THE USE OF FIBER OPTIC INTERFEROMETRY TO SENSE ULTRASONIC WAVES

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ABSTRACT

A single monomode optical fiber is used to detect acoustic waves generated in a steel specimen by a standard piezo-electric transducer. This development has implications for the development of a sophisticated noncontacting technique for the high resolution detection of flaws in metals.

INTRODUCTION

This paper describes the construction of a Fizeau type optical fiber interferometer (OFI) that was used to sense Rayleigh waves (surface acoustic waves) in the presence of significant low-frequency ambient disturbances due to temperature variations, noise, air currents and vibrations. The use of a single mode optical fiber eliminated most of the instabilities in optical path lengths that plague ordinary interferometers.

A standard Fizeau interferometer is shown in Figure 1(a) [1]. Two collimated beams of light that can interfere with each other are generated from a single source as follows. Approximately 50% of the light from the source is transmitted through a beamsplitter. The reflected portion is wasted. The forward transmitted beam proceeds towards the "specimen". When it reaches the partial reflector some portion is reflected back toward the source. The rest of the light passes through the partial reflector and illuminates the specimen surface. The gap between the partial reflector and the specimen surface is referred to as the "Fizeau Cavity". The specimen surface is a poor reflector but some of the light scattered from this surface retraces the original path through the partial reflector back toward the source. Since the two returning beams are both coherent, they recombine but will be out of phase by some amount depending on the differences in the lengths of the two optical paths. They will therefore interfere optically and the resulting intensity pattern seen by the observer yields a contour map of constant optical path difference or equivalently, optical phase over the area covered by the cavity.

That is the good news. The bad news is that most interferometers suffer from unequal drift in the optical paths of the two beams caused by such factors as temperature and pressure variations, vibrations of optical elements, and slow object motion. These low frequency deviations mask the wanted displacements and reduce the sensitivity of the interferometer. Another problem often encountered in making interferometric measurements of engineering subjects is the difficulty in gaining access to a particular region of the specimen. The manipulation of coherent light with mirrors and prisms is inconvenient at best and often not possible when the need is to illuminate a specimen in a confined area. Both problems, drift and the need for convenient access, are greatly reduced by using monomode optical fiber probes as coherent light pipes to illuminate and receive light at the observation area. Interference is not destroyed when the beam is guided coherently via total internal reflection.

Figure 1(b) shows the basic composition of an optical fiber interferometer (OFI) designed to sense ultrasonic surface waves as they pass underneath the tip of the fiber. It is based on the Fizeau configuration. The output from a continuous wave Argon-Ion laser is split by a beam splitter. One of the beams is wasted, the other is focused into a monomode optical fiber. This light then travels down the optical fiber towards the probe is held close to the specimen surface. There is some internal reflection (Fresnel reflection) of a portion of the light from the glass to aid interface at the output end of the optical fiber back up the fiber. It serves as the reference wave. For a clean optical fiber to air interface, as used here, the Fresnel reflection is around 5% of the incident light [2]. The part of the light (approximately 95%) which is not Fresnel reflected at the specimen or active end of the optical fiber, emerges from the fiber and is scattered by the surface of the specimen. A tiny fraction of the scattered light is reflected back into the optical fiber where it joins and interferes with the internally reflected reference wave. The instantaneous intensity of the combined beams, as they propagate back through the optical fiber, depends on the phase difference between them. Upon exiting the passive end of the optical fiber, the light beam is recollimated by the focusing lens and deflected by the beam splitter so that approximately half of the returning light is available to be sensed by the photodiode. The amplitude of the output from the photodiode will change in correspondence with the changes in the Fizeau cavity. A system of this kind is relatively rugged and easy to manipulate. The only precise alignment required is where the light is launched from the laser into the optical fiber. The adjustment at the output end or sensing tip of the fiber was not nearly as critical, but it must be done with care.

EXPERIMENTAL SET-UP

In the experiment described here the sensing end of the fiber was held by a vacuum chuck mounted on a 3-axis translation stage. In order to obtain an optimum signal from the interferometer, the fiber tip was positioned approximately normal to the surface of the specimen. The alignment of the optical fiber tip with respect to the specimen is done as follows: The reflection back from the specimen is adjusted manually until it appears to be centered on the fiber tip. The stand-off distance is then adjusted with a micrometer to achieve maximum contrast in the interferometer signal. This occurs when the intensity of the internal reflection at the fiber tip is equal to the portion of the reflection from the surface of the specimen that is picked up by the fiber tip.

The intensity of the light resulting from the superposition of two interfering waves is a function of the length of the Fizeau cavity. When this length changes it causes a shift in alignment, and hence a phase difference, ϕ, between the two waves. The intensity, I, of the combined wave thus depends on the phase difference as $I=K\cos^2(\phi)$ [3].

The sensitivity of the OFI to changes in the length of the cavity is proportional to the slope of the intensity of its output. It is zero at the minimum and maximum light intensities because the slope of the intensity curve is zero at phase angles of $\phi=0,\pi,2\pi$---. The maximum sensitivity of the OFI is obtained at positions halfway between two adjacent intensity extrema ($\phi=\frac{\pi}{2}, \frac{3\pi}{2}$ --)because the slope of the intensity curve is greatest at these points. This makes the sensitivity a function of the linear phase difference or the length of the Fizeau cavity. Since the specimen beam traverses the cavity twice, the dependence of sensitivity on the stand-off distance of the fiber tip is affected by changes of Fizeau cavity length of less than one quarter of a wavelength of light and is spatially periodic. Thus measurements that rely on accurate measurement of amplitude require tight control over the initial length of the Fizeau cavity.

The most significant feature of the OFI is that the reference and object beams are aligned internally in the optical fiber. In fact, the only place where the reference and object beams are not subject to the same temperature, pressure, vibration, or velocity change is the cavity between the optical fiber tip and the specimen. In the ultrasonic tests reported here suitable signals have been obtained with cavity lengths as long as 1 cm and as short as almost 0 cm (the fiber tip was almost touching the specimen). The best stand-off distance depends on the percent of the original beam which is Fresnel reflected at the tip and the extent of scattering from the specimen surface. The strongest signals, for the test bar used here, were obtained at cavity lengths of 0.5 mm or less. The specimen did not have mirror surfaces. On the contrary; they were as machined low carbon steel surfaces.

In order to bring the two coherently interfering light beams to the photodetector, the output light from the passive end of the optical fiber is directed to a collecting lens focused into a 50μm diameter multimode fiber which has its output end connected to a photodiode. The multimode fiber can be used to bring the interfering light to the detector because at this stage only the time varying amplitude of the light is important. It is not necessary to retain coherence. The different modes that can propagate in the input fiber to the photodiode does not significantly affect the amplitude information. This was demonstrated by the observation that the signal to noise ratio (S/N) of the output from the diode improved as the power input into the passive end of the fiber increased. If the random modal noise had increased significantly the noise would have increased as the intensity of the laser light became greater because the random fluctuations of light intensity would have greater contrast.

Even though the optical fiber is a very low loss component, there are always some losses due to bending and Rayleigh scattering (scattering by particles very small compared to the wavelength of the radiation being guided down the core of the fiber). This lost radiation is scattered into the cladding and/or out of the optical fiber. Often low frequency ambient (thermal and/or mechanical) vibrations cause observable pulsations in the signal. These vibrations change the phase of the light reflected from the specimen which in turn interferes with the Fresnel reflection and modulates the light propagating back along the optical fiber. When some of the modulated light is scattered out of the optical fiber, the "glow" along the fiber itself will appear to flicker.

ULTRASONIC DETECTION

The high frequency variation in amplitude of the signal from the photodetector carries information about the nature of the R-waves as sensed by the OFI. This varying current is amplified and converted into a voltage which may be fed into an ultrasonic signal processing system. In the setup shown in Figure 1(b), the photodiode voltage is sent to a high pass amplifier (the receiver portion of the pulser receiver) followed by a stepless timing gate where part of the signal to be sent to the oscilloscope or specturm analyzer is selected. All but the optical components of this instrumentation are the same as would be used in a conventional ultrasonic experiment.

In order to obtain a reference calibration of the input signal to be detected by the OFI, a standard pitch-catch R-wave setup (Figure 2) is used. When there are no flaws between the transducers, the receiver records the undistorted ultrasonic input signal. Figure 3 shows the oscilloscope display of the input pulse detected with 80 mm between the opposing faces of the transducer wedges. The lower trace has a total displayed time base of 50μs. Taking the Rayleigh wave velocity, C_R, (in steel) to be 2.96mm/μs gives a flight time of 27μs. If subtracted from the 47μs total travel time shown in Figure 3, this gives a delay of 10μs for each transducer wedge. (This delay must be taken into account in evaluating all time-of-flight data recorded during experiments using transducer wedge excitation.) The detailed structure of the wave can be seen in the expanded trace shown on the upper half of the screen. It was recorded with a total display time of 5μs.

Figure 4 shows the time domain display of the ultrasonic signal as seen by the OFI system and set-up shown in Figure 1(b). Details of the steel test specimen is shown in Figure 5. The three waves in Figure 4 can be identified as follows. When an R-wave in the steel specimen passes underneath the sensing tip of OFI, the gap between the tip and the surface (Fizeau cavity) changes rapidly (in the MHz range) and by a very small amount (1 to 20 nm). These changes modify the phase difference between the reference and reflected wave and cause changes in light intensity at the photodiode. The first pulse (at 36 μs) in the display of Figure 4 occurs when the incident, R_i, R-wave generated by the transmitting piezoelectric transducer first passes underneath OFI on its way, from left to right, to the slot. Remembering the 10μs delay in the transducer wedge, a travel time of 26 μs is obtained for the 78 mm distance from the front of the transducer to the point where the OFI senses the wave. This yields a wave velocity, C_R, of 2.88 mm/μs, compared to the C_R = 2.96 mm/μs used for steel. Unlike other ultrasonic techniques which employ piezoelectric contact transducers, optical fiber sensing does not interfere with the ultrasonic wave. It therefore passes unaltered under OFI and proceeds toward the slot. The next two pulses (at 48μs and at 50μs) are the reflected waves returning from a narrow slot machined in the metal specimen as shown in Figure 5.

When the R-wave encounters the slot, it may be partially reflected, partially mode converted, and/or partially transmitted as described below. For the case when the detecting transducer is on the same side as the ultrasonic source, only the incident surface wave, R_i, and the R-waves reflected from corners 1 and 2 (R_1 and R_2) are detected. Figure 6 shows the sources of these reflected waves. The first reflection in Figure 4 is the R-wave reflection from corner 1 at the open end of the slot at the surface of the specimen. This wave is called R_1. The portion of the incident R-wave that is not reflected or mode converted at corner 1 travels down the slot. Some of its energy is reflected from the tip 2 as wave R_2. It then propagates back to the OFI. The R-wave speed in steel is 2.96mm/μs and the slot length is 2.8 mm. In Figure 4 the two reflections appear to be almost 2μs apart. Therefore, the total difference in path length for the signals R_1 and R2 can be estimated to be 5.88 mm. This predicts a slot length of

2.94 mm, which compares very well with the actual length of 2.8 mm.

CONCLUSIONS

This research successfully demonstrated the feasibility of using a flexible fiber optic element to detect ultrasonic waves and, through their analysis, flaws in a test sample. The ultrasound was generated with a standard R-wave piezoelectric transducer on a steel specimen. The resulting ultrasonic wave train was then detected by a optical fiber interferometer (OFI) and displayed on an oscilloscope. The resulting time-of-flight information was related to the location of a machined slot in the surface of the specimen.

REFERENCES

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(3) Dally, J.W., Riley, W.F., Experimental Stress Analysis, Second, McGraw-Hill, New York, NY, 1978, pp. 375-376.

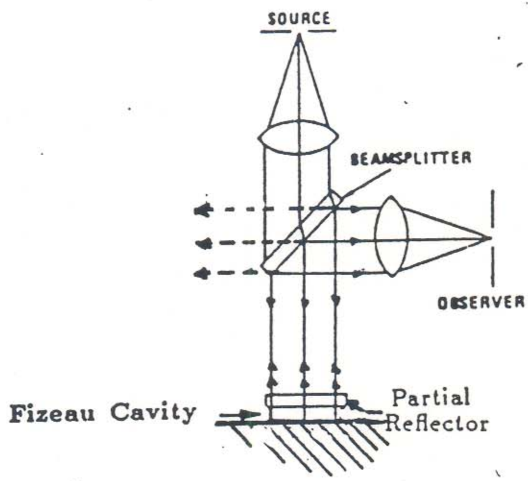

FIGURE 1(A). FIZEAU INTERFEROMETER

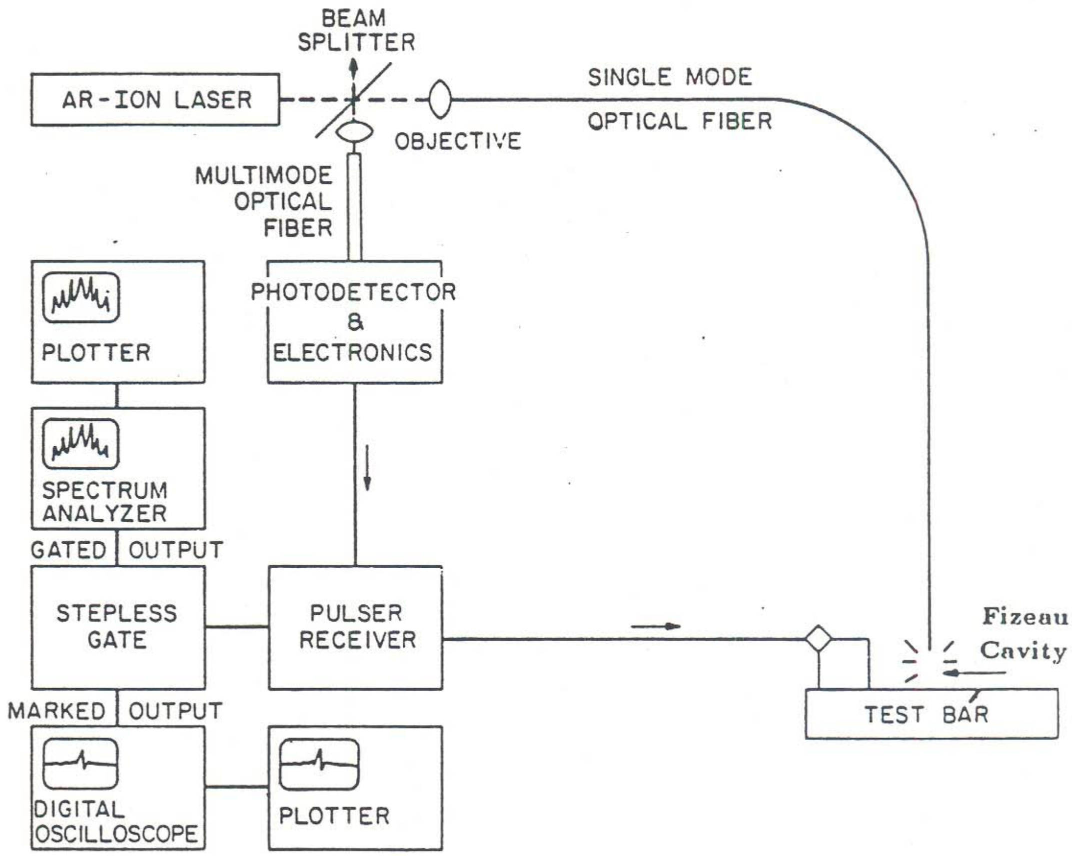

FIGURE 1 (B). FIBERTIP INTERFEROMETER

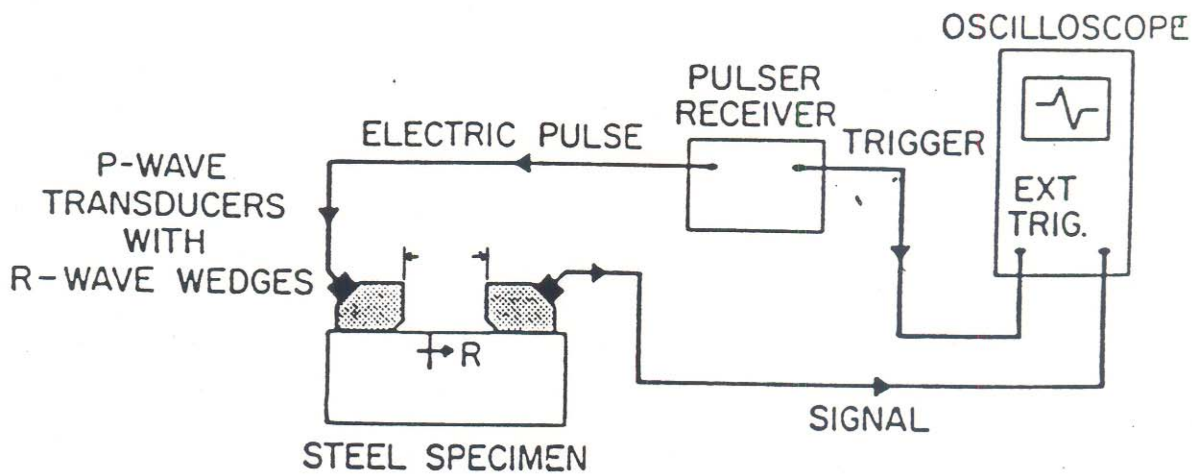

Figure 2. Ultrasonic Pitch-Catch Set-Up

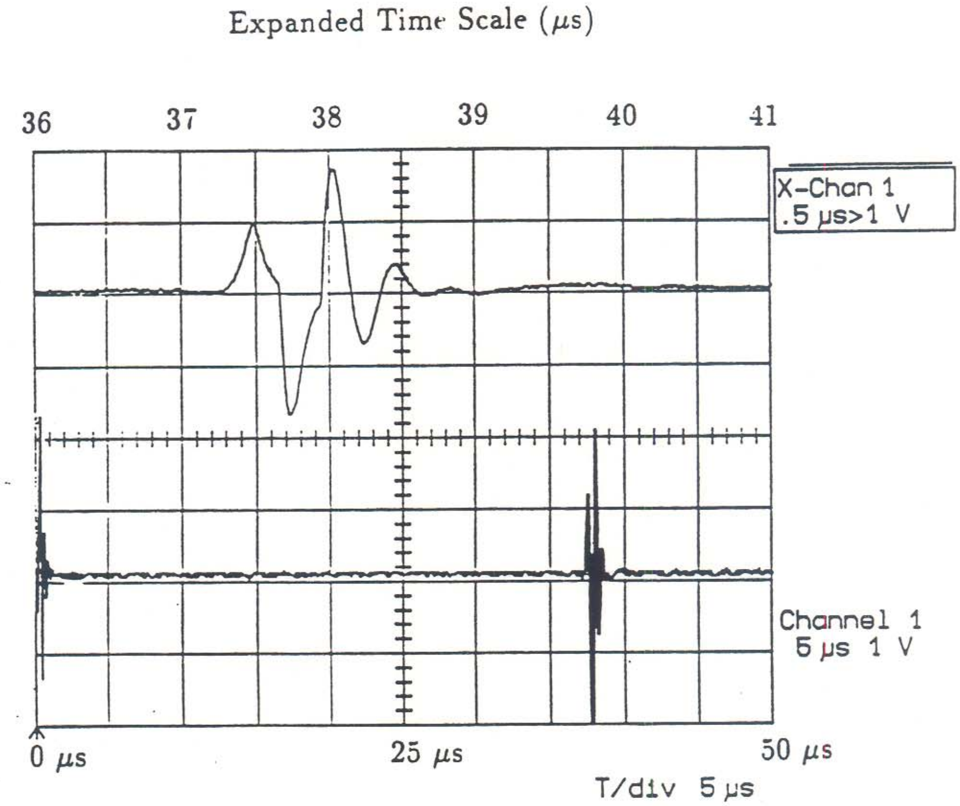

FIGURE 3. SIGNAL FROM SET-UP IN FIGURE 2

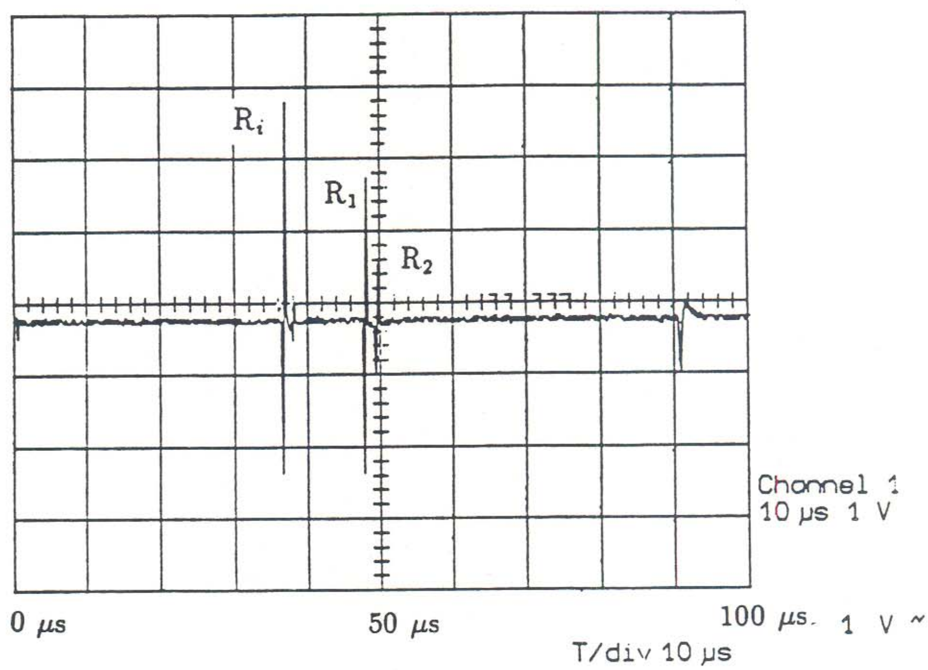

Figure 4. Signal from OFI in set-up of Figure 1(b)

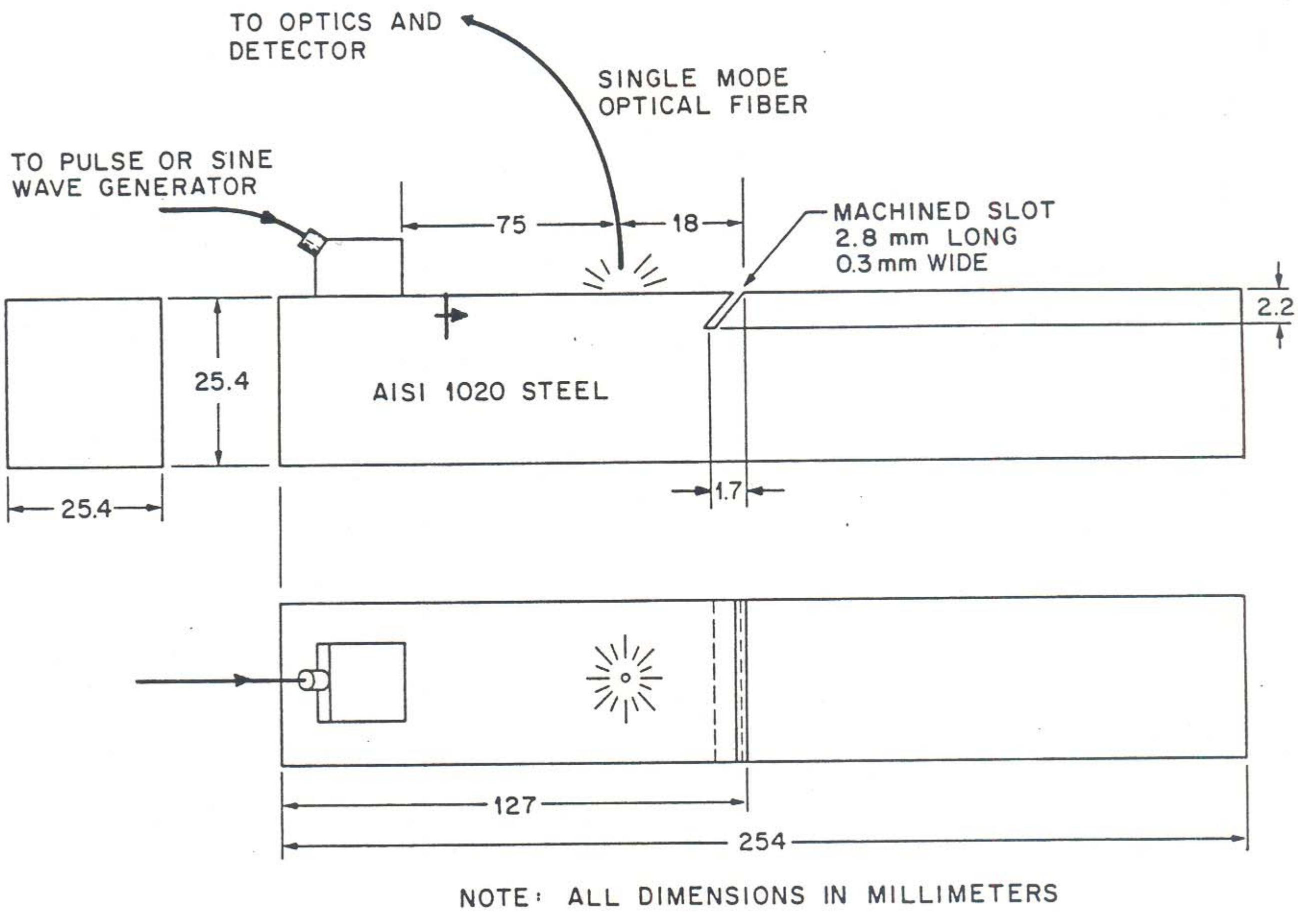

FIGURE 5. SET-UP ON STEEL BAR

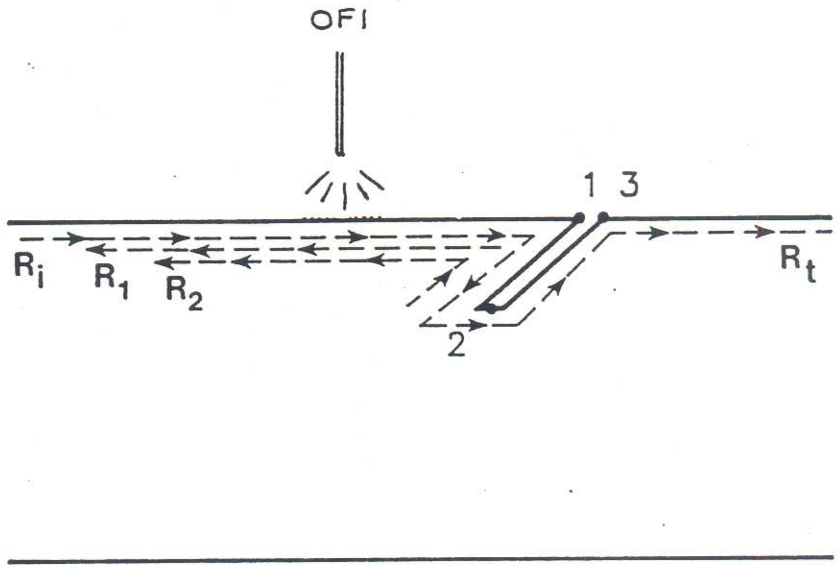

FIGURE 6. SOURCES OF WAVES SENSED BY OFI.