Damage detection by using features of nonlinear ultrasonic modulation in vibrating structures

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Abstract

Due to the high need for structural health monitoring in aerospace applications, numerous, quite mature linear ultrasonic NDT techniques have been developed for the detection of defects. Typically guided waves are used, which are based on mode conversion and reflection of probe waves by a defect, provided the defect is open, resulting in an acoustic impedance mismatch. However, in practical applications defects are often 'closed' when not under substantial stress.

Although nonlinear ultrasonic NDT techniques adequately tackle this issue by making use of signal features resulting from defects opening and closing under sufficiently high stress, most of them do not allow the differentiation between different sources of nonlinearity, which makes the defects undistinguishable from e.g. nonlinearity induced by mechanical contacts.

Here, we aim to detect damage, addressing the practical difficulties of monitoring vibrating structures. Typical defects were created by fatigue facilities and detected in aluminium plate-like samples using PZT transducers to generate and detect probe waves. The presented diagnostic algorithms compare features of the nonlinear relation between the amplitude of the transmission probe wave and the load on the sample with a threshold value, in order to assess the state of the sample. The applications are robust to environmental changes and are based on durable components, while being sensitive to vibrating defects.

1. Introduction

Due to the tendency of using lightweight materials for aircraft industry there is strong demand in the development of non-destructive evaluation techniques having monitoring capabilities. Structural Health Monitoring (SHM) offers interesting options to assess the state of components, thereby reducing the costs spent on scheduled maintenance and the possibility of keeping these components in operation for much longer than originally foreseen. In both situations, it is important to detect damage at the earliest possible stage in order to ensure the reliability and safe use. Most SHM systems make use of one or a combination of more non-destructive testing (NDT) techniques. Many NDT techniques are available for the testing different aircraft components and e.g. can be found in 'Introduction to Non-destructive Testing: A training guide' by Paul E. Mix (1). Some of them, for example acoustic emission and resonance analysis, are not appropriate for use in a complex noisy environment with restricted implementation areas for the sensors. In some cases, it is difficult to incorporate a sensor inside solid components, such as for the eddy current method. The development of a successful SHM technique depends on boundary conditions set by different factors. The sensing system, especially the sensors, should be cheap, durable and robust. Taking into account the possible environmental and boundary conditions, the ultrasonic method is one of the most promising choices. For validation of ultrasonic technique, electrical crack gauges (ECG) were used. Interestingly, crack gauges could also serve as independent defect detection technique as well as in a SHM system.

Several linear and nonlinear ultrasonic NDT techniques are available, nevertheless their practical implementation is still limited, this is even more the case for 'online' in-flight monitoring. Linear ultrasonic NDT is based on the detection of mode conversion, attenuation and reflection of probe waves by a defect. Provided the defect is open, it results in an acoustic impedance mismatch. However, in practical applications, in particular in unloaded conditions, defects can 'close' and return to their quasi-homogeneous condition. In such cases, effects on the probing acoustic waves are absent. Techniques, based on nonlinear ultrasonic, have been developed to resolve the problem of 'closed' cracks. Acoustic nonlinearity arises when acoustic waves propagate through regions with wave dependent material parameters, such as nonlinear elastic properties or nonlinear effects at a defect.

In general, four types of nonlinear ultrasonic effects are used for defect detection. The most well-known, higher harmonics detection (2-5) can be used when a probe wave induces a nonlinear elastic response of the medium, which, in turn, modulates this probe wave. The non-elastic response of the medium can arise from non-Hookean elasticity or from contact acoustic nonlinearity (CAN). Higher harmonic analysis is very sensitive to fatigue damage and allows the detection of early-stage crack formation. However, it is very sensitive to other not-defect related inhomogeneity in the sample or in the sensing system. Sub-harmonic detection, where lower harmonics resulting from the vibration of the defect are investigated, is similar to higher harmonic detection, but it is only sensitive to closed cracks and thus more robust (4). Nonlinear resonant ultrasound spectroscopy measures changes in resonance frequency, due to nonlinear effects (6) but as mentioned above, it is not adequate for online monitoring in noisy environments. Probe wave amplitude modulation, the fourth nonlinear effect, is generated by dynamically opening and closing of a defect by vibrations in the sample (clapping). The corresponding changes in mode conversion at the defect result in a modulated transmission of the probe waves. Waves induced in an intact sample are not modulated. Detecting features caused by vibro-acoustic modulation reveal in this way the presence of a defect (6). A detailed review on nonlinear techniques for NDT was published by K.-Y. Jhang (7), who focused on the detection of micro damage. Nevertheless, the implementation of nonlinear ultrasound based approaches into practical SHM systems has remained limited till today. One reason is that NDT techniques that do not differentiate between nonlinear contributions that originate from a targeted defect and from other locations, are not a suitable implementation while the object of interest is in operation. In particular, mechanical contacts in vibrating/operational structures also interact with probe waves. Thereby, generating nonlinear features in the signals of interest, which are undistinguishable from the ones are caused by probe wave interaction with the crack. In order to filter out

unwanted wave packets from the signal a well-designed transducer configuration, in combination with dedicated signal processing, is needed to resolve this. Hence, defect detection and monitoring during operation employing nonlinear ultrasonic requires corresponding sensing systems, signal analysis and diagnostic algorithms.
This work presents diagnostic algorithms based on nonlinear ultrasonic in order to detect defects in vibrating structures.

2. Study design

2.1 Methodology

Consider a crack in a sample that is closed when the sample is not loaded and that opens when the sample is under load. When a sufficiently large cyclic load is applied on the sample, the crack opens and closes depending on the load applied. In the proposed method, throughout the cyclic load, a transmission measurement is performed using a high frequency (HF) probe wave. If the crack is closed, the probe wave does not encounter a region of acoustic mismatch and achieves normal transmission through the crack zone. When the load increases, the crack starts to open resulting in mode conversion of the probe waves at the open part of the crack. The transmission amplitude cyclically changes from high transmission at low applied load to low transmission at high loads, and thus the probe wave transmission amplitude undergoes nonlinear modulation and more mode conversion. On the other hand, cyclic loading of an intact sample does not change the propagation properties in the monitored region. Hence, no modulation of the probe wave transmission is expected. Therefore, monitoring the properties of the modulation can be used to differentiate between an intact and a damaged sample.

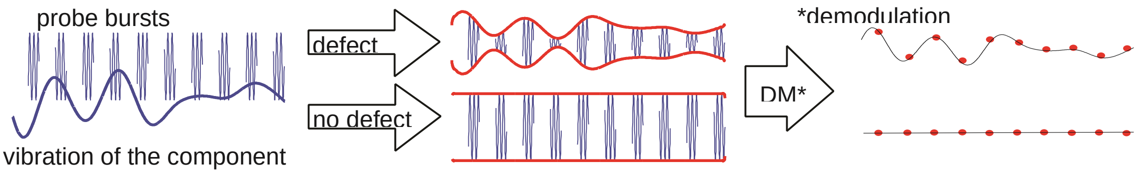

Figure 1. General concept of the developed crack detection method: the vibration of the component opens and closes a crack and thereby modulates the probe waves. In the absence of a crack no modulation is detected

In the proposed sensing system, ultrasonic waves are used to monitor the transmission in the region of the defect. The emission and the detection of the probe waves was performed by two commercially available piezoelectric transducers. The piezoelectric transducers were chosen for their simplicity in operation, general availability, low price, compact size, and long lifetimes. As mentioned above, also the probe waves interacting with mechanical contacts are modulated in a nonlinear way, since ‘clapping’ of vibrating contacts induces cross-modulation and other forms of nonlinearity. The resulting signal features therefore cannot be differentiated from the ones generated by defect related nonlinearity. The only solution is to filter them out of the analysed probe signal.

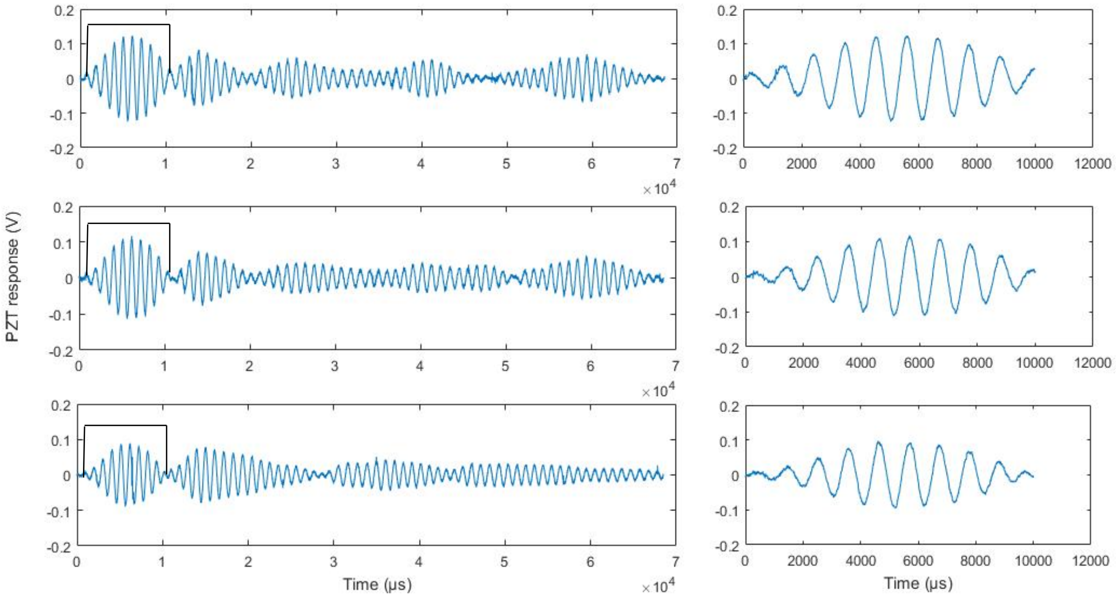

Figure 2: Left: Three high-passed PZT responses at different stages of the fatigue loading (top: begin; middle: middle; bottom: end) and the selected time gate. Right: The same signals after time gating.

With a short burst, temporal discretisation can be achieved by making use of a time gate for the signal trace, i.e. selecting and processing only waves arriving at the receiver transducer within a specified time window. In this approach, waves that have trespassed a path that is different from the one of interest, are discarded. It is thereby important that when the sample has a limited thickness, the probe waves are of the Lamb type, and different modes travel at different group velocities so that one can focus on the plate waves with the highest velocity. The time gate window – with respect to the transmission of the burst wave signal and its duration time – can be chosen to include only the wave packet of a mode and path of interest. The combination of short probe waves bursts and a time gate allows to discard reflections from boundaries and mechanical contacts since only Lamb wave packets are chosen in time window with a certain group velocity and travel distance.

2.2 Experimental details

In order to validate the proposed approach, a fatigue crack was initiated and grown in a small plate using a MTS-810 load bench. The sample and the details of the setup are depicted in Figure 3. The sample was an aluminium (Al 2024-T3) plate of 1 mm thick, 300 mm length and 80 mm width. In order to accelerate the formation of a crack and to force its position, a 3.5 mm diameter hole was drilled in the middle of the crack zone. The outer edges of the plate were clamped by the grips of the MTS-810 loading bench, which was programmed to apply a sinusoidally varying (10 Hz) tension loads between 4000 N and 12000 N along the longitudinal direction of the sample. The cyclic sinusoidal load served two purposes. On one hand, the pulling mimicked, in an accelerated fashion, the fatigue inducing loads that the component could undergo under operation. On the other hand, the load cycle produced periodical modulations of the elastic response of a slowly growing crack, which in turn were detected via modulations of the probe waves propagating through the crack region.

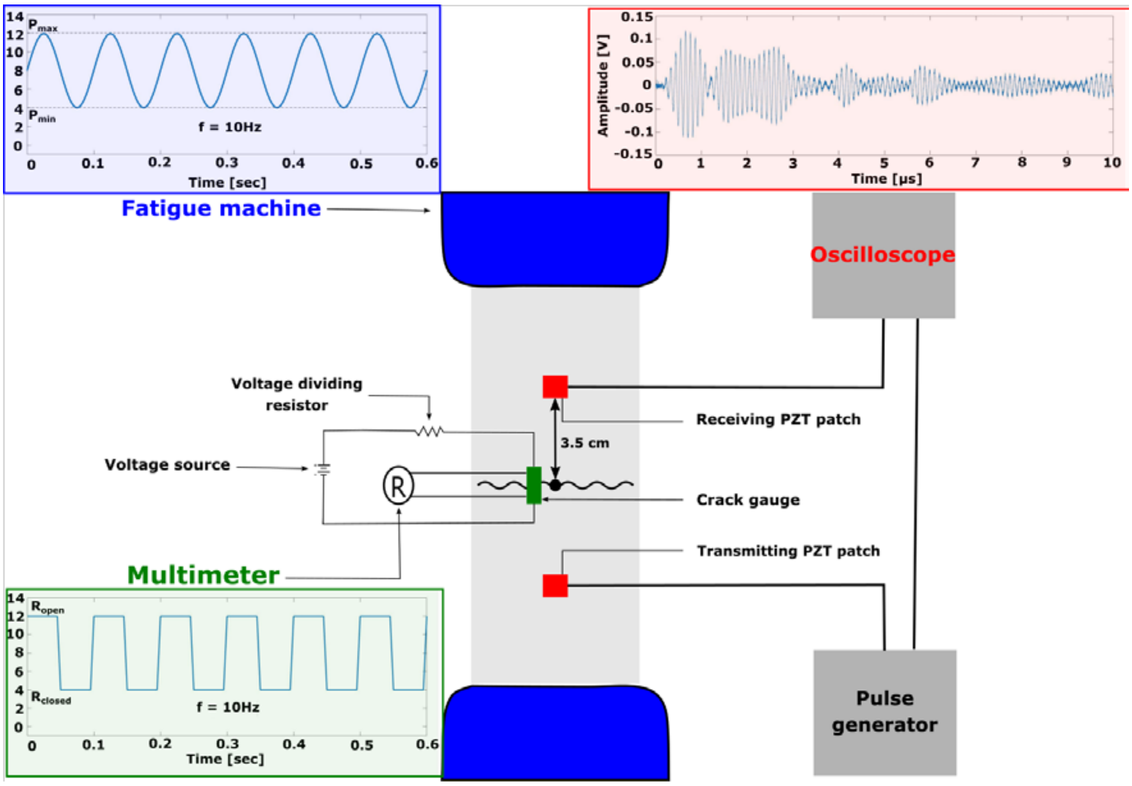

Figure 3: Schematic representation of the setup.

The setup consists of three main parts: the ultrasonic and ECG data acquisition system and the fatigue equipment. As mentioned above, the ECG method was used for validation of the ultrasonic response. They were synchronized in a way that the data acquisition from the ultrasonic and ECG parts was conducted only in high and low loads of the corresponding fatigue cycle. This differentiation between two load states allows to estimate the difference in wave propagation behaviour between minimum and maximum loads.

The actuating-sensing system consisted of two PZT transducers with a diameter of 10 mm with 1mm thickness. The probe wave was piezoelectrically excited by a 240 kHz burst of 5 periods. The mechanical load on the sample was measured by the controller hardware of the MTS-810. The transmission measurements were grouped in sets of 20 measurements for one fatigue cycle. One set were measured around every 15 minutes, but as soon as crack initiation became noticeable to the eye, the measurement rate was increased to 1 per minute.

2.3 Results and discussion

The transmitted amplitude was quantified by the amplitude A_i^j of the peak frequency in the Fourier spectrum of the gated wave PZT response for measurement *i* of set *j*:

$$A_i^j = \max\left(abs(fft(gated\_PZT\_response_i^j))\right) \qquad (1)$$

Since for every transmission measurement a corresponding load measurement was available, so that transmission at minimum (±4000 N) load $A_{4000}{}^{j}_{mean}$ N and the transmission amplitude at maximum (±12000 N) load ${A_{12000}}^{j}_{mean}$ N could be evaluated. The preliminary results are presented in Figure 4. Both the low load and high load signal start to change some time before the first crack occurs. This infers that in some cases, the low load signal (cfr the one that is used in linear ultrasonics), could be used for early detection of crack growth. However, in practice, the low load signal amplitude can also drift because of effects that are related to other, non-harmful effects. In view of this, the added value of having information about the high load signal, is that it can help to discriminate between effects of crack growth and other effects.

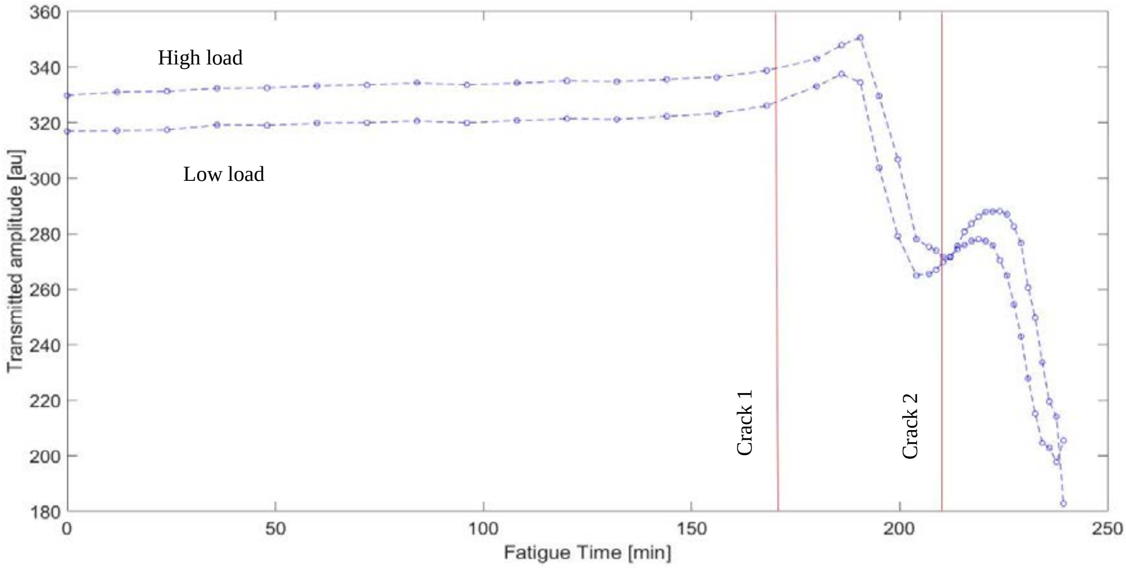

Figure 4: Transmission amplitudes versus fatigue loading time .

The first hair crack was observable on the right hand side of the sample's stress concentrator after around 170±10 min. Eventually, after 40 min, i.e. after around 210 minutes of the fatigue test, it reached the extension in approximately 10 mm. The crack growth started on the left hand side of the stress concentrator. Two significant changes in the transmitted amplitude signal can be identified occurring around approximately the time of crack initiation are shown on figure 4 (crack 1 – right had side initiation, crack 2 – left hand side initiation from the stress concentrator).

The results of two explored diagnostic algorithms, both based on the nonlinear modulation of the transmission amplitude, are illustrated in figure 5. Both plots are showing very similar trends. The horizontal line represents the mean value of the transmitted amplitude of the intact sample. The first algorithm, shown in figure 5 (a), is based on differences of the amplitude transmission between the high-load and low-load states during fatigue cycles. In the initial – undamaged – health state of the sample the variation of the amplitude differences is very small, whereas well before crack visibility by eye, presumably 10 minutes before (around (150 min) 90360 cycles of fatigue test) it starts to decrease dramatically. Thus, it could be beneficial for early-stage crack detection. In the second approach, shown in figure 5 (b), the negative cross-correlation between the two signals (low-load and high-load conditions) is depicted. It provides the numerical time difference for which the high and low load signals are best aligned in time and most similar to each other in shape. In other words, the goal is to find the optimal time difference by shifting the high-load signal with respect to the low-load signal where these signals are most similar to each at corresponding fatigue time [8]. Before the visually observable crack initiation, the negative cross - correlation approach does not show any change. In the case of the differences between two load conditions (figure 5(a)), however, there might be already an earlier indicator emerging before visual crack observation. As long as the crack appeared first on right side of the stress concentrator, the ECG system responded just with second crack initiation on the opposite side of stress concentrator.

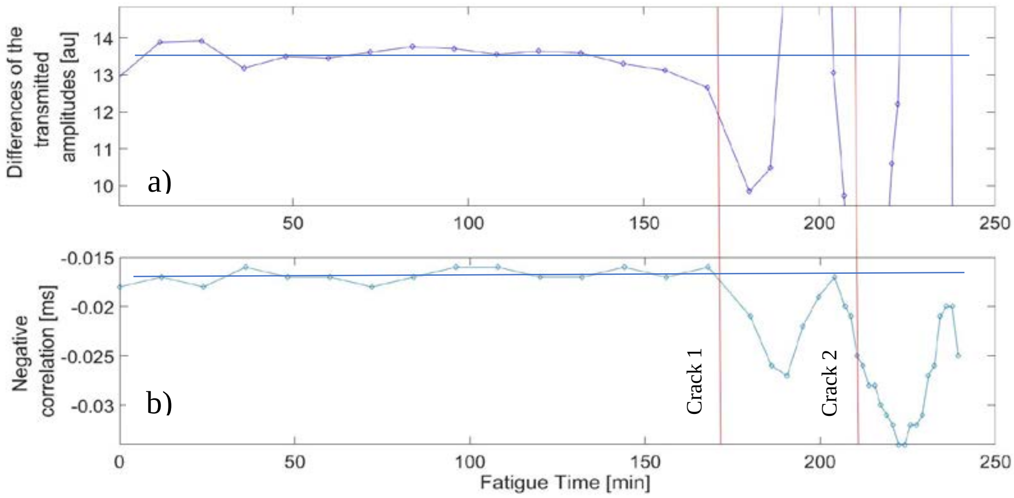

Figure 5: Illustration of defect detection thresholds based on two tentative diagnostic algorithms: a) difference between transmitted amplitudes at high/ low - load conditions versus fatigue time b) negative correlation analysis versus fatigue time.

3. Conclusions

A laboratory setup, which allowed to acquire experimental data on initiation and development of a fatigue crack in a component under dynamic loading conditions, was designed and implemented. Preliminary results of two proposed diagnostic algorithms are presented. Monitoring of the US system response allows to detect and estimate the early-stage initiation of the cracks under loading conditions. Further cross-validation is envisaged by placing a strain gauge on both side of the crack concentrator, so that the both, the ultrasonic and ECG system, can detect crack growth, whatever side of the stress concentrator it appears.

Acknowledgment

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