Applications of Fiber Optics in Experimental Mechanics†

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ABSTRACT

Fiber optics provide a powerful new tool for use in experimental mechanics. Applications range from excitation to illumination to detection to information transmission. Interesting examples include applications in holo-interferometry, laser speckle photography, laser doppler velocimetry, photoelastic spectral analysis and numerous other experimental techniques in which fiber optics may be used to manipulate light. In addition, fiber optics are finding uses in a wide variety of strain, pressure, crack, temperature, displacement and motion sensing transducers. This presentation will review the special characteristics of various types of optical fibers that fit them to these non-communications related roles. A few applications will be described in detail and many others mentioned briefly in order to illustrate the numerous advantages to be realized from the use of fiber optics in experimental mechanics.

1. INTRODUCTION

While most of the stimulus for the rapid development and extensive deployment of optical fiber technology seen in recent years has come from the communications industry, significant applications are now being realized in other areas, many of which are directly relevant to experimental mechanics. 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 experimental mechanics applications ranging from direct 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, $n(1-\Delta)$. 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 $\theta_C \approx (2\Delta)^{1/2}$ 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 (assuming a square cut end). 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;

$$NA \cong n(2\Delta)^{1/2}$$

The NA numerically quantifies the light gathering (or radiating) ability of an optical element. For a typical Δ of 0.01 and $n = 1.46$ (characteristic of fused silica) the NA would be 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 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, $N = 2\Delta(2\pi na/\lambda)^2$, is large the ray description is quite reasonable. However, if $a < 0.27\ \lambda/n\Delta^{1/2}$ only one mode (with two polarizations) will be guided. Such a fiber is called a mono- or singlemode optical fiber, and its output (assuming λ is in the visible, of course) will be a clean Gaussian distribution quite like that obtained by spatially

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filtering a (TEM_{00} mode) CW laser beam. Consequently, singlemode optical fibers generally make excellent 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 (20-200 μm) cores. Therefore, they are much easier to excite than are singlemode fibers whose cores are very small (1-8 μm for operation in the visible). On the other hand, singlemode fibers have much less dispersion. Multimode fibers are usually used for transmitting intensity, I, modulated signals while singlemode fiber are usually used for phase, ϕ, modulated signals. 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 pointwise information. Incoherent bundles are of use for the transmission of intensity wherever illumination intensity is all that is required. To date all such commercially available optical fiber bundles have been of the multimode type, although efforts are underway to develop coherent singlemode fiber optic bundles in order to gain the improved stability characteristics of singlemode transmission in a flexible imaging element.

1.2 Fiber Optic Sensing

The general scheme for making measurements using fiber optics is to have an illumination source (usually a laser or an LED) to excite the optical fiber through a suitable coupler, 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 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, called intrinsic sensing, or outside the optical fiber, 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. EXAMPLES

The rapid growth of interest in the use of optical fiber for measurements has, in recent years, generated literally hundreds, if not thousands of ideas, models, devices and systems. There is now a journal devoted exclusively to fiber optic sensors, and various companies are endeavoring to commercialize fiber optic gyroscopes, sophisticated medical instruments, sensors and the like. Since it is not feasible to describe, in any sort of detail, all the applications of possible interest to those working in experimental mechanics in this summary, the review of a few illustrative examples primarily concerned with displacement or vibration measurement will have to suffice.

2.1 Extrinsic Sensing

Perhaps the simplest 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. Clearly, 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 indication 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, such a simple fiber optic 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 traverses the space between them by means of a grating[4] or shutter that moves with the desired displacement. One sophisticated variation on this approach is described by Dotsch[5] et al. in which they used a ball lens located between an illuminating fiber and two adjacent receiving fibers positioned such that transverse displacement of the ball lens varies the balance of intensity captured by the two receiving fibers. In this configuration the logarithm of the ratio of the output intensities is a linear function of the displacement of the ball and independent of fluctuations in the illuminator intensity.

An even more sophisticated approach is the two wavelength, moving shutter, fiber optic displacement sensor described by Petrie et al.[6] In this multimode system successive pulses of light at two differing wavelengths, λ_1 and λ_2, are alternately propagated down the illumination fiber to the measuring location. Here they illuminate a shutter that consists of symmetrical adjacent filters, one which blocks illumination of wavelength λ_2 but not λ_1, and the other which blocks illumination of wavelength λ_2 but not λ_1. In this system the alternating λ_1 and λ_2 pulses which couple into the output fiber vary such that their output intensity difference, $I_1 - I_2$, divided by their intensity sum, $I_1 + I_2$, is a linear function of the transverse shutter displacement over a range which depends on the beam diameter and the size of the shutter. A realization of this system optimized for railroad applications was claimed to have a noise limited displacement resolution of 0.5 μm over a 4 mm displacement range and a DC to 3.5 kHz frequency range.

Yet another alternative is the so called "fiber optic lever" approach, in which a multimode optical fiber (or optical fiber array) is used to illuminate a reasonably reflecting test surface and another adjacent multimode optical fiber (or array) is used to detect the reflected illumination. Such a fiber optic "photonic sensor" has been marketed commercially for a number of years and detailed analysis of various optical fiber arrays have been published by Cook & Ham,[7] Cuomo[8] and Hoogenboom et al.[9] In all array 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[10] or used in transducers such as hydrophones[11] or gas flow meters[12] where the sensed displacement of a diaphragm or leaf spring is uniquely related to the parameter to be measured. Unfortunately, such intensity based systems are very 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 singlemode fiber optic vibration probe has been described by Laming et al.[13] 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 singlemode optical fiber which enters one port of a 4-port singlemode 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 was 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 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, singlemode 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,[14] and Menon[15] recently described a compact, two beam submersible singlemode fiber optic LDV probe fluid flow measurement.

Hirose and Tsuzuki[16] have described a singlemode optical fiber sensing system for measuring both inplane and out-of-plane vibration using both "single" and two beam configurations. The system configuration for sensing inplane 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.,[13] 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 fiber optic 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. Finally, Boiarski[17] described a simple reticle image velocimeter (RIV) which uses an LED as a source, optical fibers for illumination and detection and an imaged reticle to generate a fringe pattern for the measurement of flows in a transparent, seeded fluid or velocities on a moving, diffusely reflecting surface.

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, speckle metrology and moire interferometry.

Many workers have demonstrated the advantages of using flexible fiber optic illuminators for holography[18–22] and holo-interferometry.[23–24] Gilbert et al. and others have also demonstrated the superiority of singlemode fiber optic illuminators for a variety of applications including double-exposure,[25–29] time-average[31] and concomitant or real-time holo-interferometry (both object illumination and reference beams). They also explored the use of flexible optical fiber imaging bundles to facilitate access to remote or obscured test sites (e.g. submerged, Reference 32) while recognizing the need to provide a significant degree of mechanical immobility to the multimode bundles to assure the needed modal (phase) stability. Dudderar & Gilbert[22] also demonstrated the use of fiber optic bundles for both illumination and image transmission in pulsed laser holography, and Bjelkhagen[33–34] has studied 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.

Dudderar, Gilbert and their coworkers also evaluated the use of singlemode optical fibers as stable illuminators for objective speckle metrology,[35,36] and the use of multimode image bundles for transmitting stable intensity fields associated with both objective[35,36] and non-coherent or "white light"[37,38] speckle metrology. They also demonstrated the use of remotely generated ultra-low frequency holographic[39,40] fringe fields that could be transmitted through a multimode imaging bundle more effectively as an amplitude (rather than phase) signal for remote recording and reconstruction. To accomplish this both the object illumination and reference beams are transmitted to the site of the test subject via singlemode optical fibers. This scheme provides much greater stability, albeit at the expense of a manageable loss of resolution.

More recently, Johnson et al.[41] have demonstrated the use of singlemode optical fiber illuminators for moire interferometry as a means of simplifying the optical setup. Finally, Redner,[42,43] who has been studying techniques of photoelastic measurement by computer-assisted spectral content analysis, has offered a variety of applications of multimode optic fiber components to provide both illumination and detection links for intensity modulated signal components at various wavelengths.

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.

2.2 Intrinsic Sensing

Perhaps the most obvious example of intrinsic fiber optic sensing of interest in experimental mechanics is its use as a sensitive crack or failure detector. An elementary example was described by Simpkins & Krause[44] 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 suitable glass fiber can also be bonded to or, as demonstrated by Meltz & Dunphy,[45] embedded in test subjects of other more ductile materials. Because of the extremely brittle nature of glass, such optical fiber crack detectors 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. A technique known as optical time domain reflectometry[46] or 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 backscattering from a light wave propagating along the fiber. (Kingsley[47] provides an excellent description of OTDR in the context of fiber optic sensing.) 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 fiberglass 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.

A refinement of this approach uses the so-called "microbending" phenomena to reveal displacements along the fiber. As studied by Gloge,[48] Miller[49] and discussed by many others,[1–3] whenever an optical fiber is bent, even a little, some of the higher guided modes will "leak" out into the cladding, effectively altering the intensity of the signal to be recovered from the core. While this microbending loss may be small, its effects are accumulative along the fiber. Moreover, as shown by Fields et al.[50] and Lagakos et al.,[51] a simple mechanical devise such as a pair of sharply toothed plates as a may be used as a "deformer" to greatly increase local microbending losses. Asawa & Yao and their collaborators[52–54] have studied the functionality of such an approach for application to pressure and bending sensors. Their work demonstrated that if the modes propagating in the cladding are effectively removed or "stripped" from the fiber, most of the subsequent destabilizing cladding to core modal interactions which usually occur along the fiber can be eliminated. They too discuss the use of OTDR to monitor the core output, sometimes referred to as the "light-field" output. Lagakos et al.[55] employed "light field" microbend fiber optic sensing in the design of a wide band hydrophone.

Davis[56] also describes the operation of a "dark field" microbending system using optical fiber "taps" to monitor the intensity of the light propagating in the cladding after each of a succession of mode stripper/deformer pairs. Such assemblies may be positioned as needed along a single excited multimode fiber in order to monitor bending strains at many discrete locations. An alternative "dark field" microbending system was described by Krigh et al.[57] in which the light was coupled out of the fiber through an index matching fluid into a *transparent* deformer and from there into a detector or output fiber. This effectively combines the deformer, mode stripper, and light tap into one element, and is claimed to provide a high sensitivity (1×10^{-11}m/$\sqrt{Hz}$) and efficiency (~80% capture). In their experimental models the transparent deformers were made of epoxy or polycarbonate with sharp "teeth" which were themselves deformed by the glass fiber. The use of a stiffer deformer made of glass of the same or higher refractive index than the primary fiber coating would be expected to provide even better sensitivity.

Microbending effects might also be enhanced by redesign of the fiber itself. An optical fiber is more than just core and cladding. In order to protect the brittle glass from mechanical damage a protective plastic coating is applied during manufacture. Consequently, a conventionally designed and applied coating will act to shield the glass fiber from mechanical action and effectively reduce the local microbending induced by the deformer. On a other hand, the coating might designed to enhance microbending, e.g. if it were seeded with an appropriate distribution of sharp, hard particles. These would dig into the fiber whenever it was squeezed, bent or stretched, thereby directly generating significantly greater than normal mode losses. Such a specially coated optical fiber would represent a distributed (rather than local) sensor, but the distribution of activity along the fiber could readily be evaluated by OTDR.

Local or distributed microbending sensors using multimode optical fiber can be applied to a variety of devices where bending or stretching may be related to the desired parameter to be measured. For example, a bi-metallic deformer on a short length of specially coated or even uncoated multimode optical fiber would make a simple but sensitive temperature sensor. Finally, Belkerdid et al.[58] demonstrated a fluid level detector that uses a multiple reverse bend "vertical" optical fiber whose cladding modes are ejected into the fluid. This produces an incrementally stepped loss of output intensity with increasing depth of submersion.

While the preceding examples have involved amplitude modulation within multimode optical fibers, a high sensitivity singlemode fiber optic strain gage sensor using changes in phase has been described by Sirkis & Taylor.[59] Their approach uses two fibers: a reference fiber arrayed in a circular pattern and a sensing fiber arranged in a horizontally elongated "S" pattern. Each fiber is exposed to the same strain field, but, because of the difference in their configurations, each experiences a different overall strain. Assuming the strain is effectively uniform over the area to which the fibers are applied, 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 averaged strain value).

An alternative approach to fiber optic strain detection based on cross-talk has been demonstrated by Dunphy et al.[60] 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, I_1 and I_2. An elementary contrast function, $\frac{I_1 - I_2}{I_1 + I_2}$, may be calibrated to provide either strain or temperature measurements. If free or mounted on an unstressed carrier, the two core optical fiber would function as a measure of temperature only. On the other hand, there is an 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[61] have also developed a birefringent singlemode 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. They also demonstrate[45] the use of embedded two core and polarization maintaining optical fibers for the measurement of resideral stresses and subsurface strain in composites. Finally, Clause et al.[62] describe the successful use of OTDR to monitor the response of single core optical fiber arrays embedded in graphite-epoxy composites subjected to dynamic loadings.

3. A Final (Exciting) Example

All of the preceding examples have involved the use of fiber optics to make measurements of various responses induced by other sources. However, not only can optical fiber be used to transmit light for illumination and information gathering, it can also transmit light as a source of power sufficient to directly activate mechanical phenomena. Specifically, Burger et al.[63] have demonstrated the use of flexible optical fiber components to deliver pulses of light from a ruby laser of sufficient energy to excite detectable acoustic waves in a steel bar. They used both fiber optic bundles and 200 μm core individual optical fibers to successfully generate clean Rayleigh waves that could be readily detected by standard piezo-electric transducers. This approach has potential applications in ultrasonic testing.

4. SUMMARY & CONCLUSIONS

As discussed, the uses of fiber optics for making measurements of interest in experimental mechanics are many and varied, and the present summary has merely illuminated the surface of this subject. In addition to those described, there are evanescent coupling based liquid level sensors, doped coating chemical species sensors, Sagnac interferometer rotation sensors and so on and on[‡] – far too many to cover in this summary and not all equally applicable to experimental mechanics. However most fiber optic applications are still very new, and for all the activity the number of commercially systems presently available is quite small. In fact, most non-communication fiber applications are unique examples developed to meet a specific need or simply explore an idea. Yet, considering the many advantages of fiber optics 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 laboratory activities. Moreover, the eventual commercial realization of fiber optic sensing and measuring systems, exploiting many of the same principles discussed above, will play a wide role in the monitoring and control of everything from medicine to mass transportation to automated production to robotics.

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‡ For those interested, illustrative overviews of fiber optic sensing have been published by Davis,[64,65] DePaula and Moore,[66] Berthold,[67] Kingsley[47] and probably many others. Also a Directory of Fiber Optic Suppliers, aimed primarily at the communications industry, has recently been published by Kessler Marketing.[68]

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