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A method for crack sizing using Laser Doppler Vibrometer measurements of Surface Acoustic Waves

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ABSTRACT

The goal of non-destructive testing (NDT) is to determine the position and size of structural defects, in order to measure the quality and evaluate the safety of building materials. Most NDT techniques are rather complex, however, requiring specialized knowledge. In this article, we introduce an experimental method for crack detection that uses Surface Acoustic Waves (SAWs) and optical measurements. The method is tested on a steel beam engraved with slots of known depth. A simple model to determine the cracks size is also proposed. At the end of the article, we describe a possible application: fatigue crack sizing on a damaged slat track. This technique represents a first step toward a better understanding of the crack growth, especially in its early stages (preferably when the cracks can still be repaired) and when it is possible to assume a linear propagation of the crack front. The ultimate goal of this research program is to develop a useful method of monitoring aircraft components during fatigue testing.

1. Introduction

In the aerospace industry, non-destructive testing (NDT) plays a fundamental role. Aircraft components are inspected before they are assembled, and then are periodically inspected throughout their useful life. These components also cycled (i.e., loaded and unloaded) as the aircraft fly, land, take off, pressurize, etc. Thus, many of them are prone to fatigue cracking after some length of time. Over 80% of the inspections done to an aircraft are merely visual in scope. At regular intervals, inspectors look at various components for signs of damage. However, not all areas of the aircraft can be accessed for visual inspection and not all damage can be detected by visual means. This is where NDT plays a critical role [1]. In this project, the object of study is the airplane component called *slat track*, which is a movable support structure that connects the wing to the leading-edge slats. This article proposes that a combination of ultrasonic and optical detection, both subjects of great interest to the NDT community, may be able to detect cracking reliably in its early stages (see Ref. [2] for a good introduction to NDT techniques). While many other interesting NDT methods are currently used (e.g., ultrasonic scanning, magnetic particle inspection, X-ray imaging and other imaging techniques), we have chosen to investigate ultrasonic–optical measurements for the sake of its potential future applications. Due to several advantages over conventional ultrasonic methods (higher spatial resolution, non-contact detection of ultrasonic waves and the ability to operate on curved and rough surfaces and in hard-to-access locations) scanning multi-point Laser Vibrometer is indeed already in use in many areas of engineering applications as vibration measurements, modal analysis, damage detection and structural health monitoring [3–7].

1.1. Surface Acoustic Waves

One suitable candidate for the input signal is the Surface Acoustic Wave (SAW). Surface waves on metal components are capable of travelling great distances with little attenuation or dispersion, so they are well suited for damage detection [8–10]. These elastic waves are largely confined to the material surface, penetrating the material only to a depth of approximately one wavelength [11]. (Penetration depth is defined as the distance above which 95% of the wave energy is transmitted.) Lord Rayleigh derived expressions for the velocity of elastic surface waves propagating through a uniform material [12]. For a wave travelling along a perfect surface of an isotropic solid, the following equation [13] is a very good approximation to the SAW velocity v_r :

$$v_r = v_s(1.14418 - 0.25771\nu + 0.12661\nu^2) \quad (1)$$

where v_s is the shear velocity and ν is Poisson's ratio. When encountering roughness, near-surface residual stresses, or cracks, part of the incident wave will be reflected. Hence, measurements of the SAW taken before and after a discontinuity allow one to infer the state of the surface. Several articles have been written on the

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problem of detecting surface discontinuities by means of SAWs (see [14] and [15] for some recent works on SAWs propagation). However, the literature is limited in SAW models permitting estimation of the crack depth. In this paper, we report on measurements of SAWs in damaged materials (slat track, steel beam). Our approach uses a Laser Doppler Vibrometer (LDV) to measure the waves, detect and size cracks, and define the structural health of the material.

2. Modelling the filter effect

A model principal purpose is to predict the system response to material properties and anomalies in a given material or structure. A simple model for crack sizing is still an open question for the NDT community. Today there are only few models available. Most of them use Time Of Flight techniques (TOF) (see [16–21] for recent works in crack detection and sizing). The work discussed here aims to be a good alternative to these techniques, in situations where the longitudinal or shear wave velocity in the specimen is unknown, as well as the distance between the transmitter and receiver. In any case it is only applicable in beams-like structures with notches of parallelepiped shapes or cracks originated in pure banding conditions. In both cases we can assume a linear propagation of the crack. The model proposed is based on a principle named "filter effect" (see Fig. 1).

When a SAW encounters a discontinuity in the surface (cracks, flaws, slots, etc.), the high-frequency components of the wave will be partially reflected. Thus, the discontinuity behaves somewhat as a low pass filter for the transmitted wave. The reflected wave will consist predominantly of high-frequency components (high pass filter effect) [22]. The fraction of energy reflected is closely related to the discontinuity depth. A source pulse (input signal) can be always modelled as a sinusoidal wave with a Gaussian envelope [23]:

$$v_i(t) = A_i e^{\frac{-(t-\mu_i)^2}{2\sigma_i^2}} \sin(\omega_i * (t - \mu_i) + \pi/2) \quad (2)$$

We take the output signal to be the transmitted wave that crosses the crack. This will be in the form:

$$v_o(t) = A_o e^{\frac{-(t-\mu_o)^2}{2\sigma_o^2}} \sin(\omega_o * (t - \mu_o) + \pi/2) \quad (3)$$

After a certain number of measurements (easy to perform using the LDV), one finds that the parameters of the transmitted waveform change significantly; in particular, σ_o and ω_o vary with the crack depth. To estimate these parameters, a nonlinear, least-squares algorithm is used. Hence, given the known input data and observed output data, we estimate the coefficients $X = [A_o, \mu_o, \omega_o, \sigma_o]$ of Eq. (3) that best fit the data. After obtaining optical measurements with the LDV and estimating the parameters of the output pulse, we apply a FFT to Eq. (3):

$$V_o(f) = A_f e^{\frac{-|f-f_0|^2}{2\sigma_f^2}} \quad (4)$$

where $\sigma_f = \frac{1}{\sqrt{2\pi}\sigma_o}$ and $f_o = \frac{\omega_o}{2\pi}$. Finally, the cut-off frequency F_C is calculated as:

$$F_C = f_o + \frac{1}{2}\sigma_f \quad (5)$$

Hence, F_C is tied to the filter effect due to the crack, in Section 5.2 we will look for a linear relationship between this frequency and the crack depth.

3. Experimental set-up

To create the SAWs, a Panametrics surface wave transducer (type VIDEO SCAN V537-RM, bandwidth: 10 MHz, center frequency: 4 MHz) with an ABWML-4s 90° wedge was glued onto the material. Propylene glycol coupling liquid is inserted between the transducer and the wedge. The signals were created by a Panametrics 500PR pulse generator, with the dumping potentiometer at its minimal value and with maximal gain. The amplitude of the pulse sent out by the generator was 150 V Peak. This equipment was able to generate high-frequency ultrasound surface waves. To detect the waves we used a Polytec PSV 300 system. The scanner head was integrated with close-up attachment (Fig. 2). This unit is recommended for measurements of small parts (⩾ 1 mm × 1 mm) or for measurements in close distance. The LDV PSV 300 system allowed continuous measurements of acoustic displacement and velocity (depending on the decoder used during the test) and gave the possibility to perform an optical scan over the region of interest. In this study, the OFV 3001 S decoder was used to obtain displacement measurements (bandwidth: 20 MHz). This signal (pulse of 10 mV Peak for the incident wave) was acquired continuously as a sequence of 2000 time samples using an HP digital oscilloscope (8-bit resolution, sample frequency: 100 MHz).

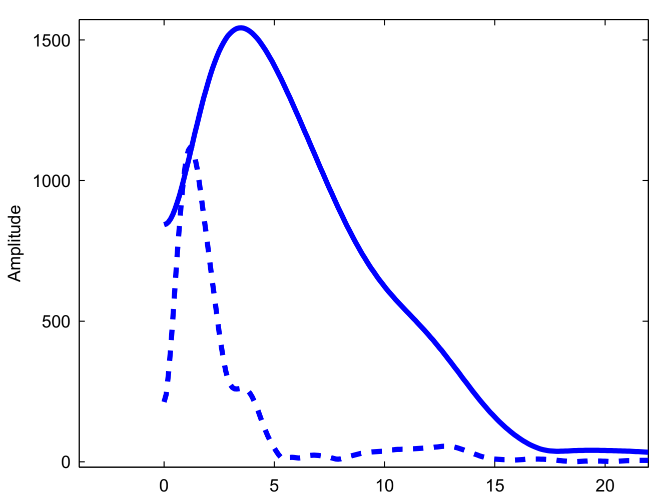

Fig. 1. The filter effect due to a crack depth of 0.4 mm. The incident spectrum (-) and the transmitted one (···).

Fig. 2. The slat track crack detection experiment: (1) The laser scanner head (2) The close-up unit (3) The SAW transducer (4) The slat track under test.