Non-contact detection of pulsed acoustic displacements
for the evaluation of sub-surface defects

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Abstract

The development of optical methods for detection of ultrasound is important for the technology of non-contact Non-Destructive Evaluation of materials. Several optical methods are limited in their application by their sensitivity for ambient vibrations or their complexity.

In this paper a Fiber Time Delay Interferometer is proposed which can be applied to the detection of pulsed ultrasonic vibrations. A practical instrument has been built with a detection limit of 2.10^{-11}m, determined with a detection bandwidth of 10 MHz. Results of experiments show that the method can be used for the detection of (artificial) sub-surface fatigue cracks, using pulsed ultrasonic excitation.

Introduction

Ultrasonic techniques are used widely for Non-Destructive Evaluation (NDE) of materials. For many applications in this area a non-contact inspection tool is desired. Non-contact techniques may be used for industrial inspection and quality control, for the measurement of thickness, temperature, velocity, flaws, defects and grain size. Ultrasonic inspection in areas which are difficult to access, such as corners and edges, as well as inspection of curved surfaces and objects at high temperatures, will be facilitated by non-contact methods.

For the above reasons increasing research is devoted to the development of methods for laser generation[1,2,3] and optical detection[4,5,6,7,8] of ultrasound.

For optical detection of ultrasound several methods have been suggested including knife-edge techniques and various interferometric techniques. Interferometers which measure the object velocity instead of displacement are best suited for integration into a pratical device[7,8]. The principle of operation of these interferometers is based on differential time delay. As their sensitivity is proportional to the acoustic wave frequency these interferometers have a low sensitivity for ambient low-frequency noise.

We are interested in the detection of sub-surface defects such as fatigue cracks that may develop at fastener holes in critical aeroplane structures. In this inspection problem pulse-echo detection is generally applied. Therefore, a detector is required which is able to detect transient ultrasonic pulse-echo signals with a central frequency in the range of 1 to 100 MHz. For the above application area a Fiber Time Delay Interferometer was built and tested. The concept of the device is relatively simple. Complex and fast electronics, which would be necessary for heterodyne systems, are avoided.

By combining the optical detection method with a non-contact method for generation of ultrasound, non-contact NDE is possible. We developed a method for generation of ultrasound using a pulsed laser and optical fibers[9]. The beam direction and width of the laser generated ultrasound are controlled by a Fiber-Optic Phased Array.

However, in this paper only the method for optical detection of ultrasound will be described.

Fiber Time Delay Interferometer

The principle of the method is shown in Figure 1. The object is illuminated by laser light using an optical fiber to conduct the light to the object. The light, which is scattered by the surface of the object and recaptured by the fiber, is coupled into a Mach-Zehnder type interferometer with a differential delay. The time delay is determined by The system is sensitive to the displacement (Δu) of the surface of the object during a time delay (Δt). This means that the response of the interferometer to ultrasonic frequency is not linear. The length difference (i.e. time delay) can be chosen to set the sensitivity maximum at the desired ultrasonic frequency (f_{uD}), the sensitivity drops to zero at $f_u = 0$ and at $2f_{uD}$. The response of the time delay interferometer (Figure 2) is given by:

$$R(f_u) = \sin (\pi f_u \Delta t) \qquad (1)$$

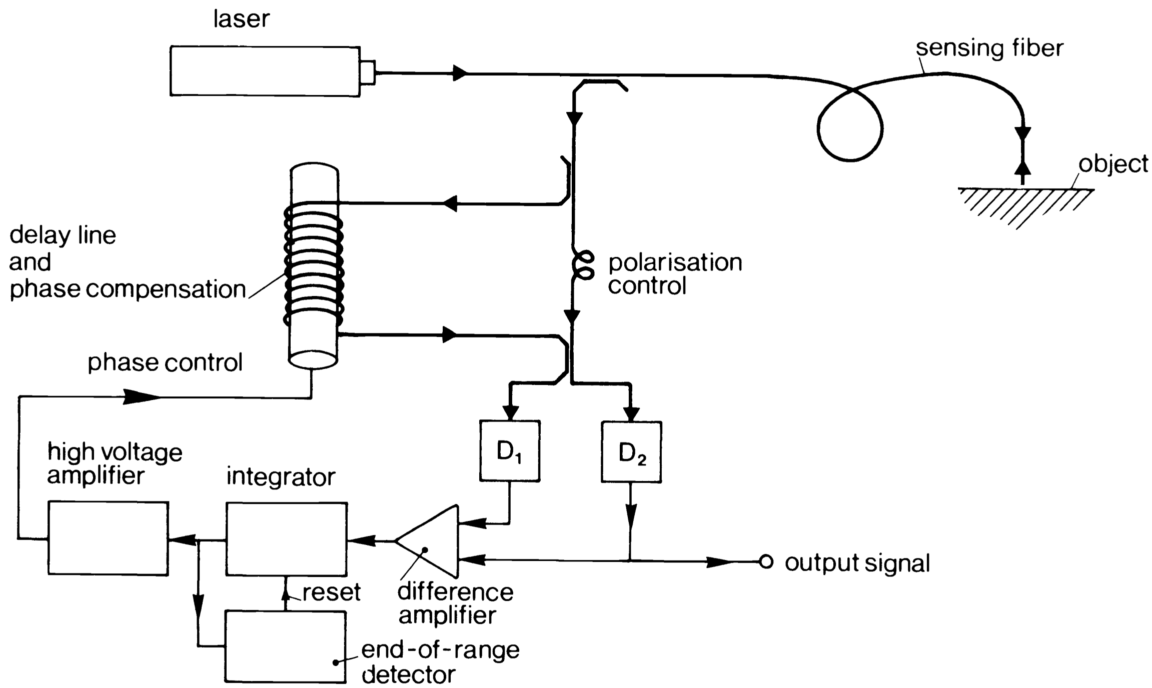

Figure 1. Principle of the Fiber Time Delay Interferometer used for the detection of pulsed ultrasonic vibrations.

For maximum sensitivity at a desired ultrasonic frequency the length difference of the fibers in the two arms of the Mach-Zehnder interferometer must be equal to:

$$\Delta l = \frac{c}{2\ n\ f_{uD}} \tag{2}$$

where c is the vacuum velocity of light and n the refractive index of the fiber.

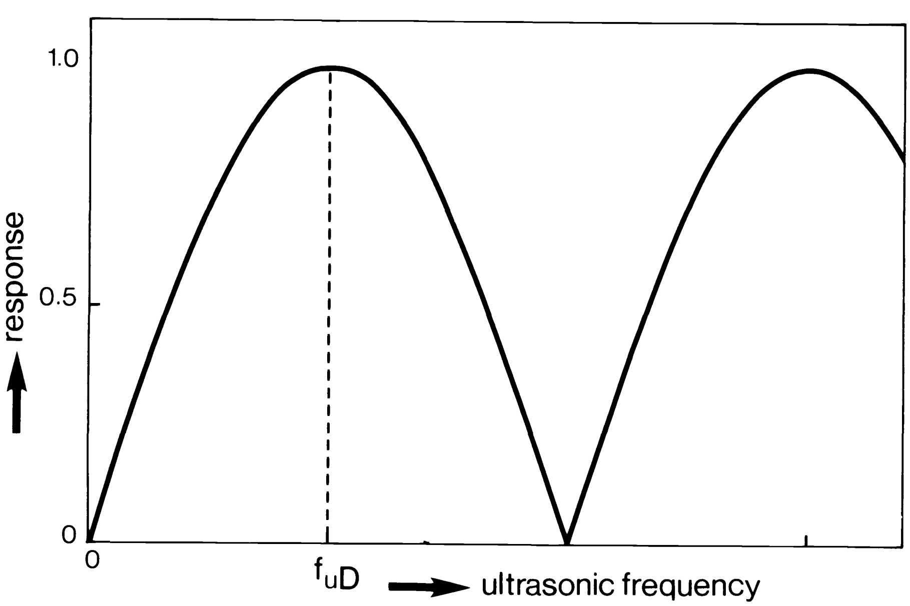

Figure 2. Response of the interferometer as a function of ultrasonic frequency. The response is periodic with a period equal to $\Delta f_u = 1/\Delta t$.

In another device[7,8] the Time Delay Interferometer is positioned directly behind the laser. In this way the laser light iluminating the object and the light reflected from it propagate through the same fiber path but in opposite directions (Sagnac type interferometer). In this way the mean optical path difference is zero and a broadband source such as a multimode semiconductor laser or light emitting diode may be employed. To use this system for detection of transient pulse-echo signals heterodyne techniques must be used. As a consequence high frequency phase or frequency modulation and frequency demodulation in a range above the ultrasonic frequency are necessary.

In the concept shown in Figure 1 the time delay interferometer only forms part of the light path for the reflected light from the object. In this way homodyne detection can be used. Therefore, the interferometer is continually stabilised to maximum sensitivity. This approach garantees the desired pulse response of the device without the need for fast electronic processing. Phase stabilisation in the interferometer part of the device is realised in a well-known way. The phase difference in the interferometer is stabilised to $\pi/2$, using a feedback loop. Specifically, the difference of the two detector outputs (which have a 180° phase difference) is adjusted to zero.

The optical path difference (in the fiber) may vary between 1 meter (for an acoustic frequency of 100 MHz) and 100 meter (for an acoustic frequency of 1 MHz). Thus, the technique requires a narrow bandwidth source, i.e. a source with long coherence length. In practice a single frequency laser may be used or, if the optical path length difference of the interferometer is tuned[10] to 2n (n being an integer) times the cavity length of the laser, a standard Helium-Neon laser may be employed.

For a pratical device this type of non-contact ultrasonic detector has several attractive advantages such as:

- Simple optical set-up and electronics.
- Low sensitivity for ambient noise.
- Arbitrary length of the sensing fiber as it is not part of the interferometer.
- The modulation depth of the detector signals is 100%, for an interferometer with two 3dB couplers and the polarisation control[11] tuned to maximum signal amplitude.
- The modulation depth is independent of surface reflectivity.

The output signal amplitude does depend on surface reflectivity, but may be normalised by dividing the difference of the output signals from the two detectors by their sum.

Detection of sub-surface defects

Optical detection device

Experiments are carried out with a laboratory set-up of the Fiber Time Delay Interferometer. The device is built in a 19 inch rack housing (Figure 3). A standard

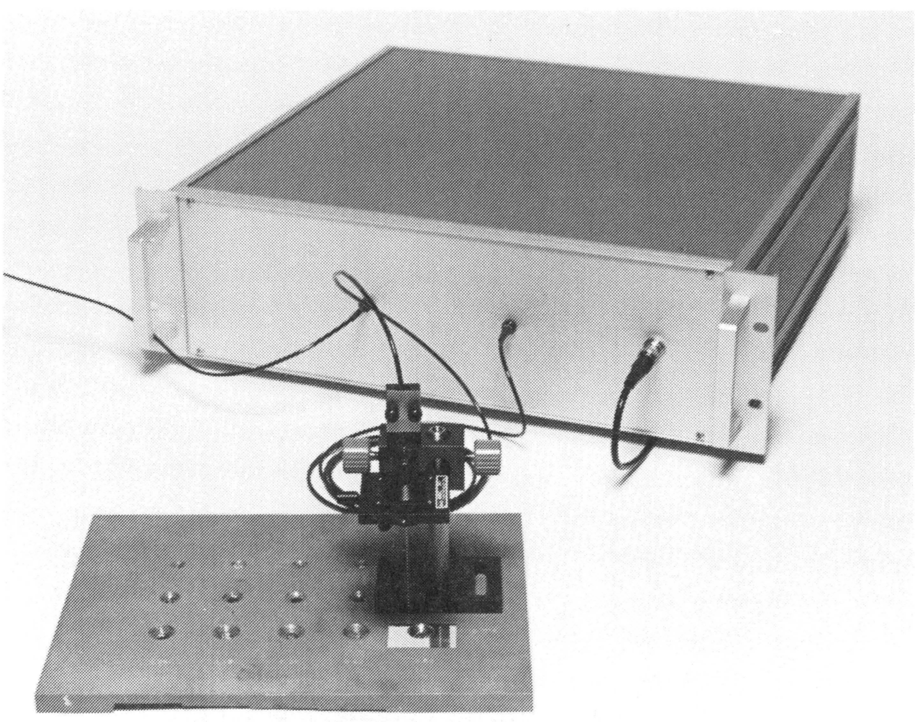

Figure 3. Fiber-optic detection device employed for the detection of sub-surface defects.

Helium-Neon laser (Spectra Physics model 120) is employed. The peak sensitivity for ultrasonic frequencies is adjusted to 5 MHz by selecting a length difference of about 20 meter between the interferometer fibers. The exact length difference is tuned to 2n (n being an integer) times the cavity length of the laser.

The total length of the delay-line is used for phase modulation as it is wrapped around a hollow piezoelectric cylinder. In this way the tuning range of the stabilisation loop is very large. As a result the end-of-range detector needs to reset the integrator (Figure 1) only during warm-up of the laser. All phase disturbances up to a frequency of about 20 kHz are compensated for. The output signal of the device is the signal from one of the two photodetectors. The signal to noise ratio can be improved by using the difference of the two detector signals.

Experimental set-up. To evaluate the method for the detection of sub-surface cracks, experiments have been carried out using an aluminium test object (Figures 3 and 4). This test object, with a number of artificial cracks of various sizes and orientations at the side of fastener holes is typical for a critical wing section of an aircraft. For the present experiments the ultrasonic pulses were generated by an immersion piezoelectric transducer. The position and orientation of the transducer and the position of the sensing fiber of the optical detection device are adjusted for maximum signal amplitude (Figure 4). The experiments are carried out in a watertank because a coupling medium is needed to transmit the ultrasonic waves from the piezoelectric transducer to the testpiece.

The noise amplitude of the device is shot-noise limited. Therefore, the signal to noise ratio increases in proportion to the square root of the optical power that is recaptured by the sensing fiber. For rough surfaces an optically reflective and acoustically thin tape can be attached to the surface of the object to increase the S/N ratio. Using tape, the the detection limit of the optical device, determinded by the rms noise level, is a velocity of $\pm 2.10^{-4}$m/s. For an ultrasonic frequency of 5 MHz this corresponds to a displacement of $\pm 2.10^{-11}$m. This detection limit is determined with a detection bandwidth of 10 MHz.

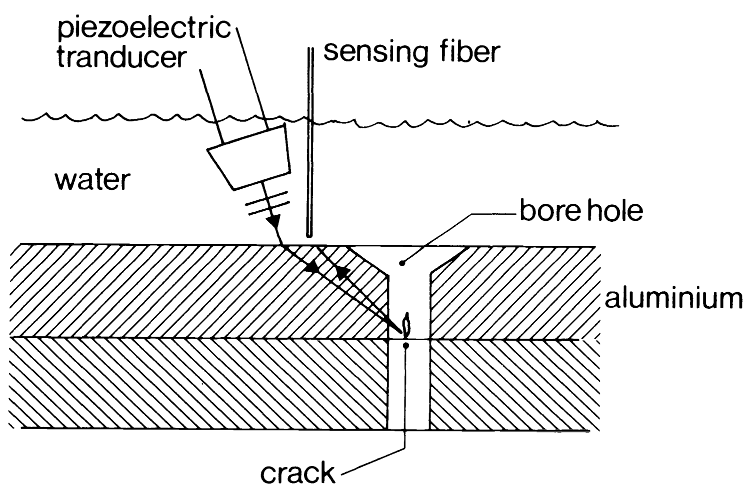

Figure 4. Experimental set-up for detection of (artificial) fatigue cracks at fastener holes using a piezoelectric transducer for generation of the ultrasonic pulses and the fiber-optic device for detection.

Experimental results. As the piezoelectric transducer can also be used for the detection of the reflected pulses, the signals from this transducer and the optical detection device may be compared (Figure 5). The ultrasonic waves detected by the piezoelectric transducer have to traverse the water path both ways. This causes a delay between the pulses detected with the piezoelectric and the optical device. Both signals contain several characteristic echo's (numbered (1)-(5) in Figure 5).

These are successively:
(1) Piezoelectric signal: Reflection of the pulse at the object surface and the optical fiber.
Optically detected signal: Vibration of the object surface due to the interaction of the ultrasonic wave with the surface;
(2) Reflection from the side of the bore hole (in both signals);
(3) Reflection from an artificial crack with an area of 0.25 mm^2 at the side of the bore hole (in both signals);
(4) Vibration of the surface of the object caused by a pulse reflected by the surface of the transducer (in the optically detected signal only);
(5) Acoustic noise floor probably caused by interference of the acoustic field in the water with the sensing fiber (in the optically detected signal only).

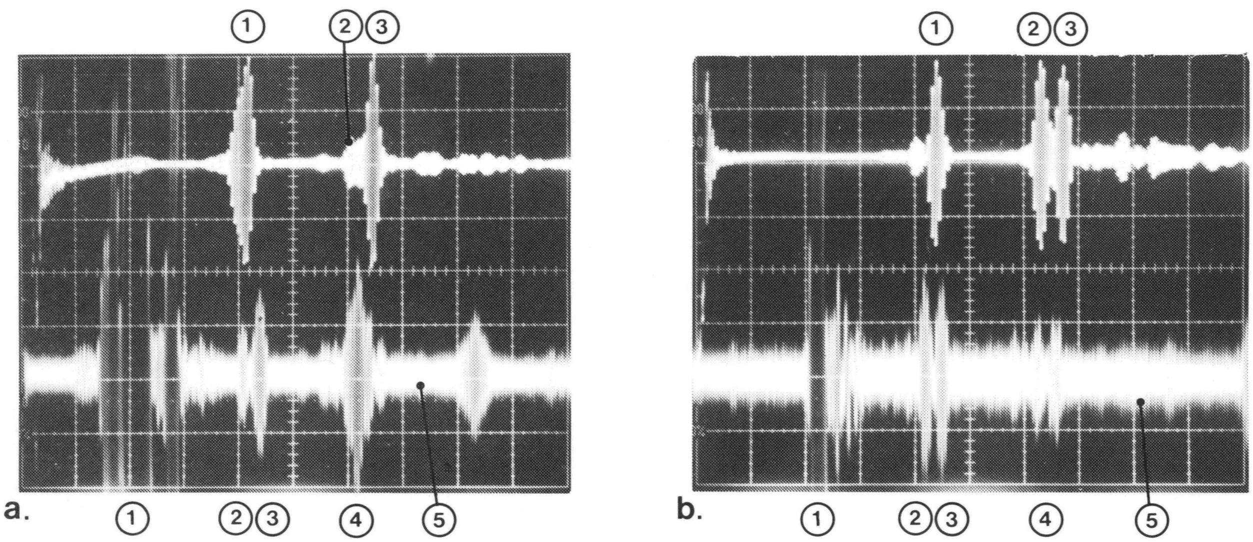

Figure 5. Comparison of the output signals from the piezoelectric transducer (upper trace) and from the optical detector (lower trace). Time/division: 5.10^{-6}s.
a. Positions for detection and generation of the pulses optimised for maximum amplitude of the reflection (3) from the crack.
b. Positions optimised for equal amplitude of the reflections from the bore hole (2) and from the crack (3).

The shot noise level in the signal from the optical detector is about 6 dB below the the signal level of No.(5). Signal No.(4) and probably also No.(5) are caused by the acoustic coupling of the water medium and will therefore not be observed if non-contact (laser) generation of ultrasound is employed in a gaseous medium (air) instead of water.

The experiments were carried out with several machines operating in close proximity and without any vibration isolation. No disturbance of the optical detector output by ambient noise or sudden vibrations was observed.

Conclusions

A fiber optic device for detection of pulsed ultrasonic vibrations was built. The device is designed for maximum sensitivity at a specified ultrasonic frequency. It possesses very low sensitivity for ambient acoustical noise. The optical set-up is relatively simple. Complex electronic processing is not necessary.

The detection limit of the device is equivalent to the detection limit achieved by other interferometric methods.

It is shown that the device can be employed for the detection of weak acoustic reflections as received from small (artificial) sub-surface cracks. This also demonstrates the potential of the method for various other applications such as inspection of coatings, thin plates and bonding of layers.

Acknowledgments

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