Applying features of nonlinear ultrasonic modulation for defect detection in vibrating structures

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Abstract. Aircraft structures are subjected to various external factors that influence their lifetime. 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.

Moreover, in most nonlinear ultrasonic NDT techniques the lack of differentiation between sources of nonlinearity makes defects indistinguishable 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, are based on durable components, while being sensitive to vibrating defects.

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Introduction

Due to the insreased usage of lightweight materials for aircraft industry there is strong demand in the development of non-destructive evaluation technologies having monitoring capabilities. If the crack initiation leading to the major or even fatal failure can be detected, action can be taken to prevent or avoid the destruction of the structure, and appropriate repairs can be carried out. Structural Health Monitoring (SHM) offers interesting options to assess the state of components, thereby reducing the costs spent on scheduled maintenance and the possibility to prolong the operational lifetime of these components than it was originally foreseen. Most SHM systems make use of one or a combination of more non-destructive testing (NDT) techniques. 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. The development of a successful SHM technologies relays on boundary conditions set by different factors. Taking into account the possible environmental and boundary conditions, the ultrasonic method is one of the most promising choices.

1. Methodology and experimental details

Several linear and nonlinear ultrasonic NDT techniques are available, nevertheless their practical implementation is still limited. This promote the development of 'online' in-flight monitoring [1]. Linear ultrasonic NDT is based on the detection of mode conversion, attenuation and reflection of probe waves by a defect. Provided that 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. Technologies, 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.

Consider a crack in a sample that is closed when the sample is not loaded and that opens when the sample is under load. Depending on the applied cyclic load on the sample the crack opens and closes accordingly. 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 [2]. 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 [3].

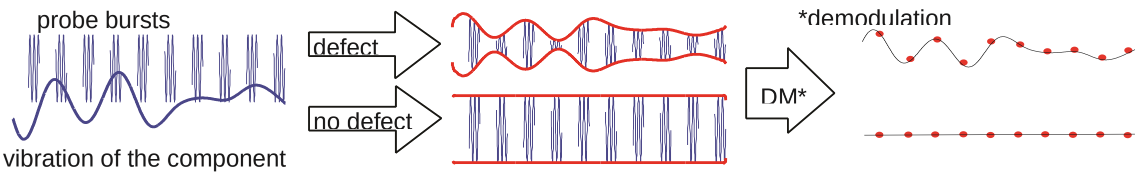

Fig. 1. General concept of the developed crack detection method: the vibration of the component opens and closes a crack and thereby modulates the probe waves. In the absence of a crack no modulation is detected[3]

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 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.

The actuating-sensing system consisted of two PZT transducers and the probe wave was 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 which were measured around every 15 minutes. When the crack initiation became noticeable to the eye, the measurement rate was increased to 1 per minute.

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*:

$$A_i^j = \max(abs(fft(gated\_PZT\_response_i^j))) \tag{1}$$

Since for every transmission measurement a corresponding load measurement was available, so that transmission at minimum (±4000 N) load $A_{4000}{}_{mean}^{j}$ N and the transmission amplitude at maximum (±12000 N) load $A_{12000}{}_{mean}^{j}$ N could be evaluated. Then two diagnostic algorithms were proposed. They are both based on the nonlinear modulation of the transmission amplitude, figure 2. The horizontal line represents the mean value of the transmitted amplitude of the intact sample.

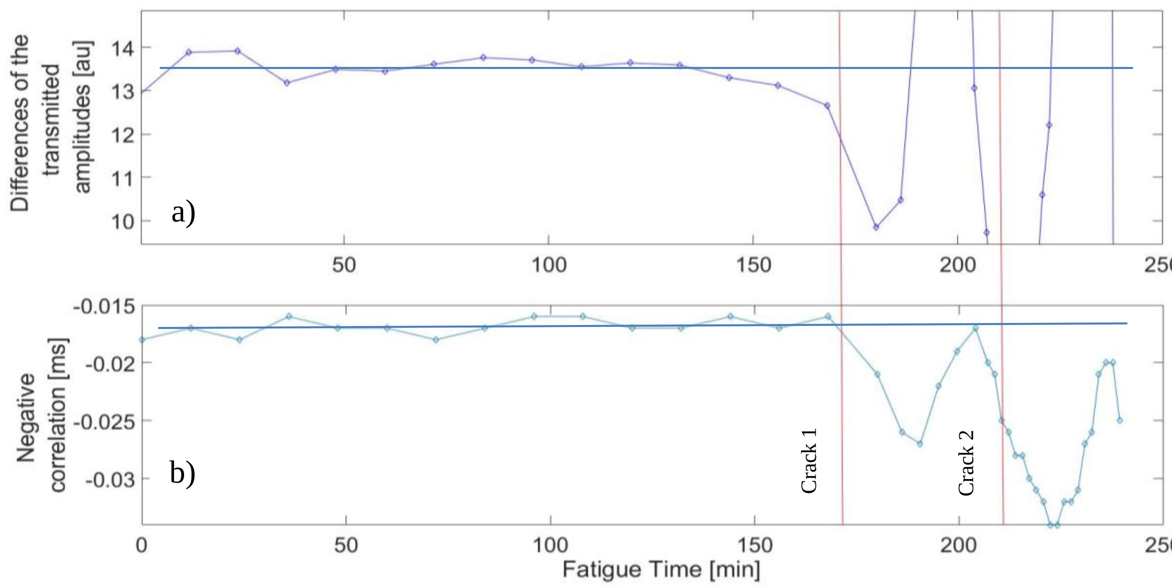

Fig. 2. Illustration of defect detection thresholds based on two tentative diagnostic algorithms: a) difference between transmitted amplitudes at high/ low - load conditions versus fatigue time b) negative correlation analysis versus fatigue time.[3]

The first algorithm, shown in figure 2 (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 2 (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 [4].

Both plots are showing very similar trends. 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 2(a)), however, there might be already an earlier indicator emerging before visual crack observation.

4. 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 high-speed camera and providing digital image correlation analysis of crack initiation process.

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