FIBER OPTIC SENSOR SYSTEMS FOR ULTRASONIC NDE:
STATE-OF-THE-ART AND FUTURE POTENTIAL

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ABSTRACT

This paper+ presents a review of the principles of both intrinsic and extrinsic fiber optic sensing (FOS) and fiber optic sensing systems and some of their potential applications to non-destructive evaluation (NDE), with special emphasis on current research demonstrationing the potential uses of fiber optics for ultrasonic NDE.

1.0 Introduction

As will be described, both single and multimode flexible optical fiber elements, individually or in any of a variety of arrays, provide useful tools for many NDE applications ranging from directed photo-thermal excitation to remote sensing. Optical fiber components have several important advantages. Since they are dielectric devices they are largely insensitive to electromagnetic interference. They may be readily adapted for use in harsh environments, and their dimensions and geometrical flexibility support compact, readily adaptable designs and facilitate access to remote or otherwise inaccessible locations.

1.1 Fiber Optics

All optical fibers guide light by total internal reflection. Consider the simplest example of a step-index fiber consisting of a core of refractive index, n, surrounded by a cladding of slightly (1.0% or less) smaller index, $(1 - \Delta)$. Any light ray following a path within the core which grazes the interface between the core and the cladding at a small angle, Θ, less than the critical angle $\Theta_c = (2\Delta)^{1/2}$ will be totally internally reflected and, consequently, guided along a zig zag or spiral path down the core of the fiber. Rays propagating at greater incidence angles will be partially or totally refracted out of the core into the cladding and/or beyond. At the ends of the fiber light emerging (or entering) the core refracts at an angle $n\Theta_c$ with the axis. This effectively defines the half angle of the cone of light within which all entering rays will be guided by (or exiting rays will radiate from) the optical fiber known as its numerical aperture or $NA = n(2\Delta)^{1/2}$. The NA quantifies the light gathering (or radiating) ability of an optical element. For a typical Δ of 0.01 and $n = 1.46$ the NA would be 0.206 or around 12°. Similar arguments may be applied to optical fibers made with more complex refractive index distributions (e.g. graded index) in which the light rays propagate along curved paths as they are guided along the core. More detailed discussions may be found in such classic references as Miller and Chynoweth,[1] Arnaud, [2] or Allan.[3]

Actually, not all rays which enter the core within the cone defined by the NA will be guided down the fiber. An exact wave theory (rather than simple ray model) analysis would involve geometrical parameters such as the core radius, a, its cladding thickness, t, and the light wavelength, λ, in the solution of Maxwell's equations. These eigenvalue type solutions demonstrate that only a finite number of discrete wave paths or modes will actually propagate along the optical fiber. If the number of such guided modes is large the ray description is quite reasonable. However, if a is less than $0.27\ \lambda/n\Delta^{1/2}$ only one mode (with two polarizations) will be guided.# Such a fiber is called a single or mono-mode optical fiber, and its output will be a clean Gaussian distribution comparable to that obtained by spatially filtering a laser beam. Consequently, single mode optical fibers generally make excellent flexible illuminators.

If there are two or more such guided modes the optical fiber is called multimode, and the greater the number of such modes, N, the more complex (or speckled) its output will appear. Multimode optical fibers usually guide hundreds (or even thousands) of modes through large diameter (10-200 μm) cores. Therefore, they are much easier to excite than are single mode fibers whose cores are very small (1-8 μm for operation in the visible). On the other hand, single mode fibers have much less dispersion, a feature of considerable importance in communications, but rather less so in FOS. Multimode fibers are usually used for transmitting intensity (I), modulated signals while single mode fiber are usually used for phase (ϕ) modulated signals. In FOS applications the two other optical parameters, wavelength (λ) and polarization (P) may also be modulated for measurement purposes. Either single or multimode fiber optics may be appropriate for λ dependent measurement, while special birefringent and/or polarization maintaining optical fiber may be used for P related applications.

Moreover, in addition to individual fiber optical elements, there are both coherent and incoherent optical fiber bundles. The former are of use in transmitting images and permit the acquisition of full-field rather than just "point-wise" information. Incoherent bundles are of use for the transmission of illumination intensity wherever intensity or energy is all that is required. To date most such commercially available optical fiber bundles have been of the multimode type, although efforts have been made to develop coherent single mode fiber optic bundles in an attempt to achieve some of the improved stability characteristics of single mode transmission in a flexible imaging element.

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Actually, if the core radius, a, is too small, *no* light will be guided by the fiber.

1.2 Fiber Optic Sensing

The general scheme for making measurements using FOS is to have (1) an illumination source (usually a laser or an LED) to excite the optical fiber through a suitable coupler, (2) an effective means of somehow modulating I, ϕ, P or λ in response to the desired variable to be measured (force, pressure, temperature, strain, displacement, velocity, etc.) and (3) a means of detecting and decoding the resulting modulated light wave signal. The transduction between the parameter to be measured and the light wave itself may be carried out either within the optical fiber which is, called *intrinsic* sensing, or outside the fiber, which is called *extrinsic* sensing. If the transduction is accomplished intrinsically, it may be either distributed along the optical fiber or localized at some especially prepared location or locations.

2.0. Extrinsic Sensing FOS (Point Sensors)

In NDE, displacement and its time derivatives are often among the most important parameters to be sensed. Since it is neither feasible nor appropriate to describe all the FOS systems of possible interest to those working in non-destructive evaluation in this survey, the review of a few elementary examples primarily concerned with displacement or vibration measurement will have to suffice to illustrate the basic concepts.

The most elementary way of utilizing fiber optics to sense displacement is to open (very neatly of course) an excited fiber and observe the variation in output as the "new" ends are moved relative to one another. Obviously, one end may be fastened to a moving subject and the other held fixed as a reference. Consequently, the change in coupling efficiency which occurs as the relative positions vary will indicate motion of the subject. Unfortunately, any motion; transverse, axial, or rotational, will produce an intensity variation at the output, and the lack of discrimination as to which places a significant restriction on the use of such a simple system. On the other hand, if one-dimensional motions are all that may be anticipated, when fitted with a stable source of illumination and the appropriate output photodetector and electronics, such a simple FOS system provides a highly sensitive amplitude varying device capable of responding to extremely fast events.

An alternative approach is to keep the illuminating and receiving ends of the optical fibers immobile and modulate the illumination as it transverses the space between them by means of a shutter, grating[4] or lens[5] that moves with the desired displacement. Since most of these more complicated arrangements also share the disadvantages of both (1) requiring some immobile attachment to the surface at the point of detection and (2) being unable to discriminate between different components of displacement. Consequently, they too are often impractical for use in NDE.

A practical, noncontacting alternative is the so called "fiber optic lever" FOS, in which a multimode optical fiber (or optical fiber array) is used to illuminate a reasonably reflective test surface while another adjacent multimode optical fiber (or array) is used to capture and return the reflected illumination to a photodetector. Such intensity modulated fiber optic "photonic" sensors have been available commercially for almost ten years and detailed analysis of various optical fiber arrays have been published by Cook & Ham,[6] Cuomo[7] and Hoogenboom et al.[8] In all configurations the return signal intensity first increases rapidly and then slowly tails off as the reflecting test surface moves away from the sensor, providing both high and low sensitivity modes of operation (depending on standoff) in a single instrument. Such systems have been developed with displacement sensitivities from microns to millimeters at frequencies from DC to over 100 kHz, and have been applied directly to study acoustic waves in plates[9]. Unfortunately, such intensity modulated FOS systems are strongly dependent on the optical characteristics of the test surface, and lose sensitivity as the reflected light intensity decreases due to reduced surface reflectivity.

A less intensity sensitive single mode fiber optic vibration probe has been described by Laming et al.[10] This instrument is simply a "single beam" fiber optic laser doppler velocimeter which uses a phase modulated laser diode to obtain the necessary frequency shifting. The output of the laser diode is coupled into a single mode optical fiber which enters one port of a 4-port (3db bi-directional) single mode coupler. The exit radiation from one output fiber is collimated through a rod lens onto the vibrating surface. Light scattered from the surface is recaptured by the lens and travels back along the same fiber through the coupler to a detector where it is combined with a reference signal generated by the back reflection from the fiber-to-rod-lens interface. The output is gated at the laser drive current frequency and fed into a frequency tracker set to measure the equivalent doppler shift, and consequently yields an output voltage proportional to the out-of-plane surface velocity at the point of interrogation. The system was claimed to offer a frequency response range to a modest 20 kHz and a velocity range of ± 0.2 m/s, with a greater range obtainable by increasing the laser diode modulation frequency if so desired. Since the relevant information in such tests is phase related, single mode fiber optics is used to assure satisfactory LDV performance. A similar "single beam" fiber optic LDV system for measuring surface vibration has been described by Kyuma.[11]

While for the most part these early FOS systems suffer from certain limitations of band width and/or sensitivity, Hirose and Tsuzuki[12] have more recently described a FOS system whose performance characteristics are better suited to ultrasonic NDE. This single mode interferometric system is designed to be capable of measuring both in-plane and out-of-plane vibration using both "single" and two beam configurations. The configuration for sensing in-plane vibration utilizes two lensed optical fibers illuminating the test surface with coherent light at $\pm 45°$ and one lensed optical fiber oriented normal to the test surface as a detector to produce a phase modulated signal sensitive to only the transverse component of vibration. The system configuration for sensing out-of-plane vibration uses the lensed optical fiber oriented normal to the surface as both a coherent light illuminator and a detector, and, as was done by Laming et al.,[10] combines the back reflected light from the test surface with the back reflected light from the end surface of the fiber to produce a phase modulated signal sensitive to only the out-of-plane component of vibration. This FOS system was claimed to be capable of a frequency range up to 30 MHz at sensitivities on the order of 0.001 nm in the normal direction and 0.05 nm in the transverse direction. Others who have successfully pursued the interferometric (phase measuring) optical fiber sensing approach include Bowers, Kino and their collaborators[13–15] who patented a FOS system employing two 3db bi-directional couplers configured to generate four "wave trains" from dynamic surface reflections which are phase modulated to yield a claimed sensitivity of 0.00003 nm at acoustic wave frequencies. This system is quite complicated to but has the advantage of being insensitive to both rigid body displacements and variations in surface reflectivity.

Also of interest for ultrasonic NDE applications, Monchalin and his collaborators[16] have recently demonstrated a wholly optical system being developed for industrial applications in which an ultrasonic signal generated by a pulsed Nd-YAG laser is monitored by an interferometer with a fiber optic input. In this realization, a laser excited optical fiber is used to illuminate a portion of the test surface covering the photo thermally stimulated region and a large aperture lensed optical fiber is used to capture the reflected light and return it to a (remotely situated) confocal Fabry-Perot interferometer. This system is configured to measure wall thickness and grain size. While not truly non-destructive, in that the low sensitivity of the optical detection system required strong ultrasonic displacements that could be generated photothermally only by laser excitation in the *ablation* regime, the system provides a claimed 8 MHz bandwidth, zero sensitivity to low frequency disturbances, and was designed to operated at a 1.5 meter standoff distance.

2.1. Extrinsic Sensing FOS (Full Field Sensors)

All of the preceding examples have involved the detection of displacement or vibration at a single point. However, fiber optics have also been applied successfully to such well known full-field techniques as holo-interferometry, a coherent optical technique of increasing interest and application to NDE.

Many workers have demonstrated the advantages of using flexible fiber optic illuminator for holography[17–23] and for holo-interferometry.[24–25] While most of these early efforts were concerned with minimizing the deleterious aspects of various often invasive *medical* procedures, several research groups including Jones, et al., Rowley, and the present authors were quick to demonstrate the superiority of single mode fiber optic illuminators (both object illumination and reference beams) for a variety of applications more appropriate to NDE including double-exposure,[26–30] time-average[31] and real-time holo-interferometry.[32] They also explored the use of flexible optical fiber imaging bundles to facilitate access to remote, obscured or even submerged[33] test sites while recognizing the need to provide a significant degree of mechanical support for the multimode bundles to assure the needed modal (phase) stability. Subsequently, the use of fiber optic bundles for both illumination and image transmission in pulsed laser holography was also demonstrated[34,35] and Bjelkhagen[36–37] studied the applications of optical fibers and optical fiber bundles to pulsed laser holo-interferometry. The use of such extremely short duration (20 ns) exposures somewhat reduces the need for mechanical stability and extends the range of measurement to highly dynamic, non-repetitive events.

The present authors also demonstrated the use of remotely generated ultra-low spatial frequency holographic[38] fringe fields that could be transmitted through a multimode imaging bundle more effectively as an amplitude (rather than phase) signal for remote recording, etc. To accomplish this both the object illumination and reference beams are transmitted to the site of the test subject via single mode optical fibers. This full-field holographic FOS scheme provides much greater stability, albeit at the expense of some loss of resolution - and it may be used for holo-interferometry.[39]

It should be noted that holographic interferometry, as yet without the incorporation of fiber optic elements, has been employed for the detection and evaluation of surface acoustic waves. For example, Wagner[40–42] has demonstrated the use of *full-field* heterodyne holo-interferometry for studies of events at displacement amplitudes and frequencies appropriate to ultrasonic NDE.

2.2. Intrinsic Sensing FOS

All of the preceding examples have involved extrinsic modulation of the light wave signal. However, there are numerous examples of applications of interest in experimental where the transduction is intrinsic - the signal is modulated within the fiber optic element itself. Perhaps the most obvious example of intrinsic FOS of interest in NDE is its use as a sensitive crack or failure sensor. An early elementary and, admittedly, rather destructive example was described by Simpkins & Krause[43] in which they utilized the sudden loss of light intensity transmitted through a tensile loaded optical fiber to trigger a high speed camera used in a study of the dynamic fracture response of silica fiber lightguide. In this case the optical fiber itself was the test subject, but for nondestructive FOS applications a suitable glass fiber can also be bonded to or, as described by Meltz & Dunphy,[44] and Claus, Bennett and May[45] embedded in test subjects of other more ductile materials. Because of the extremely brittle nature of glass, such optical FOS crack sensors can, if properly installed, usually be counted on to give a clear indication of local over-stressing at any point along their length by fracturing, with an attendant loss of transmitted intensity signaling the event. Optical time-domain reflectometry[46] (OTDR) may be used to identify where, along the length of a long optical fiber, a break or region of high strain has occurred by monitoring the "history" or time variation of the amplitude of the Rayleigh back-scattering from a light wave propagating along the fiber. (Kingsley[47] provides an excellent description of OTDR in the context of FOS.) Such an optical fiber crack detection system, consisting of an OTDR monitoring a suitably prepared optical fiber routed throughout a metal or even an epoxy fiber-glass composite structure, may be made to serve as a kind of optical fiber "nervous system" whose response would reveal the development of fatigue cracks long before the onset of catastrophic structural failure due to repeated dynamic loadings.

Instead of using OTDR, Murphy, Zimmerman and Claus[48] describe the development of an intrinsic sensing optical fiber differential interferometer using two single mode bi-directional couplers to separate and recombine two legs. One optical fiber leg is embedded in and passes straight through the test subject, while the other (non-embedded or stunted) optical fiber leg is external and acts as a reference given reasonable fiber and photodetector parameters. They claim minimum detectable distortions on the order of micro-micro strain across one millimeter. A different high sensitivity FOS strain gage interferometer responsive to deformation induced changes in phase has been described by Sirkis & Taylor.[49] Their approach uses a reference fiber arrayed in a circular pattern or loop and a sensing fiber arranged in a horizontally elongated "S" pattern. Each fiber is attached to the specimen and, consequently, exposed to the same strain field. However, because of the difference in their configurations, they each experience a different overall strain. Assuming the strain is effectively uniform over the area to which the fibers are applied (which, in ultrasonic application, limits detection to long acoustic wavelengths), the net change in length difference between the sensing and reference fibers will produce a phase change difference proportional to the strain component in the transverse or horizontal "S" direction. (If the strain is not uniform, the gage will, of course, yield some sort of an average strain value). An alternative approach to FOS strain detection based on cross-talk has been demonstrated by Dunphy et al.[50] This sensor uses a special optical fiber which incorporates two adjacent (but not touching) cores within a common cladding. The proximity of these two cores is such that there will be a strong cross talk interaction between them which persists throughout their length with an energy exchange due to evanescent coupling at a periodic rate. If a mechanical (strain) or thermal (temperature) change alters the geometrical or optical properties of the sensor, the phase of the crosstalk will change, varying the outputs of the two cores. If free or mounted on an unstressed carrier, the two core optical fiber would function as a measurer of temperature only. It is claimed, however, that there is an optical excitation wavelength at which the sensor will operate for which the fiber exhibits *inherent* temperature compensation such that its response will be related to strain alone.

Dunphy and Meltz[51] have also developed a birefringent single mode fiber for the measurement of plane stress waves in composites. This fiber is embedded in the material where it acts as a miniature, in situ, photoelastic probe. It is claimed that by using multiple wavelength excitation and measuring absolute and relative phase changes, it is possible to determine the principle transverse stresses at very high loading rates. Earlier they described[44] the use of embedded two core and polarization maintaining optical fibers for the measurement of residual stresses and subsurface strain in composites. Finally, Clause and his coworkers[48,52] described the successful use of OTDR to monitor the response of single core optical fiber arrays embedded in graphite-epoxy composites subjected to dynamic loadings. While most such intrinsic FOS systems are also sensitive to temperature, they can often be utilized as ultrasound sensors, provided one is willing to pay the price of embedding them in the first place.

3.0 Applications of Fiber Optics to Ultrasonic NDE

As described by Monchalin,[16,53] Calder and Wilcox[54] and probably many others, optical techniques may be used to both *detect* and *excite* acoustic waves in structural materials. However, despite the many advantages of using FOS and FOS systems, except for a recent paper by Monchalin and his collaborators[16] and the work by the present authors and their collaborators to be described subsequently, to date most published reports of such applications of optical techniques, whether combining excitation and detection or utilizing them individually, have involved discrete optics and required direct access between the laser sources and the test subject. Since such arrangements are by their very nature neither very convenient nor particularly safe, it is of interest to explore the feasibility of using flexible optical fiber components to enhance optical techniques for ultrasonic NDE.

3.1 The Generation of Ultrasound Through an Optical Fiber

All of the preceding examples have involved the use of fiber optics to make measurements of various responses induced by other sources. Never-the-less, until quite recently it remained to be demonstrated that a flexible optical fiber component could, in fact, also be used to transmit light as a source of power sufficient to directly excite acoustic waves. As reviewed elsewhere[55-58] *direct* photo-thermal excitation has been demonstrated by many researchers. However, all of these systems involved open exposure of unconfined pulses of high energy laser light. As part of an effort to develop a safer, more flexible system for optical-ultrasonic NDE, the present authors, in collaboration with researchers from Texas A & M University, recently reported[59,60] the first successful application of flexible optical fiber components to the delivery of light pulses of sufficient energy to excite detectable acoustic waves in a steel bar. This work demonstrated that both fiber optic bundles and individual optical fibers, when properly excited by a pulsed ruby laser, can be used to generate acoustic surface waves that could be readily detected by standard piezo-electric transducers. In this effort a series of tests were conducted using the configuration shown in Fig. 1 to excite the shiny, "as-machined" surface of a structural steel bar. Since the unprotected or launch end of such an optical-fiber component is highly vulnerable to being damaged by high energy densities, a specially-built high energy FOS launch device (based on the work of Bjelkhagen,[36]) was employed in an attempt to achieve a more robust coupling and reduce the severely undesirable effects of misfocusing, thereby extending service life. As shown in Fig. 2, this launch device consisted of either a plane quartz window or a plano-concave collimating lens at the input end which directed the incoming pulse onto the end of the 2 mm diameter fiber-optic bundle through a cell which could be filled with a volume of index-of-refraction-matching fluid large enough to assure that the absorbed energy from the laser pulses did not excessively heat the fluid and change its optical properties.

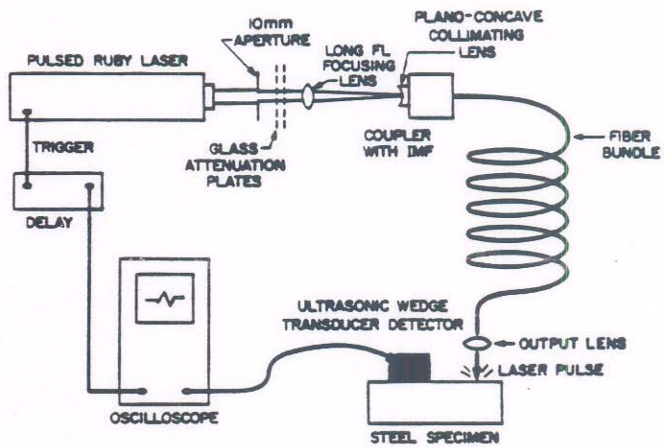

Figure 1. Schematic diagram of the system used to transmit light from the pulsed ruby laser through an optical fiber to a steel bar specimen and to detect the resulting acoustic wavefront in the specimen using a standard transducer.

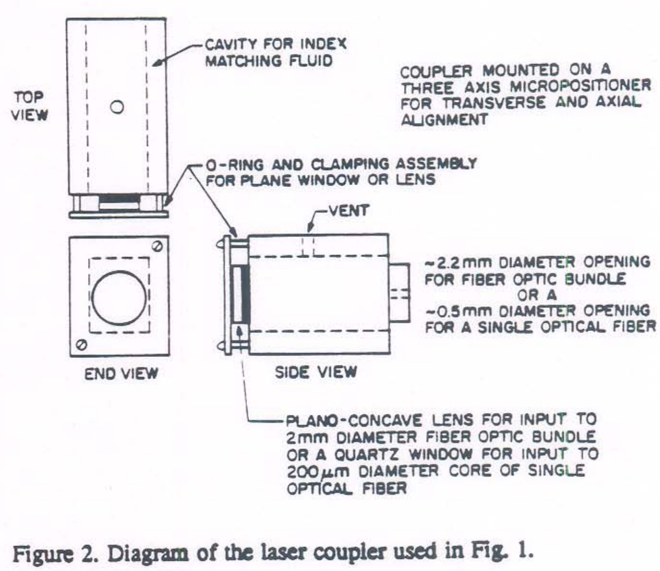

Figure 2. Diagram of the laser coupler used in Fig. 1.

In the first trials the laser pulse was launched into and guided through a 3 meter long optical fiber bundle with its output focused through an output lens onto the surface of a steel bar test specimen.

With excitation spot diameters of 1mm or less, the resulting waves were somewhat cleaner than the Rayleigh wave fronts often generated by wedge-mounted transducers. When the surface of the specimen was artificially blackened in an effort to enhance coupling energy into the metal and increase amplitude, the wave-shape became more complicated. In this case the phenomena that generate the elastic wave were no longer purely thermoelastic, but included impact from the ablation of the surface coating, with an obviously less satisfactory result in so far as the generation of Rayleigh waves is concerned.

The fundamental transmission efficiency of a fiber-optic bundle is inherently lower than that of a single low-loss optical fiber. However, these experiments demonstrated that coupling a double pulsed ruby laser output into a fiber-optic bundle with 2 mm diameter is far easier than coupling into the much smaller 200 µm core of a single multimode optical fiber. Consequently, only if the laser pulse is aligned and focused very accurately onto its core will the greater overall efficiency of a single multimode optic fiber be realized. In order to test the feasibility of using a single multimode optical fiber to transmit the laser pulses, the set-up of Fig. 2 was modified for coupling to a 0.25 mm diameter multimode optical fiber with a single 200 µm core and a numerical aperture of only 0.25. Because of the gradual spread associated with such a low NA, no output lens was required to focus the illumination from the optical fiber onto the surface of the specimen: an illuminated spot of 1 mm diameter could be achieved with a 2 mm working distance between the optical fiber tip and the specimen surface.

While it worked well with a CW alignment laser, and acceptably when launching individual ruby laser pulses into the 2 mm diameter optical fiber bundles, the existing launch device could not be aligned accurately enough to provide much more than a marginally efficient coupling of a pulse laser into the 200 µm core single multimode optical fiber.** Consequently, the single fiber system generated Rayleigh waves of much smaller amplitude than those generated in the previous tests with the 2 mm-diameter fiber-optic bundle, and the final realization of the full potential of such an approach must await the development of a superior alignment procedure and/or the incorporation of a continuously pulsed rather than a single or double pulsed laser source.

In order to confirm that Rayleigh waves generated by a laser pulse transmitted through a flexible optical-fiber bundle could be used to interrogate metal components for defects, a steel bar with a machined v-notch or "artificial flaw" was excited as described above. As expected, the transmitted wavefront (detected downstream of the "flaw") exhibited the classical double wave response associated with the interaction between a Rayleigh wave and a shallow notch.[60] Similar positive results were obtained using the single 200 µm optical fiber, albeit with significantly weaker acoustic waves.

3.2 FOS Detection of Ultrasound

Over the years many researchers have successfully demonstrated optical (usually interferometric) techniques for the detection of ultrasound,[61–67] They achieved adequate resolution using either classical or holo-interferometric techniques, but their systems are essentially laboratory/optical-bench based and of little practical use for adaptation to field applications.

Another problem often encountered in applying interferometric measurements to ultrasonic inspection involves the restrictions associated with limited specimen access. use of FOS. Steering laser light with mirrors can be difficult when trying to interrogate even a small area of specimen surface in a confined space. The use of optical fibers to illuminate the test object and to sense the small surface displacements simplifies the problem of restricted access by guiding the beam to and from almost any spot on the specimen, with the limitation that all measurements are confined to sensing displacements at one "point" rather than full-field.

On the other hand, many early FOS devices which might readily be engineered to overcome these limitations have been designed to measure small displacements encountered in quasi-static and low to intermediate frequency vibration studies.[(6–11,68–70)] While under ideal conditions the resolutions, bandwidths and sensitivities of of some of the more recently reported[12–16] FOS devices fall within the range required for ultrasonic testing, except possibly for the work of Monchalin et al.[16] and the present authors,[71–73] few if any truly ultrasonic NDE FOS applications have as yet been reported.

In the simplest case, as reported by the present authors and their collaborators,[71,72] a laser excited single monomode optical fiber may be operated as a Fizeau interferometer. As shown in Fig. 3, the unspread output from a low powered (10-20mw) CW laser is split by a variable beam splitter set to divide the output into two beams of equal intensity. While one of the beams must be wasted, the other is focused into a single mode optical fiber. This light travels down the optical fiber and a small percentage is internally (Fresnel) reflected at the output end. It then travels back through the fiber and serves as the reference wave. The remainder of the light emerges from the output end of the optical fiber and is scattered by the diffusely reflecting surface of the test subject. A small but detectable fraction of this scattered light is reflected back into the optical fiber to join and interfere with the internally reflected reference wave in its propagation back through the fiber. On exiting the optical fiber, the output is collimated by a focusing lens (the same lens used originally to launch the light into the fiber). The returning light is deflected by the beam splitter so that approximately half is passed through an aperture onto a multimode communications fiber++ connected to a fast photodetector (photodiode with custom wide band amplification electronics). Since the optical fiber is excited by coherent light, the two beams interfere destructively whenever the optical path lengths of the internally and externally reflected light beams differ by a half wavelength or odd multiple thereof. When the change in the displacement induced length of the Fizeau cavity is less than 1/4 wavelength the pure phase from the interferometer will define the displacement. If the intensities and polarizations of the internal and external reflections are reasonably equal, the intensity of the combined beams traveling back along the optical fiber will be seen to brighten and darken as the cavity length changes. A change in cavity length greater than 1/4 wavelength will shift the output signal intensity through one or more maxima and minima.

** Because of the difficulties inherent in aligning the output from a single or double pulsed laser, the existing coupling device was totally *ineffective* for coupling a double pulsed ruby laser into the 6-7 µm diameter core of a single monomode optical fiber. On the other hand, the alignment process involved in coupling the light into the 200 µm core fiber from a *continuously* pulsed Nd-YAG laser of the type employed by Monchalin et al.[16] for ultrasound generation, which would be comparable to the alignment process involved in coupling light from a high powered CW laser, should be significantly easier and energetically far more efficient, but so far has not been reported.

++ This multimode fiber is used to provide convenient coupling via its large (50 µm) core diameter. The phase preserving property of a single mode optical fiber is not required because the phase related interference is established at the detection end of the single mode sensing fiber. Therefore, only the amplitude (or intensity) of the returning light is significant.

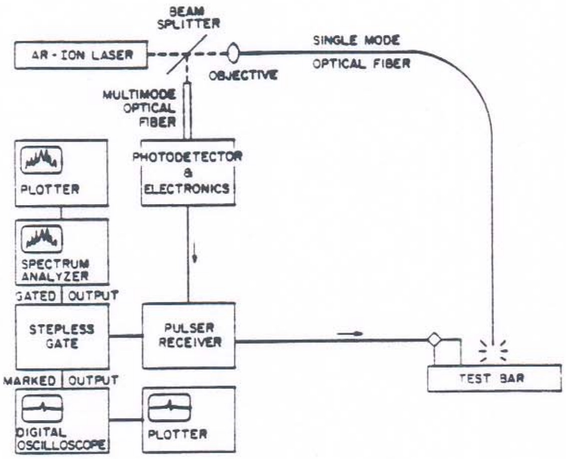

Figure 3. Schematic diagram of the test set-up for the conventional Rayleigh wave excitation and FOS detection on a steel bar test specimen using discrete optics and a single monomode optical fiber interferometer.

The intrinsic self-alignment of the reference and object beams is but one feature of this simple homodyne FOS interferometer. By virtue of its small (7.2µm) core diameter, small (0.09) NA and small (<1mm) operating standoff distance, this single mode FOS system is effectively a "point sensor" capable of resolving ultrasound at even 100 µm acoustic wavelengths. In addition, throughout most of the interferometer both beams experience the same thermal and mechanical environments - the relative phase of the two beams can change only in the Fizeau cavity.

The only critical alignments of this system are those associated with launching the light into the fiber and separating out the returning signal. In order to receive the maximum signal which occurs whenever the Fresnel and the surface reflections are equal, 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. If it were necessary to increase the intensity of the externally reflected return signal, as with a test surface of low reflectivity, a compact objective or rod lens might be added to the fiber tip to collimate the light as shown by Laming et al.,[10] Kyuma et al.,[11] and Hirose and Tsuzuki.[12] Initial tests on moderately reflective machined steel surfaces using an unlensed optical fiber interferometer of the type described above gave acceptable results with cavity lengths (or standoff distances) as long as 1 mm and as short as "none".

Figure 3 shows a schematic diagram of the entire experimental set-up, including both the optics and the electronics. Within the photodetector, the current generated by the photodiode is amplified, converted to a voltage and fed directly onto an 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 to be routed to an oscilloscope or spectrum analyzer for display and evaluation. Except for the optical fiber interferometer proper (laser, optics, and fast photodetector), most of the instrumentation used in this system was the same as would be used in a typical study employing wholly conventional ultrasonics. While it was demonstrated[71,72] that this extremely simple single optical fiber interferometer could indeed be used effectively as a point detector/sensor for ultrasonic NDE, two major difficulties were encountered: (1) separating the return signal from the much higher intensity waste illumination reflected off the input end of the fiber, and (2) coupling the return signal into the photoelectronics. Fortunately, such problems are solved quite readily by replacing the beam splitter and the single optical fiber with a 4-port (3db bi-directional) coupler.

As shown in Fig. 4, laser light, launched into one leg of the coupler, is split between the output fibers (yielding, ideally, half power in each, hence the designation 3db) so that each fiber can serve as a separate FOS interferometer if so desired. In this FOS system 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 common or shared photodiode and electronics. If the lengths of the output legs are properly matched, the returning waves from the different interferometers can also interfere with one another. However, if unwanted, this response can be avoided by trimming the output legs so that they differ in length by half the coherence length of the excitation laser (or so). Furthermore, if so desired one of these interferometers may be deactivated by immersing the output end of the optical fiber in an index matching fluid. This technique was used in order to unambiguously evaluate the internal delay inherent in a piezoelectric transducer used to excite the test specimen.

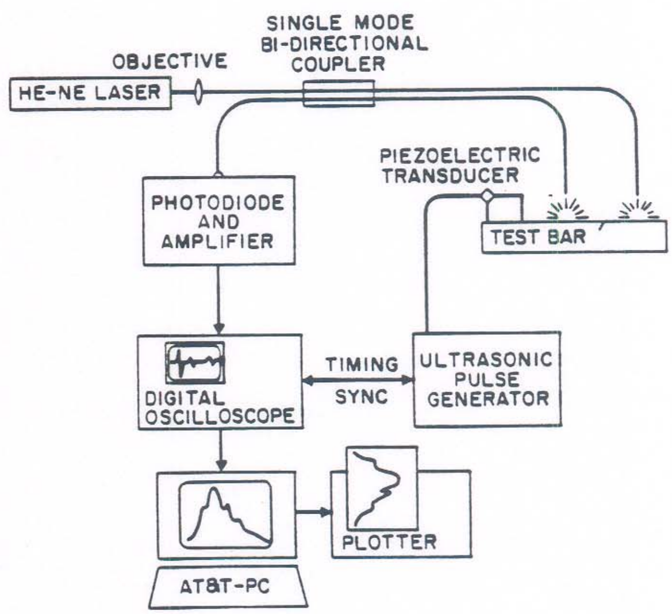

Figure 4. Schematic diagram of a test set-up for the conventional Rayleigh wave excitation and FOS detection on a steel bar test specimen using a 3db bi-directional coupler interferometer.

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

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As reported recently,[73] tests were conducted to demonstrate FOS ultrasonic detection using a 3db bi-directional coupler interferometer, Fig. 4, by positioning its output legs on either side of a machined "flaw" (a slanted slot 0.3 mm wide by 2.8 mm long and 2.2 mm deep) cut in the surface of an ultrasocially excited steel specimen as shown in Fig. 5. As with the single fiber interferometer, the output fiber tips were mounted on separate 2-axis translation stages to allow them to be moved independently relative to the specimen surface, and the Fizeau cavities were individually adjusted so that the corresponding FOS signal could be recorded with maximum sensitivity on the digital oscilloscope.

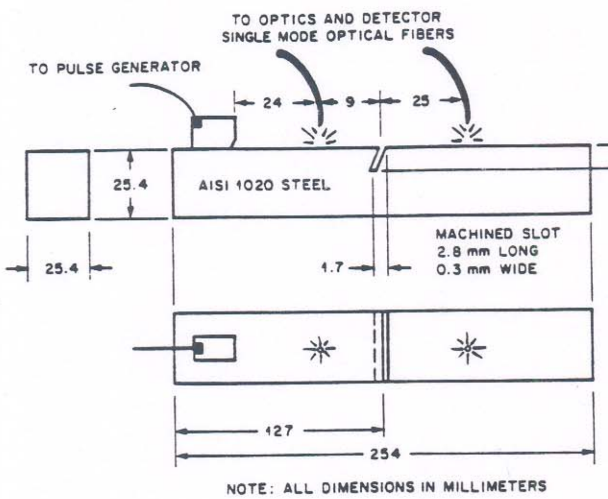

Figure 5. Diagram of the steel bar test specimen with a machined, inclined slot as a simulated "flaw".

3.3 FOS Ultrasonic NDE Data Analysis

Figure 6 shows a characteristic time-domain plot obtained directly from the digital oscilloscope in which the initial response to the Rayleigh wave excitation, R_i, is observed as a peak at approximately 18 µs. The 8 µs arrival time, obtained by subtracting 10 µs from the time trace to account for the known delay in the excitation transducer, corresponds to a distance of approximately 24 mm (using an Rayleigh wave velocity in steel of 2.96 mm/µs); the actual distance between the point of excitation and the location of the first optical fiber tip. The second peak, R_1, which appears at approximately 24 µs, represents the response measured by the first optical fiber tip as the Rayleigh wave is reflected from the flaw. The 6 µs delay between the initial response peak and the reflected peak corresponds to the round trip distance of 18 mm between the optical fiber tip and the flaw. A third peak, R_2, was recorded by the second leg of the 3db bi-directional coupler 22 µs after the transducer was excited. This delay corresponds to a path length of approximately 65 mm. Since the second optical fiber tip was located 58 mm from the transducer, the difference of 7 mm might be attributed primarily to the added time required for the Rayleigh wave to travel around the flaw. In fact, the flaw has a length of 2.8 mm and a width of 0.3 mm for a total path length (down, across and back up again) of 5.9 mm, which is at least in the right "ball park". The remaining signals are probably caused by secondary reflections or regeneration of the acoustic waves.

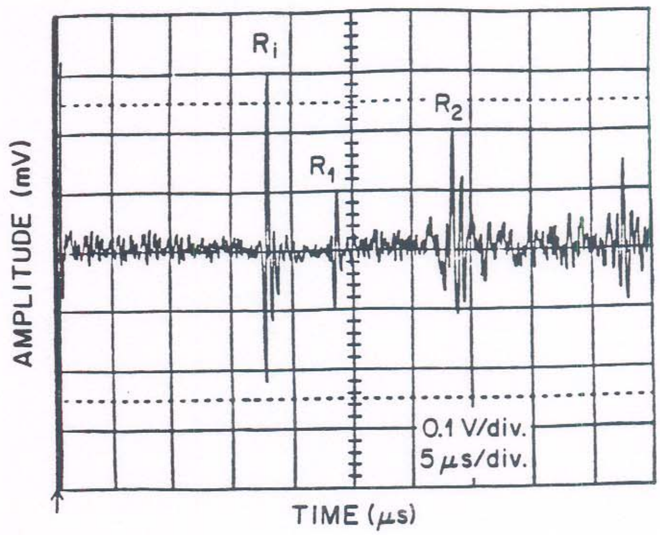

Figure 6. Time-domain plot of the system response showing the initial (R_i), the reflected (R_1) and the transmitted (R_2) Rayleigh waves in a steel bar test specimen as detected by a 3db bi-directional coupler FOS configured as shown in Fig. 4.

Clearly, a time-of-flight analysis of such time-domain data is more effective as a means of identifying and precisely locating a (machined) "flaw" than as a means of accurately measuring its length. In order to supplement the time-of-flight time-domain analysis of the digitized FOS data trace, it is both desirable and appropriate to carry out a frequency domain analysis. However, in the FOS system shown in Fig. 4, instead of using the stepless gate and spectrum analyzer, the entire digitized oscilloscope trace is transferred to a PC through a serial port and stored 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. The PC based FFT analysis of the complete data trace, which included all three peaks, exhibited many strong components at frequencies well above the cut-off frequency (around 5MHz) of the detector electronics - an indication of the need to filter the data prior to any further analysis, spectrum or otherwise. (The FFT analysis was accomplished using a fast Fourier software package provided by ikayex Software Tools and called Spectral Analysis Toolkit 1. This analysis can be performed on the PC interactively or in a batch mode.) Subsequently, a 5-point averaging was performed and the entire data set retransformed to yield a much cleaner spectrum. However, since it represents the spectrum for all three waves taken together, such an analysis is of little use for evaluating the "flaw". In order to achieve a "separation of the wavefronts" equivalent to the function conventionally performed by the stepless gate, the smoothed data file was then displayed on the screen, Fig. 7, so that the three Rayleigh waves could be windowed (gated) in the PC. This was done by using a Hanning window to individually extract the first three peaks and write each to a separate data file. All data files were made of equal size by padding them with zeros so that the same parameters can be used to expedite the FFT analysis. For comparison, frequency domain results are shown in Fig. 8 for the initial and the reflected Rayleigh waves, R_i and R_1, and in Fig. 9 for the initial and transmitted Rayleigh waves, R_i and R_2. The primary features differentiating the frequency spectra of the reflected and transmitted waves from the spectrum of the initial Rayleigh wave may be correlated with the dimensions and features of the flaw, with the advantage that the spectral analysis is performed on the same data used for the optic time-domain analysis.

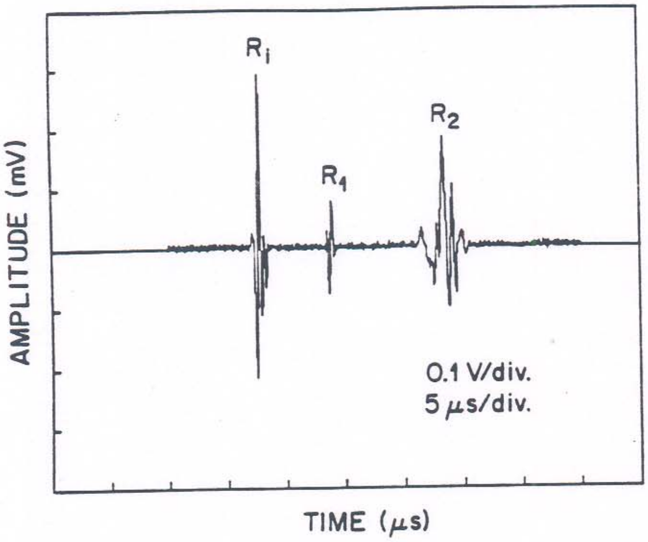

Figure 7. The same time-domain data shown in Fig. 6 after filtering to eliminate high frequency noise.

Given experience, understanding and a certain amount of skill, it should be possible to determine important aspects of the "flaw's" geometry for a rational comparison of the dominant features of these varied spectra. For example, by comparing the spectra of the initial and the transmitted waves, there appear to be significant losses of energy around 1.4MHz and its first harmonic, 2.8MHz. This 1.4MHz frequency happens to correspond to an acoustic wavelength in steel of 2.1mm, which is remarkably close to the actual slot depth and might be attributed to the absorption of some of the initial energy by this artificial flaw. At this point however, a more precise interpretation of this, or any of the other features of these spectra would be highly speculative. However, a comparison of each of these spectra reveals a significant difference in their overall amplitudes, the reflected wave falling much lower then the others. Because of this, it is not especially useful to make direct comparisons of even local differences, and some deconvolution must be performed to improved discrimination in the transform plane.

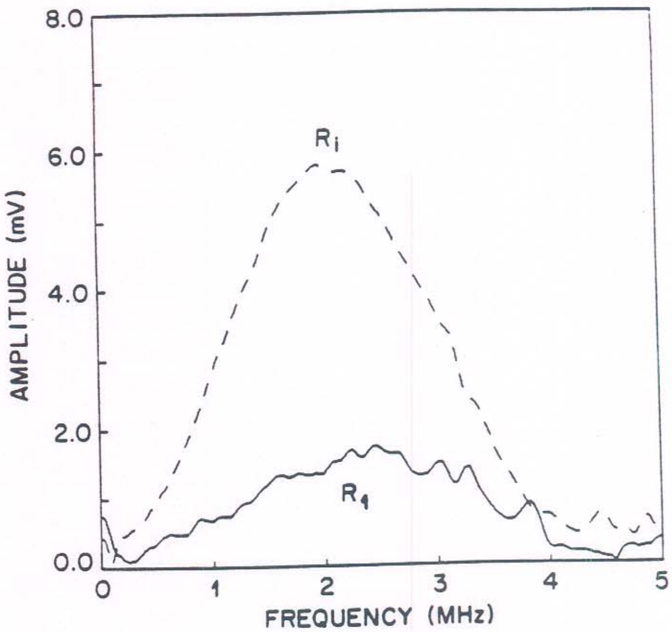

Figure 8. Frequency-domain plots of the spectra of the digitized FOS data for the initial and reflected Rayleigh waves, R_i and R_1, shown in Fig. 7.

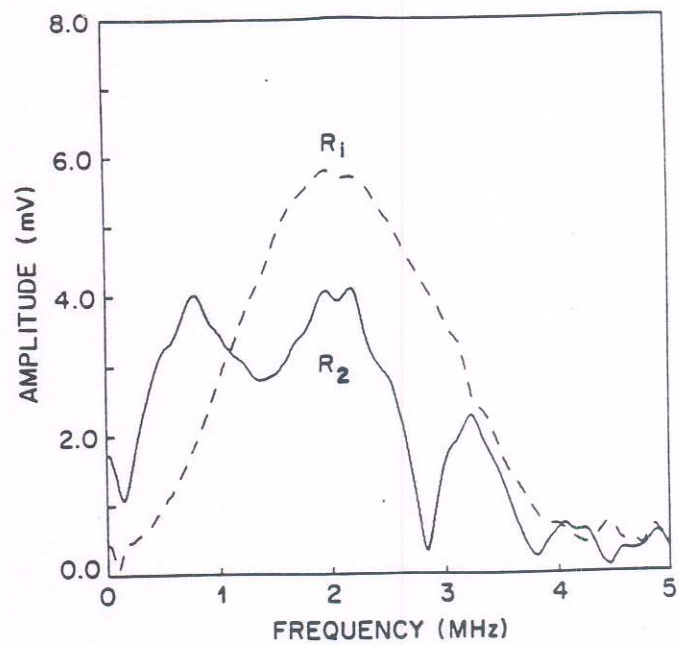

Figure 9. Frequency domain plots of the spectra of the digitized FOS data for the initial and transmitted Rayleigh waves, R_i, and R_2, shown in Fig. 7.

4.0 Summary and Future Developments

This paper has reviewed the principles of both intrinsic and extrinsic fiber optic sensing (FOS) systems and some of their applications to NDE, with special emphasis on current research demonstrating applications fiber optics to ultrasonic NDE.

Clearly, the uses of FOS techniques for making measurements of interest in NDE are many and varied, and the present summary has merely illuminated a small portion of this subject. In addition to being noncontacting (no energy absorbing mass need be attached to the test surface at the point of measurement), extrinsic fiber optic sensing and excitation techniques offer much greater flexibility, versatility, and resolution than can be obtained with the more conventional transducers currently used as sensors for nondestructive evaluation (NDE), whether by ultrasound or otherwise.

Considering the many advantages of FOS and FOS systems for measurement, it is apparent that, as a supply of inexpensive, reliable "hardware" (cabled and shielded individual optical fibers and optical fiber bundles, optical couplers, photoelectronic detector arrays, etc.) becomes more readily available, the realization of many of these new (now largely potential) applications will become routine testing activities.

At this time, FOS systems for both the detection and the generation of ultrasound have been demonstrated, and it is only a matter of time before the first, wholly fiber optic system for ultrasonic NDE will be demonstrated. Furthermore, it is reasonable to expect that, if refined to incorporate solid state lasers, FOS ultrasonics will soon provide the NDE community with a wide variety of new, extremely powerful systems for the evaluation of many types of critical structures whose complexity and/or inaccessibility make them difficult or impossible to inspect by other means.

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