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Role of Fiber Arrangements in Operation of a Double-fiber Opto-mechanical System

[1]E. Entezari and [2]H. Golnabi
[1]Department of Physics, Islamic Azad University, Tehran North Branch, Iran
[2]Institute of Water and Energy, Sharif University of Technology, Tehran, Iran

Abstract: Determination of the surface structure using the light reflection is an important issue. The aim is to study such surface reflections using an opto-mechanical system. The effects of the fiber arrangements in the operation of an opto-pair probe system for surface profiling are described. The opto-mechanical testing system consists of a double-fiber optical probe design and an electro-mechanical scanning system. Reflection signals for the plane and cylindrical surfaces made with different curvatures and materials are investigated with both probes and the results are compared. The reflection signal for the plane surface is independent of the double-fiber orientation in probe but for the curves surfaces the reflection signal depends on the fiber direction with respect to the axial symmetry of the object surface under study. The reported system provides a simple and accurate means for the object shape study by obtaining the reflection data from the horizontal and vertical arrangements. Even though it is possible to rotate the object by 90 degree to obtain such information but in practice for real big objects it is much easier to change the fiber arrangements instead of object rotation. The novelty of the reported system is the fact that provides a great potential to analyze the curved surfaces with a one-dimensional scanning arrangement.

Key words: Surface structure, intensity change, shape study, reflection signal, reflection sensing

INTRODUCTION

A variety of optical systems, scanners and sensor designs have been reported in recent studies for different applications (Babchenko and Maryles, 2007; Baptista *et al*., 2006; Donlagic and Cibula, 2005). In most of the mentioned experiments the optical fiber plays an important role in the system performance (Ruan *et al*., 2000; Yang *et al*., 2010). For scanning operation in a recent study a fast linear scanning method for a new laser scanner is reported by Xiang *et al*. (2010). Some of the successful optical fiber designs are reported by Golnabi *et al*. (2007) and Golnabi and Azimi (2007) which are based on the intensity modulation technique using fibers as the transmitting wave-guide. Many advantages of the plastic optical fibers such as the ease of operation, cost factor and precise performance requirements have led to the application of the plastic double-fiber design in different sensing schemes (Grattan and Sun, 2000). Recently surface profiling using an optical design for the small objects is reported by Golnabi (2010).

Dynamic range limitation on the system reported before motivated us to introduce the new opto-mechanical design for surface profiling of larger objects which is more suitable for the real field applications. Considering such limitations, a new opto-mechanical design is introduced which again operates based on the intensity modulation of the reflected light from a surface and it can be used for a variety of applications (Golnabi, 2011). However, as mentioned in that study it is important to investigate the role of the fiber arrangement in operation of such a system. For this purpose a similar scanning system is used to investigate the role of the fiber arrangement in the reflection response curves of the object surfaces under study. A small double-fiber optical probe in either horizontal or vertical arrangement is used for the experiment. The details of the tested probes and the related performance results are compared in this report.

MATERIALS AND METHODS

Development of the reported method and experimental work are accomplished for the period of 2009-2011 in the Institute of Water and Energy of the Sharif University of Technology. The experimental arrangement used in this research is shown in Fig. 1. It consists of a light source, a double-fiber assembly, a mechanical translational stage, a stepping motor and a stepper motor driver interface for surface scanning. A light photodetector, a digital multimeter and a PC for signal monitoring are used. As can be seen in Fig. 1, the optical part consists of the light source a double-fiber

Corresponding Author: Hossein Golnabi, Institute of Water and Energy, Sharif University of Technology, Tehran, Iran
Tel: +98 21 66164126 Fax: +98 21 66005118

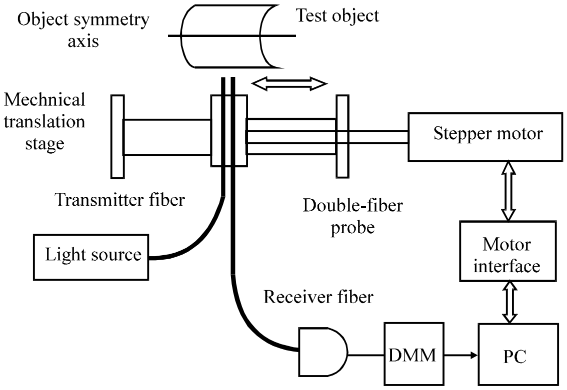

Fig. 1: Block diagram of the experiment. It includes a light source, a double-fiber, a photodetector, a digital voltmeter and a PC

assembly and a light photodetector. A double-fiber design is used in this set up in which in one end; two fibers are separated and they are attached to each other at the other end.

The attached double-fiber end as is mounted in a fixed holder in line with the surface under study. The fiber tip holder is fixed on a double-rail mechanical stage that can be scanned in one direction by using a stepper motor. The dynamic range of the electro-mechanical scanning system is about 60 cm and offers an accuracy of better than 1 mm. A 200 step rev^{-1} stepping motor is used in this design which offers a scanning speed of about 1.96 mm sec^{-1}. In addition, it is possible to vary the scanning speed for the range of 0.58 to 1.96 mm sec^{-1}. MATLAB functions are used to control the stepper motor with the PC and two electro-mechanical micro switches are used for start/stop functions.

The light source used here is a white LED operating at a supply voltage of 5 V. The Plastic Optical Fibers (POFs) as described by Haus (2010) and Senior (1992) can operate successfully at visible wavelength range and thus are used in this experiment. Two plastic optical fibers formed a double-fiber which are used in this experiment. The orientation of the fibers in a double-fiber design is shown in Fig. 2. Figure 2a shows the horizontal design in which the two similar plastic fibers placed side-by-side in the horizontal plane. In Fig. 2b, the vertical design is shown where the two similar plastic fibers are placed side-by-side in the vertical plane. Each fiber has a total diameter of 2.2 mm, core plus cladding diameter of 1 mm and the core diameter of 0.860 mm with a length of 60 cm. More experimental details about the double-fiber sensor designs and optical fiber imaging can be found by Asadpour and Golnabi (2008), Asadpour and Golnabi (2010), Haghighatzadeh *et al.* (2009) and Jafari and Golnabi (2008).

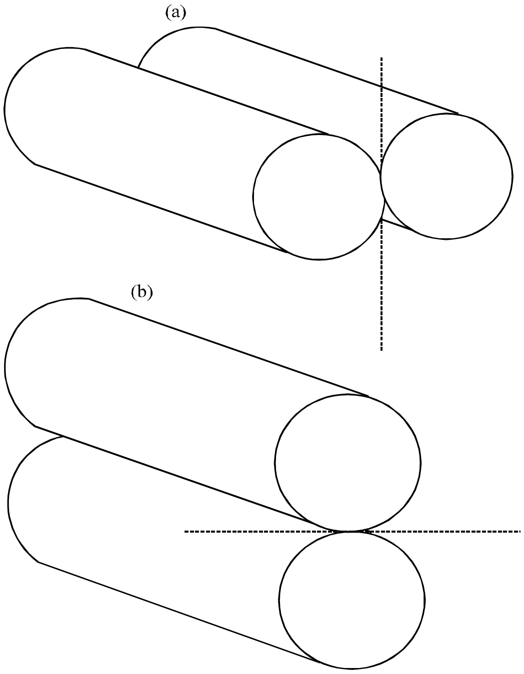

Fig. 2 (a-b): Arrangement for the fibers in the double-fiber probes. (a) Horizontal and (b) Vertical

A silicon photodiode is used for light detection and conversion of optical signal to an electric one and is reversed biased to 18 V and operates in the photoconductive mode. The electric output signal of this detector is connected to a digital voltmeter by a coaxial cable. A digital multimeter (SANWA, PC 5000 DMM) is used for the output voltage reading and data processing (±0.1 mV precision).

Operation of the double fiber probe used here is based on the intensity modulation of the light reflected off the surface of an object. The reflection concept of light from a surface based on the geometrical and wave optics can be explained. The image of the transmitted light on the receiving fiber entrance plane (image plane) is considered for analysis. In general three cases can be recognized. First, when there is no crossing between the two light cones (dead area). In this situation detector does not receive any specular/diffusion radiation. Second, when there is a crossing between the two cones (circles) of the beams, then crossing area can change from zero to a maximum value of transmitter fiber core area. Third, when the circle is totally inside the spot light or image circle, then the amount of beam crossing is always a constant but intensity of the received light in this area is decreased by increasing the distance of the moving target plane. For a similar double-fiber such as the one used here the core radius for two fibers are equal. The reflected power from the target plane to be received by the receiver fiber is obtained by the relation. Details of the overlap cross section determination are given in other references (Golnabi and Azimi, 2008; Jafari and Golnabi, 2010).

EXPERIMENTAL RESULTS

All the experiments for a given light source for different metallic and nonmetallic object surfaces are performed at the same fiber illumination power. First experiment describes the reflection signals for a convex cylindrical surface made from Aluminum (Al). Considers a cylindrical Al object with a radius of curvature of about 15 mm. The reflection voltage signals as a function of scanning distance are shown in Fig. 3 for the case of fibers horizontal and vertical in the double-fiber design. The reflected light signals are shown for the range of 5-55 mm and as can be seen, for the horizontal arrangement related signal starts from a voltage level of about 10 mV at 5-15 mm distance and reaches to a maximum value of about 32 mV at scanning distance of 28 mm and from that point on decreases. The voltage signal drops to about 10 mV at the scanning distance of about 55 mm. In this case the response curve also shows a Gaussian distribution with a base distance of approximately 28 mm.

On the other hand, as can be seen in Fig. 3, the reflected signal for the vertical arrangement starts from a voltage level of about 10 mV at 5-10 mm scan distance and reaches to a maximum value of about 23 mV at scanning distance of 28 mm and from that point on decreases. The voltage signal drops to about 10 mV at the scanning distance of about 45 mm. In general the response curve shows a Gaussian distribution with a base distance of approximately 34 mm. Comparing the results for the horizontal and vertical cases reveals two important points. First, the maximum of the peak in response curve for the vertical case is higher (32 mV) than that of the horizontal case (23 mV). Second, the base line for the vertical case is 34 mm while base width for the horizontal case is 28 mm. As a result for the cylindrical surface with the symmetry axis in the vertical position the vertical arrangement gives a higher maximum with a wider bandwidth Gaussian response curve.

In the second experiment, the reflection signals for a convex part of a cylindrical stainless steel flange are described. Consider a flange object with a radius of curvature of about 80 mm and two holes at the end parts.

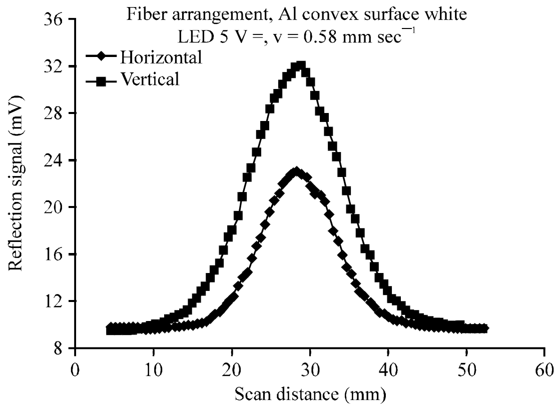

Fig. 3: Reflection signals from the Al cylindrical surface for the vertical and horizontal arrangements

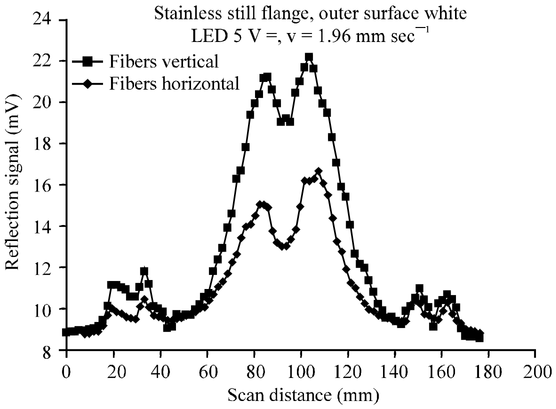

Fig. 4: Reflection signals from the flange convex surface for the vertical and horizontal arrangements

The reflection voltage signals as a function of scanning distance are shown in Fig. 4 for the case of fibers horizontal and vertical in the double-fiber design. The reflected light signals are shown for the range of 0-180 mm. For the horizontal arrangement related signal starts from a voltage level of about 9 mV at 10 mm distance and reaches to a maximum value of about 10.5 mV at scanning distance of 20 mm and from that point on decreases to about 9 mV at san distance 30 mm corresponding to the reflection from the hole. Signal starts to increase at 50 mm at a voltage level of about 9.5 mV and shows the second maximum in the response curve. From scan distance of 50-140 mm the reflected curve is from the outer part of the flange and the two maximums are observed in the center portion of the response curve. The reflected signals from 140-180 mm are because of the reflection from the second hole in the far end part of the flange.

Comparing the results for the horizontal and vertical cases reveals three important points. First, the response curves for the horizontal and vertical cases are very similar in general shape. The central portion of the reflection curve due to the cylindrical part of the flange shows the Gaussian distribution. Second, the maximum of the peak in the main response curve for the vertical case is higher (22 mV) than that of the horizontal case (16.8 mV). Third, the base line bandwidth for the vertical case is 89 mm while for the horizontal case is 79 mm. As a result for the cylindrical surface with the symmetry axis in the vertical position the vertical arrangement gives a higher maximum with a wider bandwidth Gaussian curve as is noted in the results shown in Fig. 4.

In the next investigation a comparison of the reflection signals for the horizontal and vertical fiber arrangements are described for the blue plastic bottle cap. The bottle cap has a sinusoidal grove arrangement with a spatial period of 4.5 mm and a depth of 2 mm. Figure 5 shows the reflection response curves in which the overall behavior of the curve corresponds to the cylindrical convex surface of the plastic bottle cap. As can be seen such response curves start from a scan distance of 10-80 mm for two cases. The sinusoidal oscillations in the top of this base curve are resulted as a result of the periodic fine grooved structure. Each maximum in the response curve shows the reflection from the top of the groove surface while each minimum indicates the reflected light signal from the bottom part of the grooves. There is a good correlation between the number of the maximums and minimums in the response curve and the number of the grooves on the scanned bottle cap sample. As can be seen, there is a good agreement between the response curves for the vertical and horizontal fiber arrangements (61 mm vertical and 56 mm horizontal base bandwidth). However, a careful look at Fig. 5 indicates that the vertical arrangement gives a higher reflection signal (10.8 mV) in comparison with the horizontal fiber arrangement (10.6 mV). Such feature is notable for the reflection curve resulted from the cylindrical base surface and also for the sinusoidal undulation due to the grooved structures on the surface.

In many industrial plants bottle liquid filling is used in the manufacturing production lines and thus inspection of such process is an important function. In the next study the reflection from the glass surface of a cylindrical bottle for the case of empty bottle and bottle full of milk are discussed. The cylindrical glass bottle used in this experiment has a diameter of about 65.2 mm and a height of 200 mm. Figure 6 shows a comparison of the reflection signals for different fiber arrangements for the case of empty bottle. The reflection voltage signals as a function of scanning distance for the case of fibers horizontal and vertical in the double-fiber design are compared. The reflected light signals are shown for the range of 15-85 mm and as can be seen in Fig. 6, for the horizontal arrangement related signal starts from a voltage level of about 8.6 mV at 15-20 mm distance and reaches to a maximum value of about 11 mV at scanning distance of 50 mm and from that point on decreases as. The voltage signal drops to about 8.6 mV at the scanning distance of about 85 mm. In this case the response curve also shows a Gaussian distribution with a base distance of approximately 53 mm.

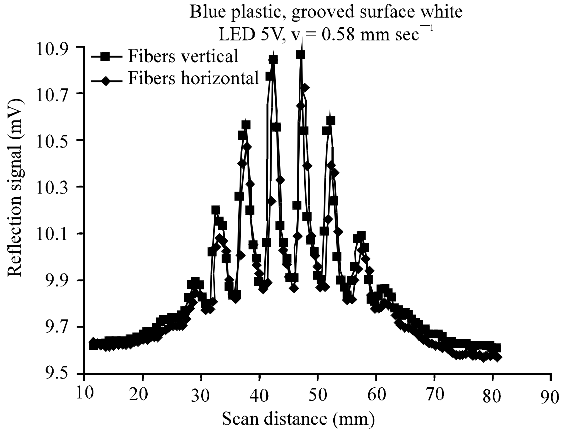

Fig. 5: Comparison of the reflection signals from the blue plastic bottle cap

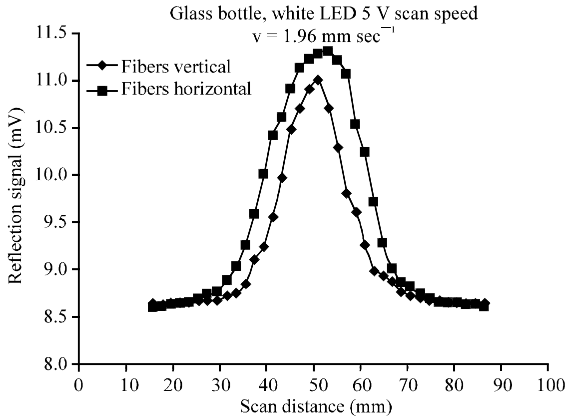

Fig. 6: Comparison of the reflection signals for different fiber arrangements from the empty glass bottle

As can be seen in Fig. 6, the reflected signal for the vertical arrangement starts from a voltage level of about 8.6 mV at 15-20 mm scan distance and reaches to a maximum value of about 11.2 mV at scanning distance of 50 mm and from that point on decreases as shown in

Fig. 6. The voltage signal drops to about 8.6 mV at the scanning distance of about 85 mm. In general the response curve shows a Gaussian distribution with a base distance of approximately 48 mm. Comparing the results for the horizontal and vertical cases reveals two important points. First, the maximum of the peak in response curve for the vertical case is a little higher than (11.2 mV) that of the horizontal case (11.0 mV). Second, the bandwidth for the vertical case is 48 mm while for the horizontal case is 53 mm. As a result for the cylindrical surface with the symmetry axis in the vertical position the horizontal arrangement gives a slightly higher maximum with a little wider bandwidth Gaussian curve.

Figure 7 shows the reflection response curves for the same glass bottle full of milk for the case of horizontal and vertical fiber arrangements. The reflection voltage signals as a function of scanning distance are plotted in figure for the case of fibers horizontal and vertical in the double-fiber designs. The reflected light signals are shown for the range of 5-90 mm and as can be seen in Fig. 7, for the horizontal arrangement related signal starts from a voltage level of about 8.6 mV at 5-15 mm distance and reaches to a maximum value of about 18.5 mV at scanning distance of 50 mm and from that point on decreases. The voltage signal drops to about 8.6 mV at the scanning distance of about 90 mm. In this case the response curve also shows a Gaussian distribution with a base distance of approximately 80 mm for the horizontal fiber arrangement.

As can be noted, the reflected signal for the vertical arrangement starts from a voltage level of about 8.6 mV at 5-10 mm scan distance and reaches to a maximum value of about 16.0 mV at scanning distance of 50 mm and from that point on decreases. The voltage signal drops to about 8.6 mV at the scanning distance of about 85 mm. In general the response curve shows a Gaussian distribution with a base distance of approximately 75 mm. Comparing the results for the horizontal and vertical cases reveals two important points. First, the maximum of the peak in response curve for the vertical case is higher (18.5 mV) than that of the horizontal case (16.0 mV). Second, the curve bandwidth for the vertical case is 75 mm while for the horizontal case is 80 mm. As a result for the cylindrical surface with the symmetry axis in the vertical position the horizontal arrangement gives a higher maximum with a wider bandwidth response curve.

Now compare the results for the case of empty and full bottle for the same fiber arrangement. For the vertical arrangement, as can be seen in Fig. 7, the response curve for the case of milk filling shows the higher reflection signal (peak signal value of 16 mV) and the empty bottle shows the reflection signal (11 mV). For the horizontal arrangement, as can be seen, the response curve for the case of milk filling shows the higher reflection signal (peak signal value of 18.5 mV) and the empty bottle shows the reflection signal (11.2 mV). However, for both arrangements, the case of full bottle shows a higher reflection with respect to the empty glass bottle. The background signal for this case is about 8.6 mV that is related to the stray light signal power and dark current noise equivalent power of the detector.

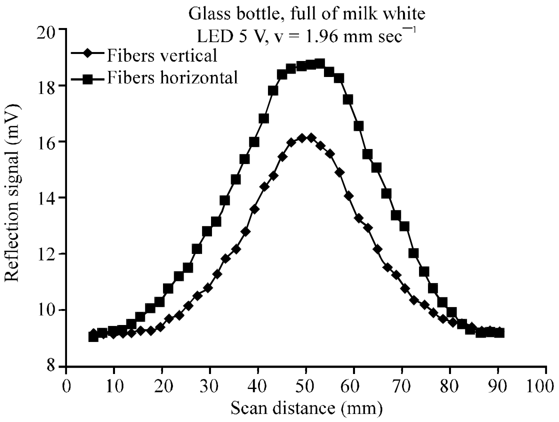

Fig. 7: Comparison of the reflection signals for different fiber arrangements from a glass bottle full of milk

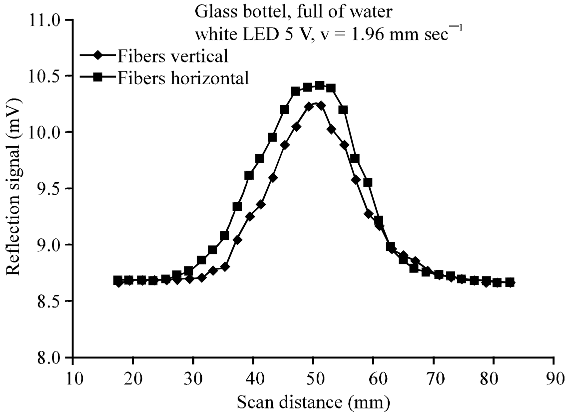

Fig. 8: Comparison of the reflection signals for different fiber arrangements from a glass bottle full of water

In the previous study consider the results for the case of the glass bottle full of water for the fiber vertical and horizontal arrangements. As can be seen in Fig. 8, the response curves for the case of water filling are shown for the range of 15-85 mm. For the horizontal arrangement, as can be seen, the response curve for the case shows the higher peak reflection signal of 10.4 mV and for the vertical case is 10.22 mV. As described the background signal for this case is similar to the previous experiment (about 8.6 mV). The observed difference in the response curves and their maximums indicate the high sensitivity of the reported reflection method which can be useful for the case of liquid filling inspections and vision systems in the related production lines.

DISCUSSION

Performance of an opto-mechanical system using two different fiber arrangements is discussed in more details in this section. Considering the light reflection results the following remarks can be made. For the cylindrical metallic convex surfaces, the vertical fiber arrangement parallel to the cylinder symmetry axis shows a higher reflection signal with respect to the horizontal fiber arrangement. The curve bandwidth for the vertical arrangement is higher than that of the horizontal position. A similar behavior is noted for the reflection results from a convex flange surface. The reason is that for the vertical reflection the reflecting element acts like a plane stripe surface while for the horizontal arrangement a convex reflective surface element is acting for the transmitter and receiver fibers. The given argument is support of the reflection results given in other researches (Golnabi and Azimi, 2008; Golnabi, 2010; Yang *et al*., 2010).

Macro-structures such as grooves can be easily recognized from intensity modulation of the reflected light. Details of the reflection curve are noted to match with the real grooved surface structures. The reported reflecting signals for reflective plastic surface are slightly higher for the vertical arrangement in comparison with the horizontal fiber arrangement. A similar observation is made for the big object surfaces very similar to the results given for small surfaces (Golnabi, 2010).

For the empty glass surface the reflection signal for the vertical and horizontal fiber arrangements are very close in values and response curves. The signal for the horizontal arrangement is a little higher than that of the vertical arrangement. For the glass full of milk (refractive surfaces), in contrary to the metallic surfaces, the reflection signal for the horizontal fiber arrangement is higher than that of the vertical arrangement. In the case of water filling, the horizontal fiber arrangement shows a higher peak reflection signal of 10.4 mV in comparison with the 10.22 mV for the vertical case.

The fiber arrangement and the position of the object surface with respect to the fiber position are important in reflecting signal measurements. It is noted that for the curved surfaces the fiber arrangement in vertical or horizontal positions are sensitive to the symmetry axis of the object surface under study. For the case of the reflective surfaces the vertical arrangement shows a higher signal while for the empty glass is almost similar and for the refractive surface. In contrary the vertical arrangement gives a lower reflection signals and response curve bandwidth. As expected, the reflection signal for the plane surface is independent of the double-fiber orientation in the tested probes as observed in other research works (Golnabi and Azimi, 2008).

CONCLUSION

The effect of the fiber arrangement in the double-fiber probe performance is described in present study. Useful reflection information for different surfaces is given here and it is shown that reflection data can be used effectively in surface profiling as indicated in other reports. Our results show that reflecting signals can provide information about the structure of the surface and in particular, can provide information about the shape and structure of the object surface under study. By experimenting different object surfaces it is noticed that the reflected signal depends on both the axial position of the object surface, surface curvature and the double-fiber arrangement and the probing distance. Using this technique one can extract 2-D information concerning the shape or physical properties of a surface under study. As a result surface structures, steps and existence of a reflecting layers or coating on a surface can be recognized with a high accuracy just by exchanging (horizontal or vertical) fiber arrangement in the optical probe. As shown the uniform plane surface is insensitive to such a geometrical variation while the curved surfaces can be distinguished by comparing the reflection data for two given arrangements.

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