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Reflective-type fiber-optic displacement sensors have demonstrated their usefulness in measuring reciprocating and rotating target motion, detecting surface finish, and profiling surface characteristics and thickness.

F-O Displacement Sensors For Dynamic Measurements

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Light-conducting (glass) fibers can be arranged in bundles to create reflective-type displacement sensors that detect the intensity of light reflected off a target surface and convert it to an analog voltage. These devices can provide extremely stable, highly repeatable linear displacement measurements with sub-microinch accuracy.

The basic elements of these devices are a sensor tip, a fiber-optic cable, and an optoelectronic amplifier (see Photo 1). Various displacement/output voltage functions can be created by changing the distributions/arrangements of light-transmitting and light-receiving fibers.

Inside the amplifier, the fibers can be grouped into one or more transmit and one or more receive bundles. Light sources can be incandescent bulbs, LEDs, or laser diodes. Photodiodes are generally used to convert received light into electrical signals. At the sensor tip, transmit and receive fibers can be mixed into various geometrical arrangements to customize the sensor response to particular needs.

Among the advantages these devices offer are small size; intrinsic safety; freedom from EMI/RFI; excellent temperature stability and range (cryogenic to 800°F); noncontact sensing; sub-microinch resolution; wide bandwidth (DC-200 kHz); and the ability to operate with most materials, black or white, conductive or nonconductive.

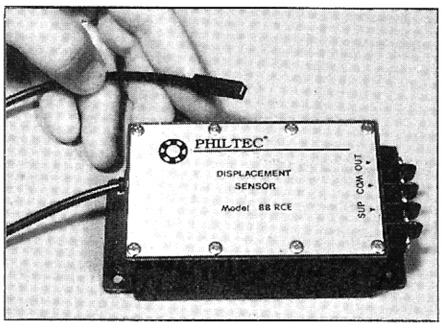


Photo 1. *The basic elements of fiber-optic displacement sensors are a sensor tip, a fiber-optic cable, and an optoelectronic amplifier to provide an analog output voltage signal.*

The sensors have been successfully used with metals; with composites such as fiber glass, ceramics, and polymers; and with paints, glass, and papers. They can also operate when submerged in clear liquids such as water, glycerin, and oils, provided there is no contamination from particles or air bubbles. In short, these transducers are suitable for any application where the optical path is not subject to fouling and the surface texture is relatively smooth.

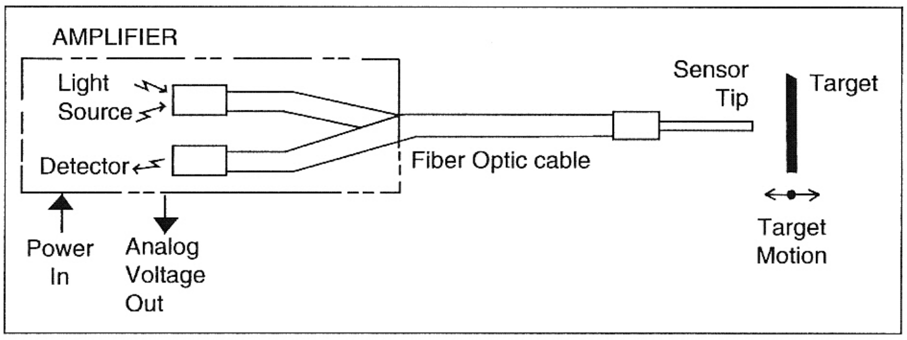


Figure 1. *Reflectance-dependent sensors use simple distributions of transmit and receive fibers in the circular sensor tips. The fibers are grouped into one transmit and one receive bundle at the amplifier end of the cable.*

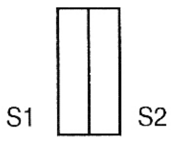
SENSOR TYPES

Two types of sensors have been developed to cover a wide range of applications. In reflectance-dependent models, the sensor output signal is a function of target motion as well as of target surface reflectivity. In reflectance-compensated types, sensor output is dependent only on target-to-sensor distance (motion).

Reflectance-dependent (RD) sensors (see Figure 1) use simple distributions of transmit and receive fibers within circular sensor tips: random mix, side-by-side, or concentric. The fibers are generally grouped into one transmit and one receive bundle at the amplifier end of the cable. These devices can measure variations of target reflectivity, detect parts of differing contrast, or precisely measure reciprocating motion.

Typical applications include ultrasonic welding horn vibration, computer disk magnetic head tracking, disk scratch detection, valve stem motions, acoustic speaker vibrations, and structural vibration studies.

Reflectance-compensated (RC) sensors are created from more complex distributions of fibers at both ends of the fiber-optic cable. At least two independent sensors must be configured at the sensor tip in order to implement reflectance compensation. In one configuration, two adjacent rectangular areas of fibers are used:



S1 and S2 (individually) must be two different RD sensors. The output voltage V from S1 is proportional to the product of the motion M_1 and the reflectance R_1 that it sees:

$V_1 \alpha M_1R_1$

And likewise for S2:

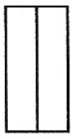
$V_2 \alpha M_2R_2$

Reflectance compensation is derived from the ratio of the two sensor output voltages when both sensors see the same level of reflectivity, i.e., when $R_1 = R_2$:

$$V_{RC} = \frac{V_1}{V_2} = \frac{M_1}{M_2} \qquad (1)$$

Because the fiber areas are usually very small, R_1 does indeed equal R_2 in a great many applications. For example, a part can undergo a uniform color change as it changes temperature; RC sensors can accurately detect thermal growths in the presence of changing reflectivity. Consider also moving or rotating continuous parts. Although reflectance variations of 25% or more are quite commonly found over the entire surface of the material, it is usually safe to assume that there are negligible reflectance variations within the small area covered by the fiber-optic sensor. With translating targets there is a preferred orientation of the sensor areas with respect to the direction of target travel.

preferred target motion
>> >> >> >>
sensor face lines in plane
of the paper



When the two sensor sections are lying one behind the other, as shown above, each sensor will detect identical portions of the target surface, and the reflectance-compensated derivative will be the most accurate.

Typical applications include precision spindle runout, bearing/rotor dynamics, parts profiling, and sheet stock gauging.

In-Phase Reflectance Compensation. Because the sensor sections are aligned one behind the other with respect to the direction of target travel, the RC sensor just described can provide an out-of-phase method for achieving reflectance compensation. The method works well with continuous surfaces because $R_1 \cong R_2$.

There are many instances, however, where $R_1 \neq R_2$. For example, when the edge of a part (or an abrupt reflectance change such as that caused by a printed character on paper) passes across the area of the sensor, there will be a time during which sensors S1 and S2 see two completely different target contrasts. When that happens, $R_1 \neq R_2$, and the ratio V_{RC} is erroneous, if not totally meaningless.

Where out-of-phase compensation is inappropriate, in-phase compensation is required. This is accomplished by electronically superimposing sensor S1 over sensor S2 using delay means such that when the ratio V_1/V_2 is taken, R_1 is precisely equal to R_2.

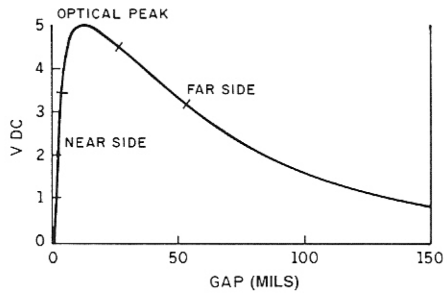


Figure 2. *The reflectance-dependent sensor output function has three distinct regions of operation: the*

APPLICATIONS

The type of fiber-optic displacement sensor best suited for a particular application is determined not only by the usual physical parameters for displacement sensors, e.g., standoff, operating range, resolution, and accuracy, but also by whether the target surface will maintain a constant level of reflectance. Unchanging reflectivity is truly maintained only in reciprocating motion applications, where the sensor will "see" the same area of the target at all times as the target moves toward and away from the sensor.

Reciprocating Motion (Vibration). RD sensors are normally used for reciprocating motion and small amplitude displacement measurements of vibrating targets. A typical output voltage function for this type of sensor is shown in Figure 2. The region of maximum voltage output is referred to as the "optical peak." The usable operating range includes linear ranges on both sides of the peak as well as operation at the peak itself, because the peak can be configured to be rather flat. Operation in the

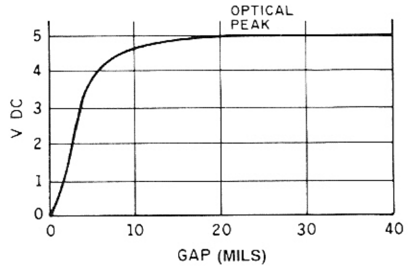


Figure 3. *The optical peak of a reflectance-dependent sensor is a region in which the device is completely insensitive to target motion.*

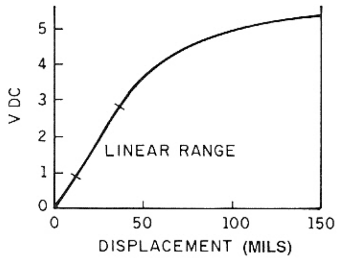


Figure 4. *The reflectance-compensated sensor output function rises gradually to a peak value.*

near-side region gives extremely high sensitivity with limited operating range; sub-microinch accuracies are achievable. Operation in the far-side region gives only moderate sensitivity, but offers a larger operating range and standoff capability.

These devices are excellent choices for use in vibration studies; as motion transducers where the target is moving along the axis of the sensor; and for detecting or sorting targets of various contrast (reflectance). A gain adjustment provides calibration to various target reflectances; in situ calibration is performed simply by positioning the sensor's tip-to-target gap until the peak voltage reading is attained, and then adjusting the gain control to set the peak reading at 100% F.S. This allows the sensor to perform precision linear displacement measurements on almost any material.

Surface Finish/Contrast. When the RD sensor is positioned at its optical peak, it is totally insensitive to motion. On the other hand, it is very sensitive to changes in the target surface, e.g., texture or contrast, or color variations. These sensors can therefore be used to accurately measure the variation of surface finish or reflectance in applications where the target passes under the sensor within the bounds of the optical peak.

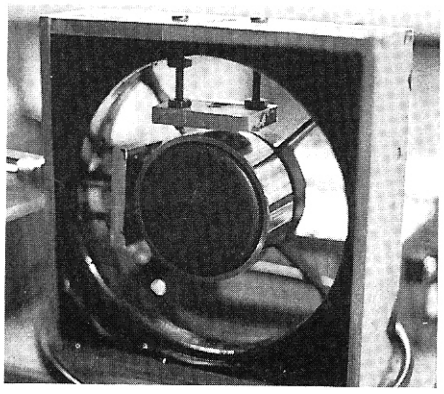


Photo 2. *These sensors can measure rotating targets of various shapes and materials.*

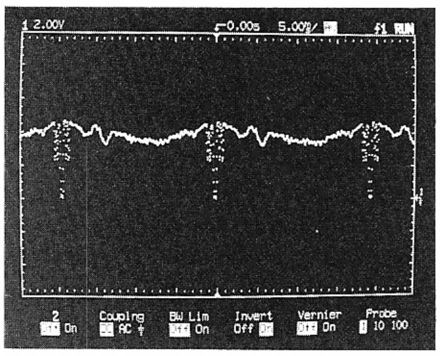


Figure 5. *With a reflectance-dependent sensor, output voltage changes caused by reflectance variations are mixed with output voltage changes due to displacement (gap) variations.*

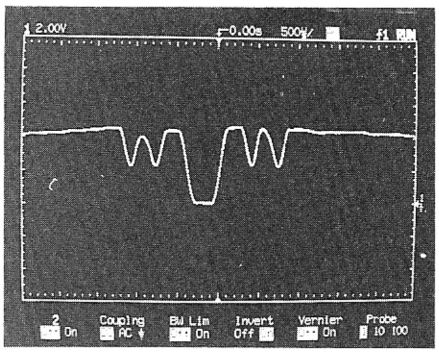


Figure 6. *The reflectance-dependent sensor erroneously shows the center groove to be the deepest. In fact, both outer grooves are 10 mils deep and the center groove is only 4.5 mils deep.*

Figure 3 shows the optical peak region obtained using a random mix of transmit and receive fibers. The peak can be configured to be broader and at a greater standoff distance from the target by using side-by-side distribution of fibers.

Surface Profiling/Thickness on Moving Targets. RC sensors should be used in applications where the target moves across the face of the sensor and accurate gap information is required. These devices overcome the limitations of the RD models and work well with any smooth or specularly reflective target. Applications include precision spindle runout, industrial machinery shaft runout/vibration, thickness gauging, and vibration studies. Figure 4 is a typical response curve, where the output is positive going with increasing displacement. There is no far side of operation beyond the peak output.

A SS shaft was monitored with both types of sensors to illustrate their performance differences (see Photo 2). Three identical slots measuring $^{1}/_{8}$ in. wide by 0.010 in. deep and $^{1}/_{8}$ in. apart were cut into the shaft, and 0.0055-in.-thick black electrical tape was placed into the center slot.

The trace in Figure 5 shows the output of an RD sensor. Large signal variations appearing at 1/rev. erroneously indicate shaft runout or excessive vibration. The area containing the three slots appears as downward-going spikes.

An expansion of the trace in the slot area (see Figure 6) shows that this sensor is not well suited for profiling the shape of the slots. The reason is that the reflectance-dependent nature of this device allows the black tape to cause the signal output to drop to zero over the center slot. It should be kept in mind, however, that the reflectance sensitivity of the device is quite useful in high-speed timing/counting, or when it is important to monitor the surface reflectivity or finish.

Two traces are shown in Figure 7, a reflectance-dependent signal above and a reflectance-compensated signal below. The bottom trace gives the true picture of shaft runout/vibration, which is much less than that indicated by the RD sensor. This test illustrates the effectiveness of the RC sensor when it is used on targets of a continuous nature.

Figure 8 shows the response of both sensors to the slot area where the target surface is discontinuous. Note that the reflectance-compensated trace at the bottom contains a voltage spike at each leading and trailing edge of a surface discontinuity. This is inherent with the RC sensor because its output is a ratio from two sensor sections that are side by side (i.e., out of phase with respect to the direction of target travel). The ratio output becomes meaningless when half of the sensor covers a target and the other

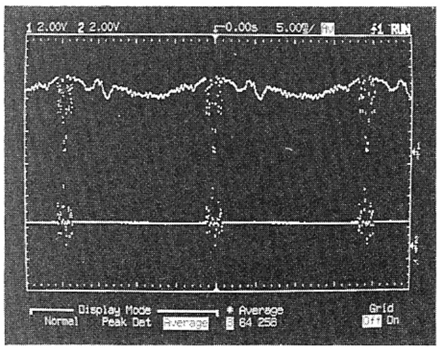


Figure 7. *Where the target surface is continuous (away from the slotted area), the reflectance-compensated sensor very effectively eliminates the signal variations caused by reflectivity variations.*

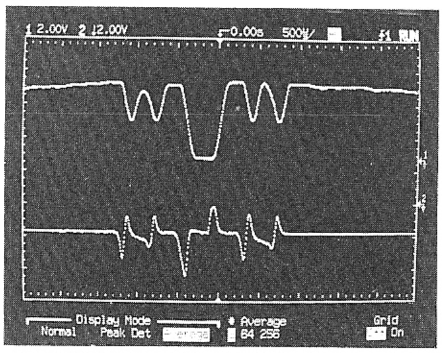


Figure 8. *In the slotted region, where the target surface is discontinuous, the out-of-phase reflectance-compensated sensor generates many voltage spikes that mask the true shape of the part.*

half does not. Although the RC sensor compensates for the presence of the black electrical tape, the closeness of the slots to one another and their small size cause many spikes that make it impossible to accurately profile their shape.

To accurately profile small, discontinuous surfaces, an in-phase RC sensor is needed. The output of such a device appears as the lower trace in Figure 9. The sensor, which has 0.012-in.-wide fiber sections, eliminates the voltage spiking errors that arise when edges of parts pass under it. The trace of the in-phase sensor, in the lower half of the figure, clearly reveals the shape of the grooves.

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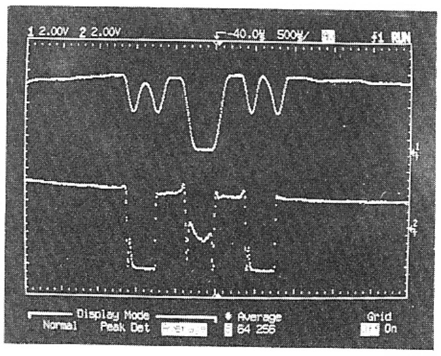

Figure 9. *The true depths of the three slots are revealed through the use of in-phase reflectance compensation.*

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