in terms of the amplitude (2f and 4f).

As expected, the harmonics that may result from the crack motion due to high amplitude ultrasonic waves are mixed with those introduced by the acquisition system. To extract the contribution of the crack to the harmonics, the amplitudes of the fundamental frequency and its harmonics have been compared when increasing the loading force. Figure 9 shows the power spectra and the corresponding amplitudes as a function of loading force at an excitation voltage of 1000 V_{pp} with a sinusoidal wave packet of 24 cycles.

Clearly, both the fundamental frequency and the corresponding harmonics are influenced by the increased loading force. As it can be seen, the higher harmonics decrease dramatically as soon as the force reaches 30 kN. In Figure 4a and 5b, this value corresponds to 85 % of the transmitted signal. At larger values of the loading force, e.g. at 340 kN, the fundamental frequency, and the 2nd harmonic were still recordable, while the 3rd and the 4th vanished.
To get more insight into amplitude evolution of the fundamental frequency and its harmonics as a function of the applied force, the amplitude of each spectrum trace at each force step was selected and normalized to the amplitude of the first trace. Figure 10 shows amplitude variation of the fundamental frequency and its harmonics at fixed excitation voltages and for a variable number of cycles. It can be observed that the amplitude of the fundamental, 3rd and 4th harmonics decrease dramatically as the applied force reaches 30 kN (Figure 10a, 10c). However, in the case of the 2nd harmonic, a sudden increase of the amplitude is observed. This may suggest the nonlinear contribution of the crack in terms of second harmonic generation at the crack faces. Obviously, the number of cycles used has much more effect on
harmonic generation at this specific level of applied force. In the case of a reference measurement, the amplitude of the harmonics remains unchanged over a long period of time. It can also be observed that the 3\textsuperscript{rd} and 4\textsuperscript{th} harmonics have an abrupt decay compared to the fundamental and the 2\textsuperscript{nd} harmonic, which decrease smoothly as the force applied increases. It should be noted that due to small amplitude values of the 4\textsuperscript{th} harmonic, the relative noise level in Figure 10d is higher compared to Figure 10a, b and c.

3. Conclusion

Transparency of cracks has been studied experimentally by monitoring reflection and transmission of ultrasonic waves by applying compressive loading. It has been observed that reflection-based techniques suffer less from crack transparency than transmission-based techniques.

It has been demonstrated that the use of the setup for harmonic detection requires careful measures when detection of cracks using harmonics generation is considered. A complete suppression of harmonics generated by the acquisition system remains difficult, even when using signal attenuators or filters. As a consequence, it has been proposed to take a reference measurement of harmonics of the acquisition system prior to measurements on a real crack.

The nonlinear signature of the crack interface was identified by monitoring the amplitude variation of harmonics as a function of applied compressive loading for various input signals and excitation voltages. It has been observed that harmonics generation at the crack faces depends on different parameters, such as input signal and number of cycles.

The use of nonlinear acoustics in addition to linear reflection/transmission provides additional information on the crack motion. This nonlinear signature has great value when detection of tight cracks is considered. Although this technique is not yet mature in terms of implementation, nonlinear imaging will gain more ground in the NDT field.
References