THE USE OF FIBER-OPTICS FOR TAP-NDE

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Abstract

Thermal-Acousto-Photonic Nondestructive Evaluation (TAP-NDE) is a powerful new fiber optic based technique for the ultrasonic evaluation of flaws in structures and components. In this technique, pulses of laser light may be guided through a fiber optic probe to excite acoustic waves required for nondestructive interrogation. Alternatively, fiber optic interferometry may be used to detect the response of a structure subjected to acoustic wave excitation by either conventional or thermal-acoustic means.

This paper describes improvements made in the detection phase of TAP-NDE by incorporating a bi-directional optical fiber coupler and PC-based signal analysis. When used as a pointwise sensor, the coupler replaces a number of discrete optical components and eliminates many of the problems encountered in prior research. By using the two legs of the coupler for sensing, it is possible to simultaneously capture the signal generated by the excitation, and signals transmitted and reflected from a material flaw. Spectral analysis and comparison of these signals on the PC provide information sufficient to characterize the flaw, and eliminate much of the laborious and time consuming data transfer and reduction associated with earlier work. Feasibility tests are conducted with the coupler and techniques of signal analysis and interpretation on the PC are discussed.

Introduction

In previous work the authors and their colleagues demonstrated that an individual single monomode fiber could be combined with discrete optics to sense ultrasonic waves generated using a standard piezoelectric transducer. The sensor, called an optical fiber interferometer (OFI), was based on a Fizeau configuration where changes in length of the optical cavity produced intensity modulations which were recorded using high speed photoelectronics. Even though the OFI had some limitations, it was applied successfully to characterize a flaw in a metal specimen by studying Rayleigh waves reflected by, and transmitted around, the flaw. Acousto-optic time-domain reflectometry and properly gated spectrum analysis were shown to be effective OFI signal evaluation techniques, however, both techniques were conducted using a cumbersome data reduction system.

The present research has been directed toward improving this approach for monitoring acoustic waves in steel by designing a compact optical system with more efficient techniques for data acquisition and processing.

Optical Fiber Interferometry

Many fiber optic-based sensors have been designed to measure extremely small displacements encountered in quasi-static and low to intermediate frequency vibration problems [1-6]. While the resolution of these devices under ideal conditions was within the range required for ultrasonic testing, the combination of response time and sensitivity available with them were not high enough to permit the characterization of flaws by digital spectral analysis. This problem was overcome by the authors and their colleagues when they combined high speed photoelectronics with laser based fiber optic interferometry, and produced an elementary optical fiber interferometer (OFI) capable of carrying out remote measurements of Rayleigh waves (surface acoustic waves, also called R-waves) in steel specimens [7,8].

Figure 1 shows a schematic associated with the ultrasonic interrogation of a steel bar described in Reference 8. The unspread output from a laser is split into two beams of equal intensity by a variable beam splitter. One of the beams is launched into the input end of a singlemode optical fiber, the other beam is wasted. A small percentage of the beam propagating down the optical fiber is internally (Fresnel) reflected at the output end and serves as the reference wave. The remainder of the light emerges from the output end of the fiber and is scattered by the diffusely reflecting surface of the steel bar. A small but detectable fraction of this scattered light is reflected back into the optical fiber to interfere with the internally reflected reference wave in its propagation back through the fiber. Upon exiting the optical fiber at the original input end, the returning light is collimated by the same lens used to originally launch the light into the fiber. Half of this collimated output beam is deflected by the beam splitter through an aperture and collecting lens onto one end of a multimode optical fiber which guides the light to a fast photodiode with custom wide band amplification. As illustrated in Figure 2, both beams experience the same environment as they pass throughout the interferometer, such that the relative phase change only occurs within the measuring cavity. So long as the intensities and polarizations of the two reflections are reasonably equal, the light output from the optical fiber will be seen to brighten and darken as the reflecting test surface moves towards (or away) from the optical fiber tip. A displacement induced change in cavity length of one quarter of an optical wavelength is sufficient to shift the output intensity from a maximum to a minimum or visa versa.

Figure 2 also illustrates the main advantage of using an OFI over a standard contact transducer. By positioning the optical fiber between the excitation and the flaw, the OFI can be used to detect an initial

and a reflected R-wave. A contact transducer, positioned at the same location, would absorb the R-wave and the crack would never be detected! The OFI can also be positioned in the more conventional location, beyond the flaw, to detect the transmitted R-wave.

While the OFI showed great potential as a superior detector/sensor for ultrasonic NDE, two major difficulties were encountered; namely, separating the return signal from the much greater intensity reflected off the input end of the fiber, and coupling the return signal into the photoelectronics. Fortunately, these problems can be solved quite easily by replacing the beam splitter and the single optical fiber with a bi-directional coupler as shown in Figure 3.

In Figure 3, a 3 dB coupler is configured with two input and two output fibers. Laser light, launched into one leg of the coupler, is split equally between the output fibers so that each fiber can serve as a separate OFI. Each internally reflected reference wavefront interferes with the corresponding object wavefront, and the return signals pass back through the remaining leg of the coupler to the photodiode and electronics. One of the OFIs may be deactivated by immersing the output fiber in an index matching fluid, thereby, minimizing the internally reflected return signal and the corresponding reference wavefront. This technique is illustrated in the experimental section when one of the legs of the coupler is used to calibrate the internal delay inherent in a piezoelectric transducer. This information is required, since the transducer is used for excitation of R-waves in a subsequent test.

The use of the bi-directional coupler simplifies the optical system and has an added advantage when carrying out remote measurements of R-waves associated with ultrasonic interrogation of a flawed specimen. In this case, the output fibers can be positioned on either side of the flaw to simultaneously capture the initial, the reflected, and the transmitted R-waves. An experiment is conducted to illustrate this approach.

Data Analysis

In addition to the optics, Figure 1 illustrates the electronics used in prior research. Within the photodetector, the current generated by the photodiode was amplified, converted to a voltage and fed either into an oscilloscope to allow acousto-optic time-domain reflectometry, or directly into a standard ultrasonic signal processing system incorporating a high pass filter amplifier and a stepless gate. This latter component was used to select desired parts of the time varying signal so that they could be routed to a spectrum analyzer for evaluation.

The spectrum analyzer can only process a continuous signal and works by applying discrete filters on the input which translate into an amplitude spectrum of the gated signal. Meaningful data will be obtained provided that the input is relatively stable while being analyzed. Fluctuations in amplitude of the input due to instabilities in the OFI and random electronic noise can be reduced by continuous averaging.

After passing through the spectrum analyzer, signals were transferred to a computer for smoothing by boxcar averaging, thereby, removing high frequency noise from the spectrum. This process was repeated for a number of signals recorded at different locations on the specimen so that comparisons could be made. The differences in response were used as a basis for flaw detection.

The major disadvantages of this method are that it is hardware intensive and a significant amount of continuous data transfer is required. The electronics shown in Figure 3 provide an alternative method for analysis. In this case, the time domain signals recorded on the oscilloscope are transferred to a personal computer (PC) where they are stored as data files. The functions of gating and spectrum analysis are replaced by computer programs which select and transform the data to the frequency domain using FFT algorithms. The application and implications of this method are discussed in the following section.

Ultrasonic Experiments on Steel Test Bars

Initial tests to generate and detect Rayleigh waves were run by coupling a standard piezoelectric transducer and wedge to the machined, unpolished, and flaw free surface of a rectangular steel bar. The detection system shown in Figure 3 was used to sense the R-wave by positioning one of the 1-m long output legs of the bi-directional coupler 32 mm from the front surface of the transducer. The other output leg was deactivated by immersing it in a matching index fluid.

In order to receive the maximum signal from the OFI, a translation stage is used to move the fiber tip linearly in and out from the specimen surface. This permits the operator to adjust the amount of light recaptured by the fiber tip and thereby match the intensity of the internally reflected reference wave. Relatively large fluctuations may occur in the cavity length over time, typically on the order of the wavelength of the light used for interrogation. However, the frequency of these fluctuations are orders of magnitude slower than the transient surface displacement caused by acoustic excitation. Therefore, the cavity length remains relatively constant over the duration of the test, and the modulations in intensity which occur are only due to the acoustic excitation.

Figure 4 shows a characteristic time domain plot of the R-wave response. With a Rayleigh wave velocity in steel of 2.96 mm/μs, the travel time between the transducer and the OFI would be approximately 10.8 μs. Since the actual time delay shown in Figure 4 was around 21 μs, the travel delay across the transducer wedge must be around 10 μs. This result agrees with tests run using two identical piezoelectric transducers where the total delay was found to be 20 μs. In computing travel times in all subsequent experiments, where R-waves were generated using the transducer wedge and detected by the OFI, this 10 μs internal delay is subtracted from the measured times of flight.

A second test was conducted to demonstrate the full potential of using the bi-directional coupler by positioning its output legs on either side of a machined "flaw" cut in the surface of the steel specimen as shown in Figure 5. Each of the output fibers were mounted on separate translation stages to allow them to be moved in and out relative to the specimen surface. The fiber offset was adjusted so that signal could be recorded with maximum sensitivity on the digital oscilloscope.

Figure 6 shows a characteristic time domain plot in which the initial response to the R-wave excitation is observed at approximately 18 μs. The 8 μs arrival time, obtained by subtracting the 10 μs delay in the transducer, corresponds to a distance of approximately 24 mm (using an R-wave velocity of 2.96 mm/μs); the distance between the point of excitation and the location of the first OFI. The second signal observed at approximately 24 μs represents the response

measured by the first OFI as the R-wave is reflected from the flaw. The 6 μs delay between the initial response and the reflected signal corresponds to the round trip distance of 18 mm between the OFI and the flaw. A third signal is recorded by the second leg of the bi-directional coupler 22 μs after the transducer was excited. This delay corresponds to a path length of 65 mm. Since the second OFI was located 58 mm from the transducer, the difference of 7 mm must be attributed to the increased time for traveling around the flaw. In fact, the flaw has a length of 2.8 mm and a width of 0.3 mm for a total increase in path of 5.9 mm. The remaining signals may be caused by secondary reflections or regeneration of the acoustic waves.

Next, in order to obtain frequency domain information, the oscilloscope trace is transferred to a PC through a serial communications port. The computer archives the signal in a file along with the control codes required to replay the file to the oscilloscope.

Once in the computer, the file is stripped of the control codes and each digitized data point is assigned an (x,y) value corresponding to time and voltage, respectively. This file is then displayed on the screen so that the three R-waves can be windowed (gated). The block of data for each window is written to a separate data file. All data files are made of equal size by padding them with zeros so that the same parameters can be used to expedite FFT analysis.

The amplitude spectrum of each file is obtained using a fast fourier software package (provided by ikayex Software Tools and called Spectral Analysis Toolkit 1). This analysis can be performed interactively or in a batch mode.

The dominant features differentiating the frequency spectrum of the reflected and transmitted waves from the initial wave correlate with the dimensions and features of the flaw. In Figure 7, a superposition of the frequency data from the initial and reflected waves, the curves show significant attenuation of the frequency components of the reflected wave centered around 1.8 MHz. The flaw depth of 2 mm corresponds to a frequency in steel of about 1.5 MHz. The incident wave has few components of lower frequency (longer wavelength). So, most of the frequencies in the incident wave are at least partially reflected by the flaw. Figure 8, on the other hand, compares the spectrum of the initial wave with that acquired by the second OFI after transmission around and/or past the flaw. Frequencies higher than 1.4 MHz tend to be attenuated, since they do not penetrate as deeply into the material as the lower frequencies and are attenuated by the flaw. The lower frequency components, corresponding to acoustic wavelengths greater than the flaw depth, penetrate deeper than the flaw and are well represented in the transmitted signal.

The main advantage of this approach is that spectral analysis is performed on the same trace used for acousto-optic time-domain reflectrometry. The fact that the method can be applied to a single pulse may ultimately prove significant, since earlier work by the authors and their colleagues has demonstrated that suitable acoustic waves may be generated by exciting a steel bar with a pulse of laser light guided through a noncontact optical fiber probe, and that such photonically generated acoustic waves may also be used to interrogate for flaws [9,10]. The synthesis of these two fiber optic-based techniques for the excitation, interrogation and evaluation of materials and structures would provide a thermal-acousto-photonic (TAP) nondestructive evaluation capability with broad applications in many areas of reliability testing and certification.

Conclusions

This study has demonstrated that a bi-directional coupler can be used as a powerful tool of great potential for monitoring acoustic waves in steel, and likely many other important materials as well. Its point sensing and noncontact features permit the acquisition of considerably more information than can be obtained using a conventional piezoelectric transducer detector and/or an elementary OFI. These features were enhanced with the addition of PC-based spectral analysis which makes it possible to study a single trace containing the initial, the reflected, and the transmitted Rayleigh waves propagating in a flawed test specimen.

Acknowledgments

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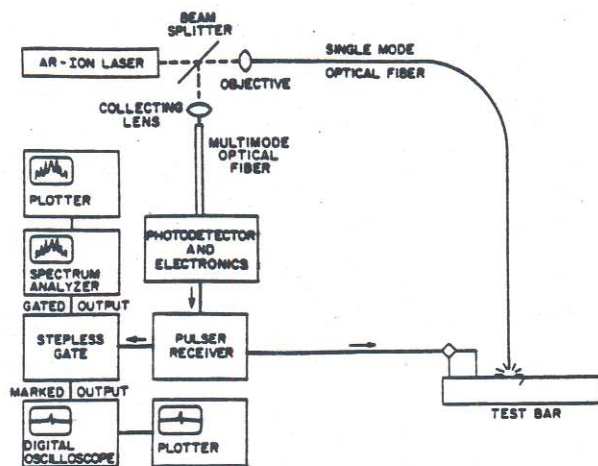
Figure 1. Schematic of a test setup for the conventional R-wave excitation and OFI detection on a steel bar using a beam splitter and discrete optics.
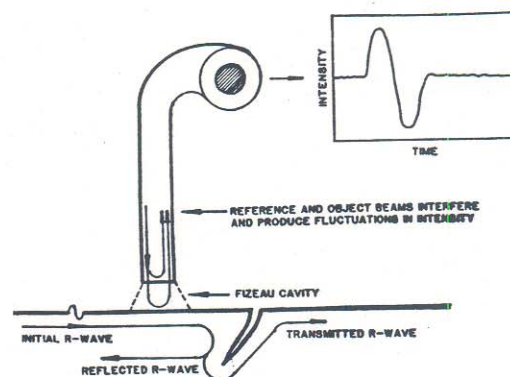

Figure 2. Schematic of an optical fiber interferometer (OFI) showing the Fizeau cavity and the various R-waves which may be detected by the sensor.
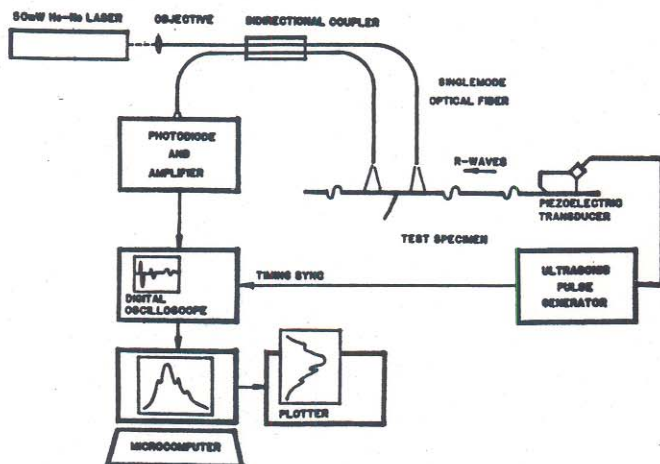

Figure 3. Schematic of a test setup for the conventional R-wave excitation and OFI detection on a steel bar using a 3 dB bidirectional coupler.
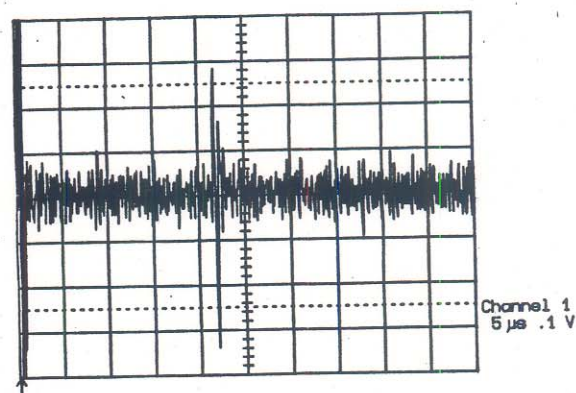

Figure 4. Time domain plot of an R-wave recorded on the surface of a flaw free steel specimen. An OFI was positioned at a distance of 32 mm from the front face of a standard piezoelectric transducer and wedge.
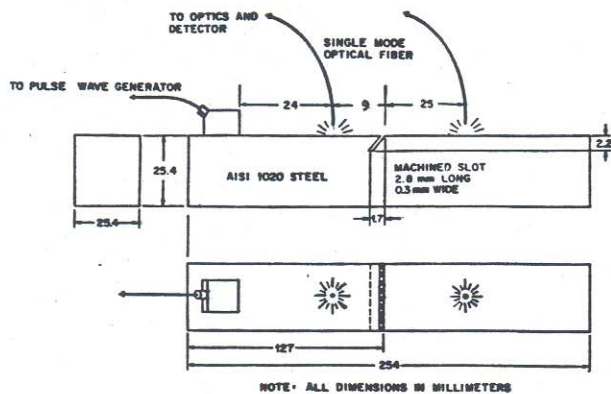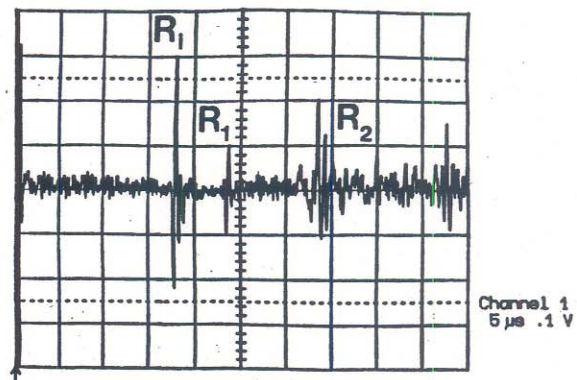
Figure 5. Steel bar test specimen.

Figure 6. Time domain plot of the initial (R_I), reflected (R_1), and transmitted (R_2) R-waves in a flawed steel bar obtained using the bidirectional coupler.
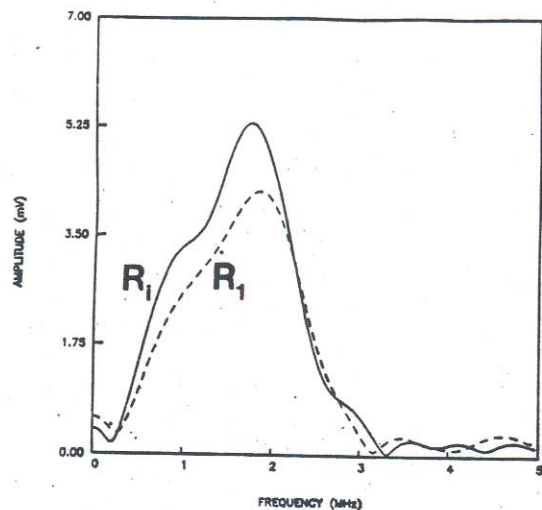

Figure 7. Plots of the spectra of the digitized data for the initial and reflected R-waves, R_I and R_1, shown in Figure 6.
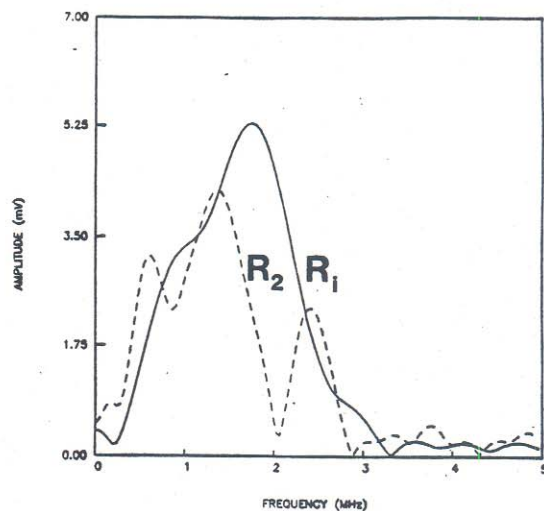

Figure 8. Plots of the spectra of the digitized data for the initial and transmitted R-waves, R_I and R_2, shown in Figure 6.