Chapter 1

Introduction

1.1 Introduction

Recently, fiber optic sensors (FOSs) receive considerable research efforts due to their high sensitivity, detection speed and abilities to be used in harsh environments. Other main merits in favor of the use of FOSs in sensing applications are compact, low cost fabrication process and compatibility with other optical components. Intensity-based FOSs are the earliest and the most widely used sensors to date because of their low cost, easy installation and high sensitivity. Optical multimode plastic fiber is typically used as a probe for intensity-based fiber sensors. They have many advantages, such as better signal coupling, larger core radii, able to receive maximum reflected light from target, and higher numerical aperture. Plastic optical fibers (POFs) are also capable of providing larger dynamic range of sensing and this allows for more accurate displacement measurements. Based on the merits of the multimode fiber, it seems to be perfectly suitable for optical sensor application. Hence, in this work, various fiber optic displacement sensors (FODSs) are proposed based on intensity modulation technique in conjunction with the plastic multi-mode fiber. The applications of the FODS are also described in this thesis.

In this chapter, the background and recent progress on FODSs will be discussed and presented. Recent development of the applications of the FODS will also be discussed. An overview on the thesis content is given at the end of this chapter.

1.2 Aim of this work

Fiber optic displacement sensors are widely employed for the measurement of displacement, strain, pressure, vibration, temperature and liquid refractive index etc., primarily due to their compactness, light weight, high sensitivity and immunity to hostile environments. FODSs inherit two primary advantages; which include ultra-accurate and non-contact sensing and flexibility in incorporating the optical sensors into compact and composite structures [1]. However, some demerits remain to be the challenges in the development of the displacement sensor. For instance, the random changes in the transitivity of optical path and variations of output power of the optical source depend on the light modulation principle which could directly affect the accuracy of the sensor [2]. Thus, the main goals of this work are to design and calibration new FODSs with high performance and to extend the application areas of the FODS as well as to improve the sensor performances. In this work, various configurations of FODSs using different sensor probes, and reflective targets are proposed. For the sensor probe, the sensor performance investigated for using a coupler and bundled fiber with various designs such as different core radial ratios, asymmetrical arrangement and different inclination angles. The experiments are also carried out for both flat and concave type of reflective mirrors. The FODSs are used for many new applications such as surface roughness, liquid refractive index and glucose concentrations measurement, liquid level, and vibration.

1.3 Recent development of FODSs based on plastic optical fiber

Conventionally, the FODSs can be classified into interferometry-based and intensity-based sensors. For interferometry-based FODSs [3, 4], two optical waves with different optical paths are combined to generate interference fringes; one optical wave, the measurement wave, is modulated by the displacement to be measured and the other optical wave, the reference wave, is not. The change in the displacement, therefore, alters the optical path difference between the two waves resulting in a shift in the interference fringe pattern. As a result, the displacement change can be deduced from the measured fringe shift with ultra-high precision. However, this technique requires complicated instruments and is bandwidth limited. In comparison, an intensity-based FODS is simple to construct, uses less expensive components, and can achieve very high bandwidth. The intensity modulation optical fiber sensors generally employ the mechanisms of misalignment losses in multimode optical fibers, absorption or scattering light losses. The amount of light collected by the bundle fiber is directly correlated to the displacement between the fiber and the reflective surface [5-20].

In the design of FODS system based on the intensity modulation, generally, many components can influence the performance of FODS. Common to the FODS system, the performance strongly depends on the environmental interference (noise) and on the relative position between the optical fiber bundle and reflective surface. However, the reflectivity of the surface also plays an important role. Thus, in order to achieve high sensitivity and large linear sensing range, it is important to select an appropriate light source, sensor probe and a target reflector. Attention should be given to the selection, the cost, the operational wavelength, the output power, as well as the stability as reported in many literatures [14, 58, 74].

In general, a pair of fiber, which is bundled together, one being the transmitting fiber and the other receiving fiber, is used as a sensor probe in a conventional FODS system. A general configuration of conventional FODS system based on intensity modulation technique is shown in Fig.1.

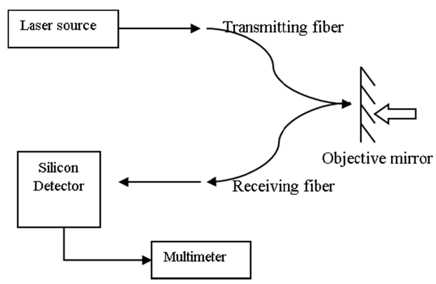

Fig.1.1: A general configuration of conventional FODS system.

Theoretical analysis of the conventional sensor, which employs two different methods are fully described by Faria in ref [5], namely geometrical and Gaussian Beam approaches. For the former approach, the simple assumption is made that the light intensity is constant within the reflected light circle. On the other hand, the light intensity outside the reflected light circle is null. This approach is apparently less accurate compared to the second approach. Gaussian Beam approach is a more realistic and more accurate method. In the approach of Gaussian beam, the power collected by receiving fiber in normalized form is given by $P_N = \frac{8}{\zeta^2}\exp\left(1 - \frac{8}{\zeta^2}\right)$ and its sensitivity is $S = \frac{4}{\zeta}\left(\frac{8}{\zeta^2} - 1\right)P_N(\zeta)$, where $\zeta = \frac{z}{z_a}$, z is the measurement displacement, $z_a = \frac{\omega_a}{\tan\theta_a}$, and $\theta_a = \sin^{-1}(NA)$, ω_a is the core radius of transmitting fiber and receiving fiber, NA is the numerical aperture of transmitting fiber. Thus, from these analyses the performance of this conventional FODS is strongly dependent on the parameter NA and core radius of transmitting fiber. On the other hand, the sensor performance is expected to improve if the light intensity collected by the receiving fiber increases. In another work, the performance of FODS is investigated based on the different types of receiving fibers [6]. This work is expanded by [7] to introduce 5 models and propose an experimental setup using two receiving fibers and two detectors to increase the intensity of the receiving light. As such, to meet these requirements, various parameters in design of FODS can be manipulated and optimized. Other literatures [8-11] have reported that the performances of FODS can be improved by using different fiber bundle structures and different inclination angles. The different arrangements of sensor probe in the fiber bundle, different transfer function and sensitivities can be achieved in the FODS and this provides greater expandability and flexibility in the design of FODS [12]. Thus, the relationship between the blind region and peak position of the transfer function to the inclination angle and gap spacing between the transmitting core and receiving core have been intensively investigated and reported in many literatures [13-16].

Another important issue for the reflective type fiber sensor is the selection of target, since the sensitivity of FODS is strongly affected by the reflectivity of target. Hence, in many earlier works [17-28], many approaches have been proposed to overcome this issue such as by using a compensation method to reduce the effect of light intensity variation. The compensation method is also widely used in designs of FODSs which can be based on the ratio of read-powers from two groups of receiving fibers [18-23] or on the ratio of the differential signal to the sum of signal of two collected powers [17, 24]. Furthermore, some alternative designs have been proposed in other works [29-30] such as by using a lens to replace the conventional flat mirror as the reflector. In our work, the possibility to use a concave mirror in FODS will be explored.

1.4 Progress in applications of FODSs

The reflective intensity modulation technique is the simplest method to achieve high precision and low cost sensing operation. This type of fiber sensor is heavily employed in various sensing areas, including measurement of displacement as well as the sensing of surface roughness [31], liquid refractive index, vibration, pressure [32], and temperature [33], etc. This is attributed to its inherited advantages such as, among others, non-contact sensing, simple structure, small size, and immunity to electromagnetic interference, etc. The sensing principle for applications mentioned above is discussed in the following sections.

1.4.1 The sensing of surface roughness

In the measurement of a product surface roughness, a popular approach is to use a three dimensional coordinate measuring machine with a rigid trigger probe. This configuration is good enough to provide high accuracy and speed in the measurement of a single discrete point of a surface. However, in industrial applications, it fails as a result of time consuming large area measurement shrivel in measurement of internal surface, as well as difficult to detect the surface inclination at the measurement point. Thus, a technology in this field is desired in the achievement of non-contact measurement to conquest these issues. Because of the technology in the non-contact sensing have the advantages in the high measurement speed, elimination of vibration, and mass point measurement. Thus, many researchers have proposed the non-contact sensing techniques by using image capturing and processing methods, whereby the accuracy is poor and the applicability is limited [34, 35]. By using free space optical technology, the sensor can provide a very good accuracy but limited dynamic range and versatility [36]. Fiber-optic based surface roughness sensors are normally based on the principle of reflective intensity modulation [37-44] due to the advantages explained earlier. However, there are still many issues and demerits (as compared to interferometry approach [45]) that need to be addressed such as light losses due to optical coupling, micro bending, and variation in reflectivity. Thus, it is critical to improve the design of the sensor system to overcome these disadvantages and make these types of sensors more practical options. In this thesis, a new surface roughness sensor is proposed using a FODS.

1.4.2 The liquid refractive index sensor

The fiber optic Liquid Refractive Index Sensor (LRIS) is vital to the design of optical instruments and also plays a major role in chemical applications. Due to the advantages of immunity to electromagnetic interference, inertness to explosive environment, high sensitivity and long distance remote measurement capability, the fiber optic LRIS has received a great deal of attentions in recent years for applications in chemical, food, beverage, medical analysis and monitor operations. In the development of fiber optic LRISs, LRIS based on intensity modulation is one of the most popular sensors owing to its many merits, like lower cost, intrinsic safety and ease-of-installation. In general, simple aliphatic alcohol in particular methanol, ethanol, 1-propanol, 2-propanol, etc., are mainly used as fuels in direct liquid fluid feed fuel cells and play a significant role as solvent in medical, biological and chemical industries [46, 48]. Due to the manifold applications of these aliphatic alcohols, different types of sensor have been developed in order to monitor the concentration of these alcohol solutions.

In this thesis, FODSs are demonstrated using an intensity modulation in conjunction with the multimode plastic fiber. In a standard FODS, the gap between a probe and reflector is filled with air. If a different media is filled between thisgap, a different sensing output characteristic can be observed as reported in many literatures [46-55]. This output characteristic can be used to interpret and measure the liquid refractive index. For instance, Chaudhari and Shaligram [48] proposed a LRIS using two fibers as sensor probe without any compensation technique. Theoretical analysis on FODS and LRIS using an inclined probe are reported by Kleizal and Verkelis [50]. Most recently, Govindan et al. [51] measured the refractive index of liquids by using fiber optic displacement sensors with two fibers bundled parallel as sensor probe. In all these devices, a small fraction of light reflected back into the receiving fiber due to Fresnel reflection is observed when the probe tip is immersed in the sample liquid. As such, these designs exhibit two common demerits, including, having an upper refractive index measurement limit and are useless for many industry applications involving corrosive substances such as acid solvent sensing. Hence, an optical fiber refractometer with compensation technique was proposed in [52] to address this issue and to minimize the effect of light source power variation, mirror reflectivity, transmitting medium opacity and bending loss.

The development of glucose sensors with high sensitivity, fast response, good reproducibility and long term stability has been the focus of researchers during the last three decades. Up to now, over 40 kinds of commercial blood glucose meters based on enzyme and electrochemical reaction were developed [56]. In real-life situation, glucose level measurement using these methods possess several demerits such as impairing responses, unpredictable drift of signal in vivo, skin incursion and inaccuracies, which restrict their widespread use in diabetes diagnosis [57]. Much effort is devoted to the development of new and improved glucose sensors that will continuously monitor physiological levels of glucose in blood over an extended period of time. Thus, new approach based on optical fluorescence sensing is being studied to overcome these demerits. An interesting direction is the development of optical needle-type enzyme sensor for rapid and simple determination of glucose level in fish blood [58]. However, this sensor has two demerits, which are poor reproducibility when the sensor is applied in different ways, and unstable response when the sample (i.e. fish) is removed [59]. Thus, an optical glucose sensor with accurate measurement and with good selectivity, low detection limit, ease-of-use, good reproducibility and stability is highly desired.

1.4.3 Liquid level sensing

In the monitoring of liquid level, many technologies are coming into play. It can be realized based on principles such as capacitive, hydrostatic, radiometric, ectro-mechanical, and optical measurements. In these technologies, fiber based Liquid Level Sensors (LLS) are preferred since they inherit many merits such as non-conductive, anti-erosion, and immune to electromagnetic interference. Generally, according to the measurement range most of fiber optic LLSs are sorted into point sensing [60-70] and continuous monitoring [71-80]. LLS in both cases can be contact [60-74] or non-contact in nature [74-80].

Most of contact sensing is based on total internal reflection of light, thus, its responses change with the refractive index of the measured liquids. In these cases, the sensing elements need to be submerged inside the liquid for detection. The first fiber optic LLS based on the variants of refractive indices of the liquids around the tip of the sensitive element was investigated by Spenner et al. [60]. Most recently, a LLS based on the use of reflective intensity at the end face of a glass fiber connected to fiber Bragg grating is proposed by Sohn [70]. However, a common problem of these sensors is the change in the effective shape of the tip when immersed in a liquid. Thus, to avoid this issue a LLS employs a fiber Bragg grating embedded inside the cantilever beam that connects to a float for indication of level changes together with temperature compensation technique is used [77]. However, this device is limited in its cost, surrounding environments, and sensitivities. Hence, an intensity modulation based LLS with low cost, and non-contact continuous monitoring is carried out.

1.4.4 Vibration measurement

Regardless of working principles, the technologies employed in the sensing of vibration can be subdivided into two categories: physical contact and non-contact. Generally, contact sensing, such as, micro-electromechanical system based strain gauges and piezoelectric accelerometers [81] emerge as very popular and cheap sensing elements, but they can only be used for bulky vibrating objects with relatively larger size to minimize their influence on the measurement. Other disadvantages of contact sensors include difficulty to reach vibrating objects in narrow spaces. On the other hand, vibration sensing employing optical techniques can overcome these limitations, which allows the development of high precision non-contact sensors. In the development of optical technologies, many optical methods have been proposed in literatures since they provide an excellent platform to develop non-contact sensors. In interferometry techniques, a laser signal beam is directed onto a moving target and the back-reflected light is recombined with part of the incident light by using different schemes such as Michelson or Mach-Zhender interferometer [81]. Interferometers are characterized by a very high performance but are also very expensive and impose stringent mechanical requirements because of their low tolerance to mis-alignment. On the other hand, laser vibrometers were also proposed using Doppler effect [82] to measure the frequency of a vibration, the amplitude is then recovered by integration with velocity. This method may not be accurate enough for measurement of very small displacements as well as expensive. Hence, optical fiber reflective intensity modulation technique has gain popularity to be applied in the design of non-contact sensing of vibration [83-90], due to its low cost, high sensitivity, etc. However, this technique is prone to measurement uncertainty caused by fluctuation in reflected power from the vibrating surface being measured. Thus, the authors of [83] have proposed a compensation method to reduce this influence by using several receiving fibers, but it requires a proper calibration of the sensor. Most recently, Perrone and Vallan [84] proposed a low cost fiber optic vibration sensor by employing a Fast Fourier Transform algorithm to extract the spectral component amplitudes. They declared the proposed sensor achieved the compensation for the target reflectivity and offsets and gains in the measurement chain.

1.5 Thesis layout

The work done is presented in six chapters. An overview of this thesis including the background of FODSs and its applications are reviewedin chapter 1. The background of plastic optic fiber, fiber optic sensors and the development of fiber optic displacement sensor are described in chapter 2. Chapter 3 proposes and demonstrates various new FODS systems using a flat target as reflector. The characteristics of these sensors are theoretically analyzed and experimentally investigated. In chapter 4, a concave mirror is proposed as a target reflector to place the flat target for various FODS. The performance of these sensors is studied theoretically and investigated experimentally. Four different applications of FODS are described in chapter 5, including, the sensing of surface roughness, liquid refractive index and glucose concentrations, liquid level, as well as, vibration. All studies and experimental results are concluded in chapter 6. Suggestions for future work on FODS are also proposed.

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