On-line Monitoring of Cracks using Ultrasonic “Multisine” Surface Waves

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Abstract. A lot of failures in mechanical components are caused by fatigue. Therefore the detection of fatigue damage at a very early stage is important. Rayleigh waves can be used to detect cracks that evolve from the surface of a mechanical structure.

In this article a method will be proposed to detect a growing fatigue crack based on the variability of the measurements due to the opening and closing of the crack. In contrast to classical ultrasonic measurement methods, that use a high voltage pulse, an optimized multisine excitation signal with small amplitude is used. Moreover this method can be used in operating conditions: the normal operation of the structure doesn’t have to be interrupted and the device doesn’t have to be disassembled.

Furthermore, it is possible to estimate the severity of the damage, i.e. the depth of the crack, since the penetration depth of a Rayleigh wave is related to the frequency.

The proposed methods are validated on a steel beam that is fatigue loaded with a force signal.

Introduction

Most of the NDT-methods [1] that are currently used in practice have an important limitation, namely they are off-line: the normal operation of the structure has to be interrupted and the device often has to be disassembled. This implies a non-availability of the device and a large life-cycle cost. Moreover the health of the device between two periodic inspections is uncertain.

Nevertheless on-line fatigue crack detection techniques cope with several challenges:

- The methods have to be robust: during operation a large amount of environmental noise is often present.
- The methods have to be reproducible and should be un-ambiguous.
- The damage, i.e. the crack, has to be detected as early as possible.
- During monitoring a lot of data has to be measured and treated so the techniques should be easy, fast and computationally simple.
- In normal operating conditions there is not much space available for sensors and measuring equipment and often the most dangerous spots of the device (i.e. the spots where the crack should occur due to high stresses) are not visible to the eye.

With regard to these challenges, the Surface Acoustic Wave (SAW) [2] technique is a suitable candidate. Indeed, the sensors and the instrumentation are quite compact and because of the use of high frequency transducers a high sensitivity can be attained while being robust with respect to environmental conditions.

Several methods that use SAW for the detection of cracks on mechanical structures were proposed in [3], [4], [5]. The method presented in this paper uses a low voltage multi-sine SAW excitation where the transmission of the signal is evaluated while the crack is opening and closing.

In the following sections an on-line method will be developed. Then the experimental set-up and the validation of this method will be discussed. Finally, conclusions will be drawn.

1. The Proposed On-line SAW Approach

Assume that the structure under test is periodically excited by a low frequent fatigue load (this load can be the operating load of the component or a simulation of the load on a test bench). While the structure is excited, a multi-sine ultrasonic surface wave (with 10 components from 1 to 10 MHz) is continuously transmitted between a sending and receiving surface wave transducer. The received transmitted signal is measured during the fatigue load sequence [6].

The transmission of these signals depends on the stress state of the structure. When the crack is closed the surface wave is almost completely transmitted, while the SAW is not transmitted through the crack when it’s open. Moreover the transmission of the surface waves is influenced by the depth of the crack since the penetration depth of the SAW is inversely proportional with the frequency. The amplitude modulation and the frequency dependency of the penetration depth are used in order to detect cracks in the structure.

The received ultrasonic (time) signals are Fourier transformed and the ten components X_i (1 to 10 MHz) can be found (Figure 1).

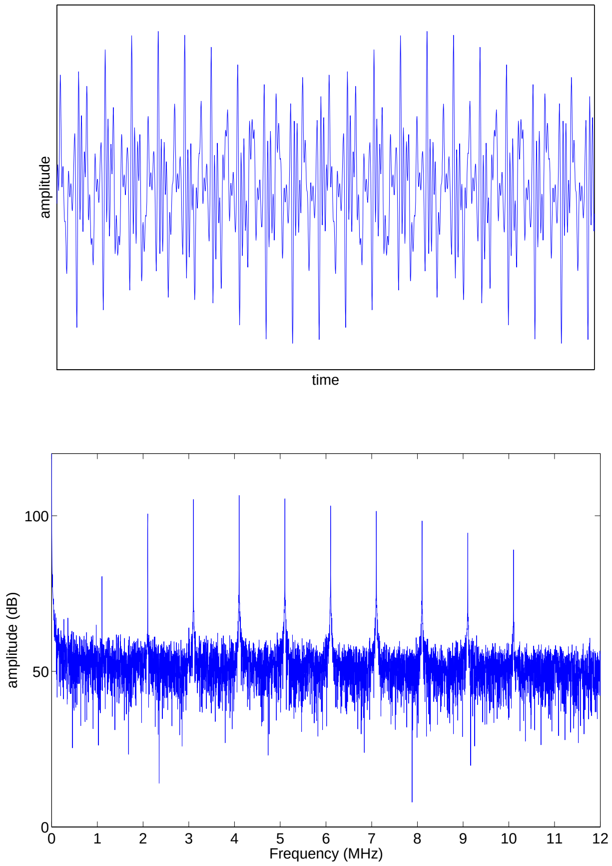

Figure 1: Multisine with 10 components in time and frequency domain

The transmission of every component is studied. Ten measurements (n = 10) are taken into account and the variability, i.e. the standard deviation of each component is evaluated:

$$S_i = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(X_{ij} - \bar{X}_i)^2}$$

When no crack is present the variability will be small. Due to changing operational conditions (e.g. temperature) and possible small movements of the sensors (the sensors are also vibrating) the transmitted signal can drift. When a crack occurs the difference between the spectral components of the received signal will enlarge (due to the opening and the closing of the crack) and the variability of the received signal will grow.

2. Experimental Set-up

2.1 Introduction

To validate the approach explained in the previous section, a steel beam is fatigue loaded in a test rig. In this way a propagating fatigue crack was created. The test set-up with a detail of the ultrasonic measurement transducers is shown in Figure 2. A crack propagation gage was glued onto the side of the beam in order to have a reference for the actual crack depth. More details with respect to the fatigue load, the crack propagation gages and the SAW transducers are given in next paragraphs.

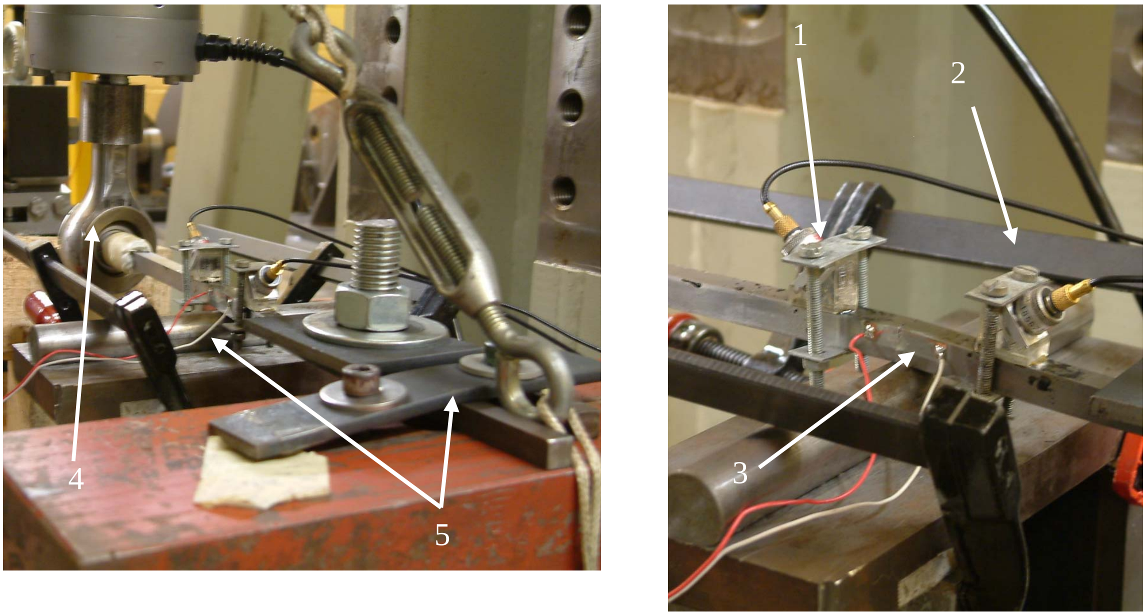

Fig. 2: Overview of the test set-up (top) and detail of the measurement sensors (bottom): (1) transmitter, (2) receiver, (3) crack propagation gage, (4) actuator, (5) beam support

2.2 Fatigue Load

The test specimen is a steel beam with dimensions 450x12x10 mm. The beam was excited by a hydraulic actuator at a frequency of 1 Hz and amplitude of 8 mm. The distance between the actuator and the beam supported on the roller is about 140 mm. In order to know when the beam is pushed down (opening of the crack) or pulled up (closing of the crack) the force on the load cell of the hydraulic actuator was measured.

2.3 Crack Propagation Gages

To obtain the crack length as a reference for the SAW measurements, Micro-Measurement type TK-09-CPA01 crack propagation gages were glued onto the side of the beam under test (Figure 3).

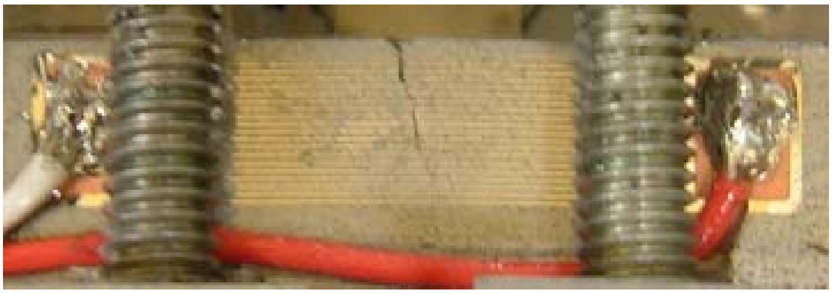

Figure 3: Crack Propagation Gage

These gages consist of a number of resistor strands connected in parallel. When glued to a surface, the propagation of a crack causes successive open-circuiting of the strands, resulting in a known increase of the total resistance. The crack propagation gage consists of 20 grid lines (strands), with a spacing of 0.25 mm. The monitoring of the crack with such a gage is very sensitive and reliable, but the use this type of sensor has several disadvantages:

- Expensive method due to the destructive nature of the gages.
- The gages can only be used on a smooth surface.
- Accessibility of the measuring spot: the gage can’t be positioned on top of the crack because all strands would snap at once. So the lateral side of the crack should be accessible.

This means that the applicability of this method is limited to simple structures and damage scenarios. The result of the crack length measurements are shown in Figure 4.

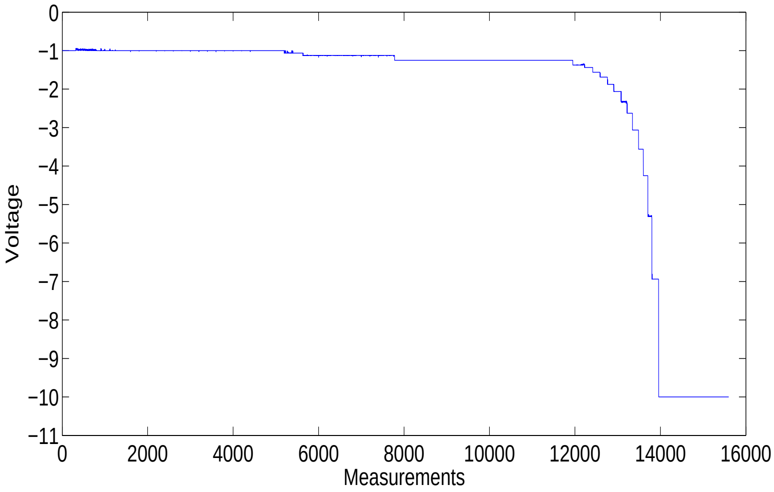

Figure 4: Voltage over the crack propagation gage

2.4 Ultrasonic SAW Transducers

To create the SAWs two Panametrics 10 MHz surface wave transducers (type V544-SM) with ABWML-4st-90 wedges were attached to the beam. Between the transducers' wedges and the beam glycerine is inserted as a coupling liquid. A multi-sine excitation signal with 10 components between 1 and 10 MHz is applied using a HP33130A arbitrary waveform generator. The received signals were measured using a digital Agilent 54624A oscilloscope.

3. Experimental Results

The evolution of the transmitted amplitude of the spectrum of the 5 MHz component is shown in Figure 5. The amplitude of the received signal is shown in function of the number of measurements. It can be seen that from a certain moment, after 6500 measurements, the amplitudes vary a lot. This variation can be explained by the existence of a crack. Depending on the stress state of the crack (open or closed) the surface waves are transmitted or not.

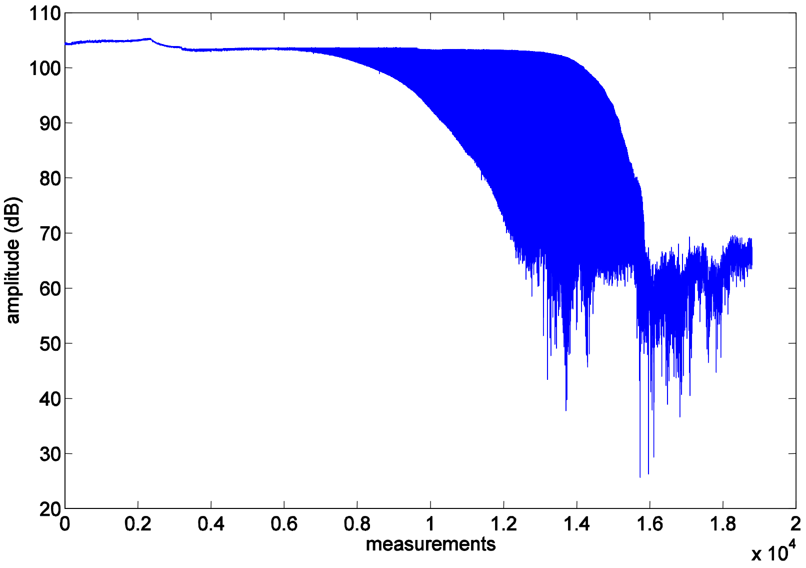

Figure 5: Amplitude of the transmitted 5 MHz component

In Figure 6, a comparison between the transmitted 5 MHz and 2 MHz components is made. One can see that the variability of the 2 MHz components starts at a later moment. This can be explained by the fact that the penetration depth of the surface waves is inversely proportional to the frequency. This means that the high frequency component is more sensitive to small cracks than the lower frequency component and is thus able to detect a crack in an earlier stage. This provides a means to estimate the actual crack depth (the 5 MHz wave penetrates about one wavelength which is approximately $\lambda = c/f = 0.6$ mm for steel, with a Rayleigh velocity c of about 3000 m/s [7]).

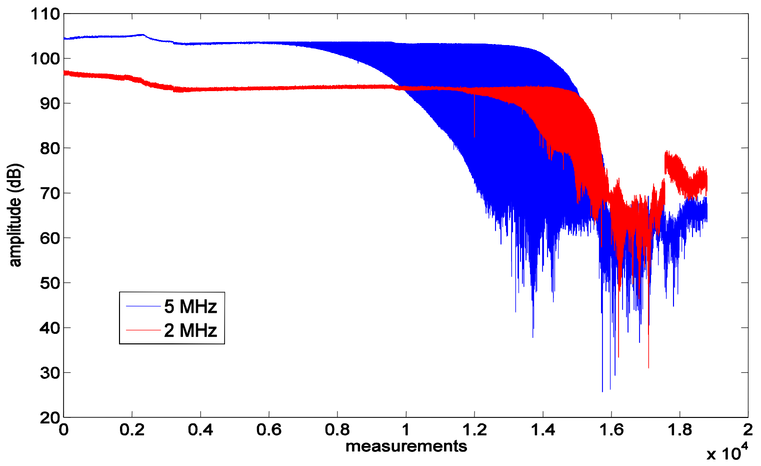

Figure 6: Comparison between the 2 and 5 MHz component

A study of the variability of the different components is made, were the standard deviation over 10 measurements is made. The results for the different components and the crack propagation gage are shown in Figure 7.

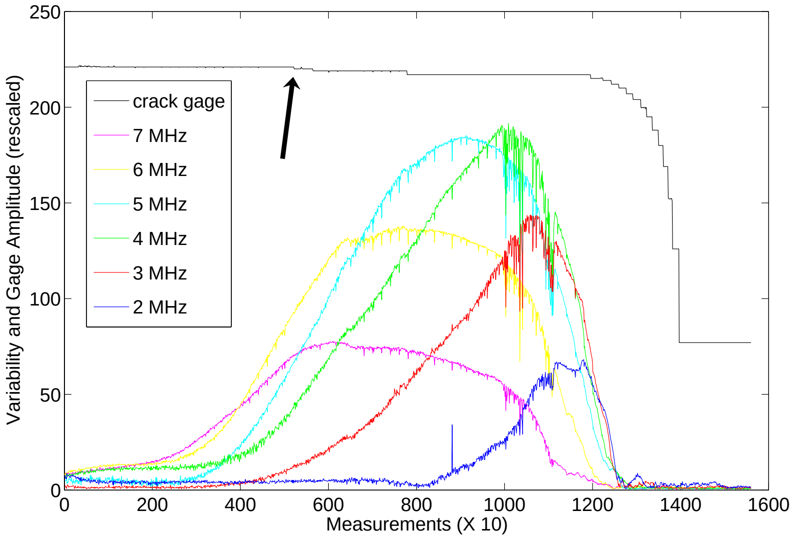

Figure 7: Variability of the transmission of the SAW

The crack propagation gage shows the growing of the crack starting at approximately measurement 5200. The evolution of the variability of the different components can easily be explained. At a certain moment, when the crack is initialized the variability starts to grow. This is caused by the variation of the transmission of the SAW due to the opening and closing of the crack. When the crack is too deep, the hydraulic actuator can't entirely close the crack, so transmission lost is permanently observed: the variability drops.

One can also remark the frequency dependency with respect to the penetration depth of the surface waves. High frequency components are more sensitive to small cracks. This is shown by the raising of the variability of the components: the higher the frequency, the sooner the variability begins to rise.

Thus, the crack growth can be detected in an early stage by use of the high frequency transmitted surface waves. The beginning of the raise of the variability of the spectrum of the transmitted wave indicates the detection of a crack. The 5 MHz component is able to detect the crack in an earlier stage than the crack propagation gage (measurement 2500).

Conclusions

In this article an on-line method was proposed to monitor the health of a structure during its operational loading. In this method a multi-sine Surface Acoustic Wave (SAW) is continuously transmitted and the transmission is recorded. The method using the variability of the amplitude of the spectrum of the transmitted wave, due to opening and closing of the crack, appeared to be able to detect the presence of a fatigue crack in a very early stage. Of course the applicability is limited to those situations where the crack opens and closes during operation. This is the case for many airplane components as for instance the slat track (device that is used to enlarge the surface of the wing at take-off and landing).

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