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Loss-Compensation of Intensity-Modulating Fiber-Optic Sensors

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Loss-compensation of intensity-modulating fiber-optic sensors

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Abstract

This report describes a new type of intensity-modulating fiber-optic sensor which has high immunity to the effects of variations in the losses of the fiber-link. A variable-splitting-ratio transducer is used to differentially modulate the intensities of the light which it transmits and reflects. Using a four-fiber optical link, light is impinged onto the transducer from either direction, and, in each case, the transmitted and reflected signals are measured. These four signals are then processed to remove the effects of the fiber and connector losses. Loss-compensated sensors of angular position and displacement are described, and their outputs are shown to be highly stable despite considerable variations in the transmissivities of the fiber-link components.

Introduction

Considerable research has been performed to develop electrically-passive fiber-optic sensors of temperature, pressure, and position for aircraft control systems.[1-3] Fiber-optic sensors are expected to reduce the weight of these systems and to provide immunity to electromagnetic interference. Fiber-optic sensors which employ some type of intensity-modulating transduction mechanism are attractively simple, but their sensitivity to fiber and connector loss-variations causes their accuracy to be insufficient for use in control systems. A loss-compensation scheme has been proposed which uses four optical splitters within the sensor to direct the light from each of two input fibers to two output fibers.[4-5] In this scheme, the sensor differentially modulates the four light beams in such a manner that the detected optical signals can be processed to remove the influence of the fiber losses. In the loss-compensation method reported here, a variable-splitting-ratio transduction mechanism is used to simplify the sensor and improve its stability. This report describes an angular-position sensor and a displacement transducer, both of which use this technique to provide high immunity to variations in the losses of the fiber-link components. The angular-position sensing method can be used to construct angular or linear position sensors with the range required for a particular application. The displacement transducer has a range which is suited for measuring the deflection of a pressure-sensing diaphragm.

Compensation method

The loss-compensated sensor is shown schematically in Figure 1. Two light-emitting diodes (LED-A and LED-B), two photodiodes with preamps (PD-U and PD-V), four micro-optic collimators (L), and four optical fibers (F-A, F-B, F-U, and F-V) are used as shown in Figure 1. The sensor uses a beamsplitting transducer whose splitting ratio indicates the sensed parameter's magnitude. Basically, the fiber losses are compensated by impinging light onto the beamsplitting transducer from either direction and, in each case, measuring the intensities of both the transmitted and reflected light. The four signals so obtained are then processed to yield an output which is a function only of the transducer's splitting ratio. The two LEDs are time-multiplexed so that the PD responses to each LED's emission can be measured. Each PD output is designated T or R to indicate whether the detected light was transmitted or reflected by the beamsplitting transducer. When only LED-A is on, PD-U's output is R_A and PD-V's output is T_A. When only LED-B is on, PD-U's output is T_B and PD-V's output is R_B. The four PD outputs are given by

$$\begin{aligned} T_A &= P_A\ C_A\ t_A\ C_V\ S_V \\ R_A &= P_A\ C_A\ r_A\ C_U\ S_U \\ T_B &= P_B\ C_B\ t_B\ C_U\ S_U \\ R_B &= P_B\ C_B\ r_B\ C_V\ S_V\ . \end{aligned} \tag{1}$$

In these equations P_N is the power output of LED-N, S_N is the sensitivity of photodiode/preamp PD-N, and C_N is the transmissivity of fiber F-N. Each of the beamsplitting transducer's transmission and reflection coefficients, t_N and r_N, respectively, is defined as the proportion of the light emitted by the input fiber F-N which is coupled into the appropriate output fiber. The compensated sensor signal Y is calculated as follows:

$$Y = \sqrt{\frac{T_A T_B}{R_A R_B}}\ . \tag{2}$$

Substituting from Equation 1 shows that the compensated sensor output depends only on the beamsplitting transducer's transmission and reflection coefficients, i.e.:

$$Y = \sqrt{\frac{t_A t_B}{r_A r_B}}\ . \tag{3}$$

Angular-position sensor

The loss-compensated angular-position sensor is shown in Figure 2. It uses a metal-coated beamsplitter, the optical density of which varies from 0 to 2.0 as a monotonic function of circumferential angle. This sensor has a somewhat different configuration than the sensor shown in Figure 1. It uses two fused-fiber coupler/splitters (C/S) and only two collimators to simplify its construction. The collimators are positioned using laboratory mounts so that their emitted beams are colinear along an axis perpendicular to the beamsplitter's surface and parallel to the splitter's axis of rotation. The optical fibers are step-index with a 100-µm core diameter and a 0.3 N.A. The collimators use quarter-pitch graded-index lenses with a 1.8-mm diameter and a 0.46 N.A. Four SMA-type connectors (C) are used at each end of the 10-m long four-fiber link. Each PD's output is digitized by a five-digit voltmeter. The LEDs and voltmeters are controlled by a microcomputer which interrogates the sensor and calculates Y.

Figure 3 shows Y, T_A, and R_A as functions of the splitter's angular position, θ, over a range of 240°. The results of this sensor calibration are used to convert values of Y to measured values of θ, designated θ_M. The sensor's sensitivity to connector-transmissivity changes, with θ fixed at 120°, was determined by demating and then remating all four connectors at one end of the fiber-link before each of 50 angle measurements. The deviations of θ_M from their mean value are shown in Figure 4. The standard deviation of θ_M was 0.2° or 0.07 percent of full scale. The relative standard deviation of T_A was 16 percent, indicating the substantial transmissivity variations which were compensated. The effect of changing the fiber-link was determined by replacing each of the four transmission fibers with two 10-m fiber segments joined together by a connector. Figure 5 shows, as a function of θ, the resulting change in θ_M relative to the data obtained using single-segment transmission fibers. The maximum change in θ_M was 0.38°. The sensitivity of θ_M to fiber bending, with θ fixed at 120°, was determined by placing 1-cm radius fiber-bends at various points in the transmission link. The measured angle θ_M was found to remain stable within $\pm 0.05°$. The effect of temperature-dependent LED-wavelength changes on θ_M was determined by heating only the LEDs, with θ fixed at 220°. Over the range 20 to 50 °C, $\Delta\theta_M/\Delta T_{LED}$ was determined to be 0.009°/°C.

Displacement sensor

Figure 6 shows the schematic of a displacement sensor which laterally translates one fiber end with respect to another to modulate the light transmitted through both fibers. Fresnel reflections from the polished fiber ends provide the reflective signals required to compensate the losses of the fiber-link. The fibers have a step-index profile with a 100-µm core diameter, and the ends which are displaced relative to one another are held approximately 25 µm apart. Figure 7 shows Y, T_A, and R_A as functions of displacement X. For sufficiently large X, R_A increases with increasing values of X, due to reflections from the stainless-steel ferrule in which the opposing fiber end is mounted. The compensated signal Y has high sensitivity to X, for values of X in the range of 10 to 80 µm. Figure 8 shows, with X fixed at 60 µm, the variations in the measured displacement X_M, for measurements taken after each of 50 sensor disconnect/reconnect cycles. The standard deviation of X_M was 0.08 µm, or 0.11 percent of full scale.

Discussion of error sources

To maintain a stable output, despite considerable disturbances to the fiber-link, the sensor's transmission and reflection coefficients must be highly mode-insensitive. The angular-position sensor achieves this by using graded-index lenses to collimate the light incident on the beamsplitting transducer. The mode-selectivity of the displacement sensor is minimized by making the axial offset of the fiber ends small compared to the fiber's core diameter. The fiber-link components are also required to have highly-mode-insensitive transmissivities to optimize the performance of the loss-compensation system. An experiment was performed to determine whether collimated-beam connectors could be used to improve the sensor's stability by making the connector losses less mode-sensitive. The connector which joins F-A to the LED-A pigtail of the angular-position sensor was disconnected and the two fiber ends were aligned using micropositioners. The effect on θ_M of connector misalignment, with θ fixed at 220°, was determined by laterally translating one of the fiber ends. To measure the effect on θ_M due to lateral misalignment of a collimated-beam connector, a graded-index lens collimator was installed on each of the fiber ends, and one collimator was laterally translated. Figure 9 shows the results of both these tests. The sensor's output is found to be insensitive to the lateral misalignment of an expanded-beam connector.

Concluding remarks

The angular-position measurement technique described here has the potential to meet the requirements of aircraft control systems for angular and linear position sensors with 8 to 10 bit accuracies. This technique may have advantages of reduced weight and size, and greater ruggedness than alternative passively-multiplexed digital transducers.[6,7] The sensor could be manufactured inexpensively if photolithographic techniques were used to deposit, onto the beamsplitter substrate, a metallic line pattern with a line-density which varied as a linear function of circumferential angle. Provided the line widths were much smaller than the diameter of the incident beams, this type of splitter would perform the same as the splitter with a variable-thickness metal coating. The displacement sensor described here illustrates the means by which this four-fiber loss-compensation technique can be used in conjunction with any mode-insensitive intensity-modulating transduction-mechanism, if fixed-reflectivity splitters are used to provide the required reflected signals.

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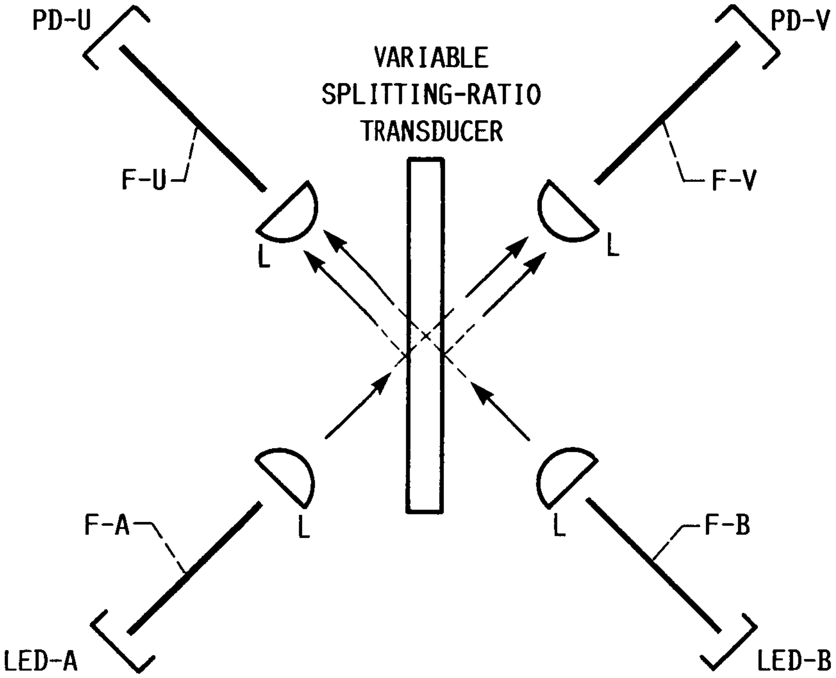

FIGURE 1.- LOSS-COMPENSATED SENSOR SCHEMATIC.

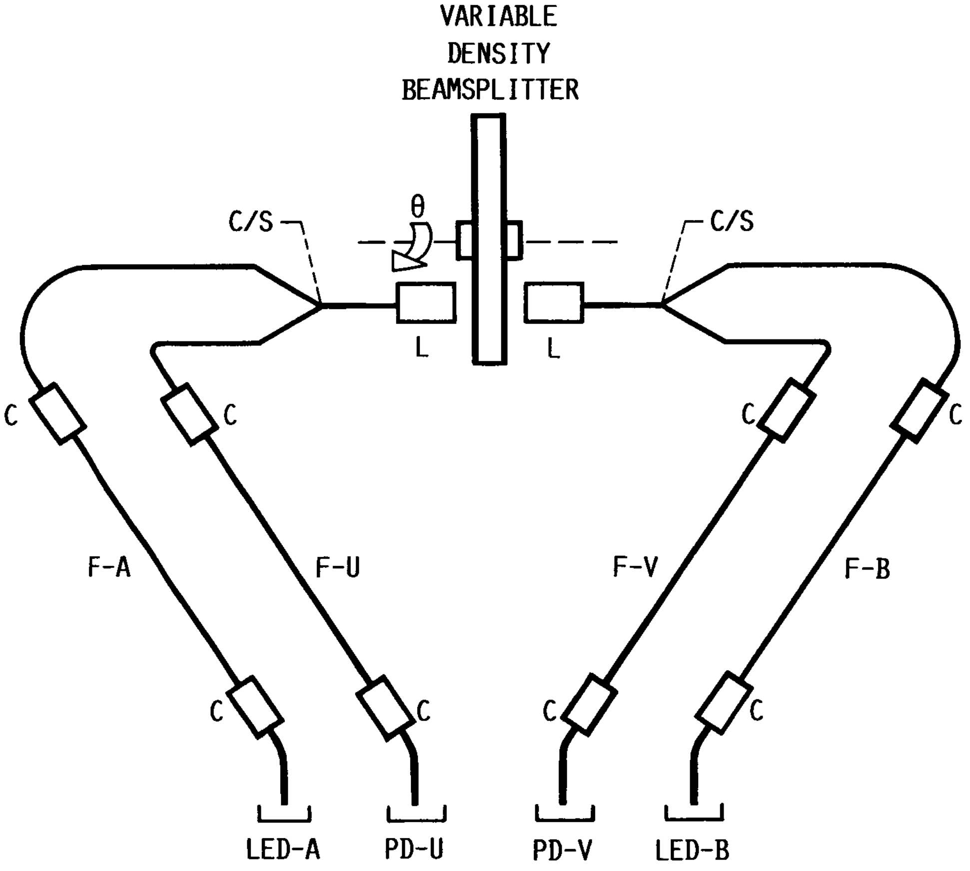

FIGURE 2.- LOSS-COMPENSATED ANGULAR POSITION SENSOR SCHEMATIC.

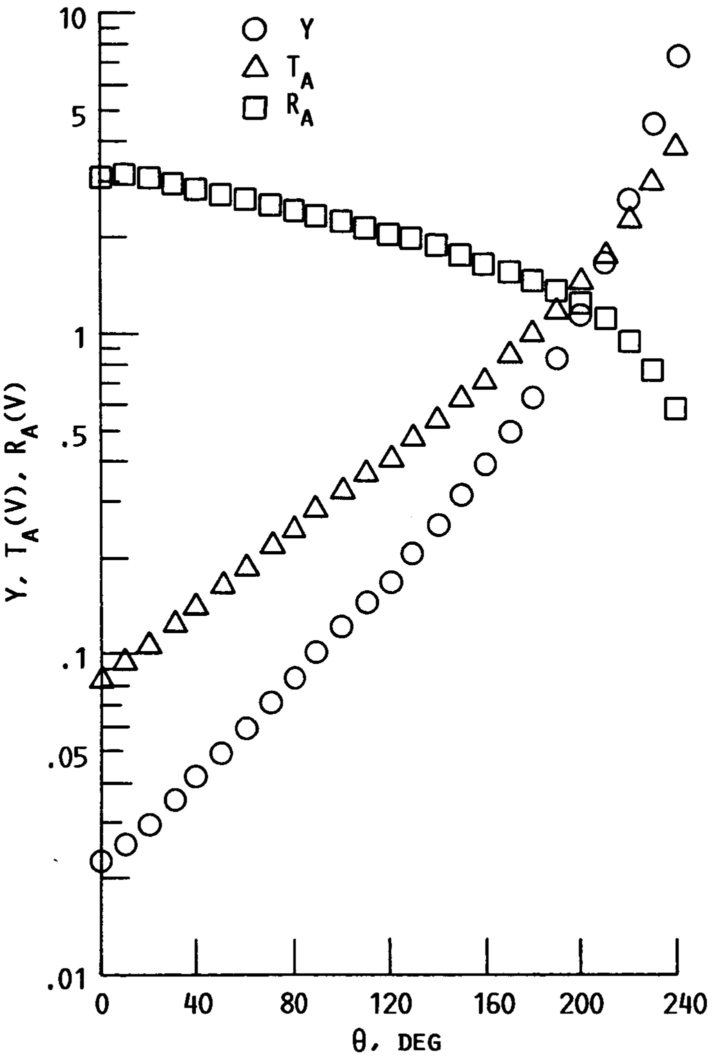

FIGURE 3.- SENSOR SIGNALS Y, T_A, AND R_A AS FUNCTIONS OF θ.

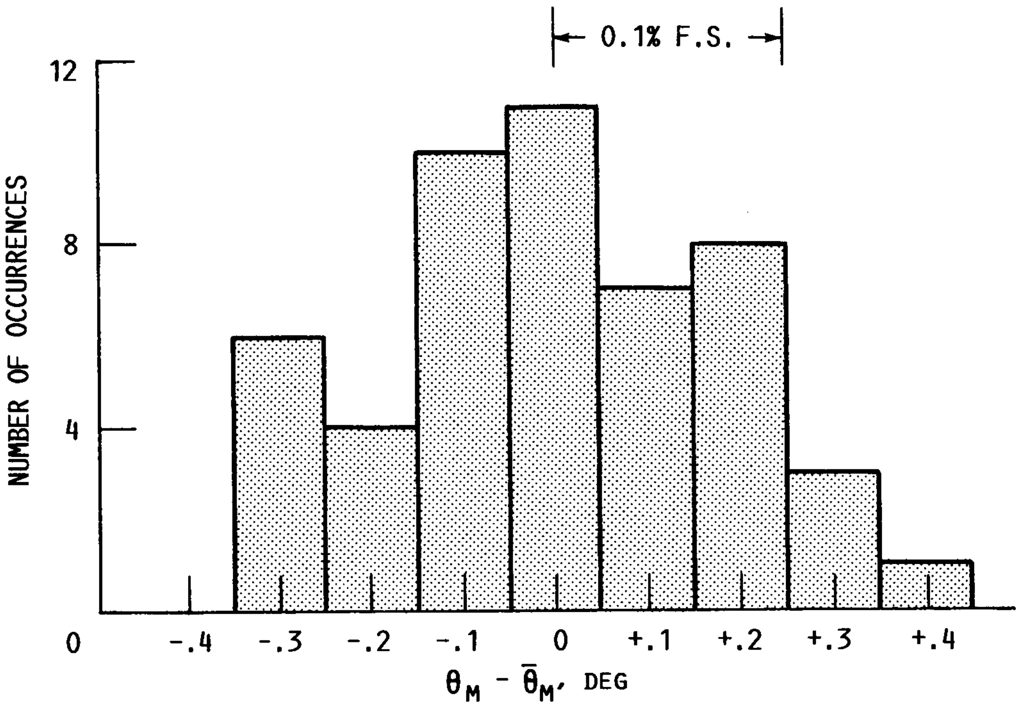

FIGURE 4.- VARIATIONS OF θ_M PRODUCED BY DISCONNECTING AND RECONNECTING THE SENSOR.

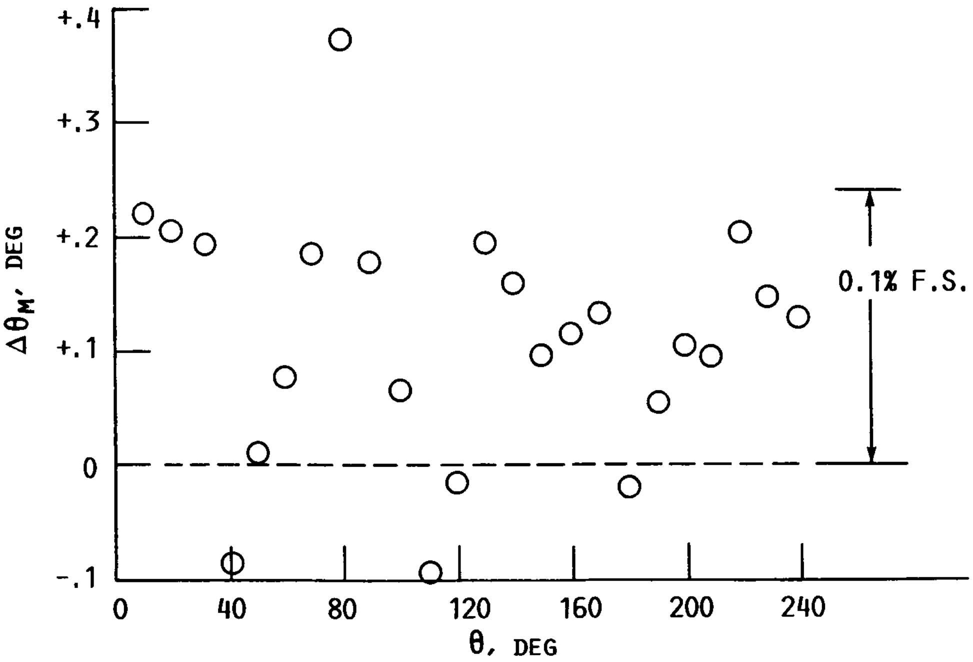

FIGURE 5.- CHANGES IN θ_M, AS A FUNCTION OF θ, PRODUCED BY REPLACING THE FIBER-LINK.

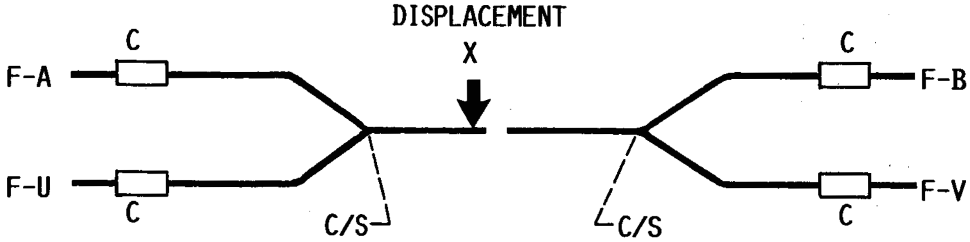

FIGURE 6.- LOSS-COMPENSATED DISPLACEMENT SENSOR SCHEMATIC.

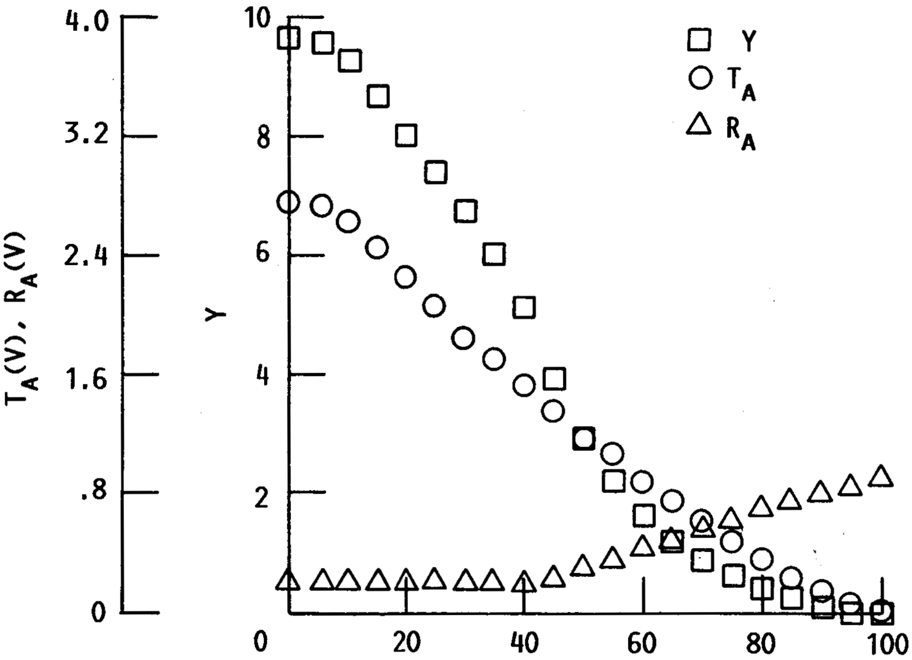

FIGURE 7.- SENSOR SIGNALS Y, T_A, AND R_A AS FUNCTIONS OF X.

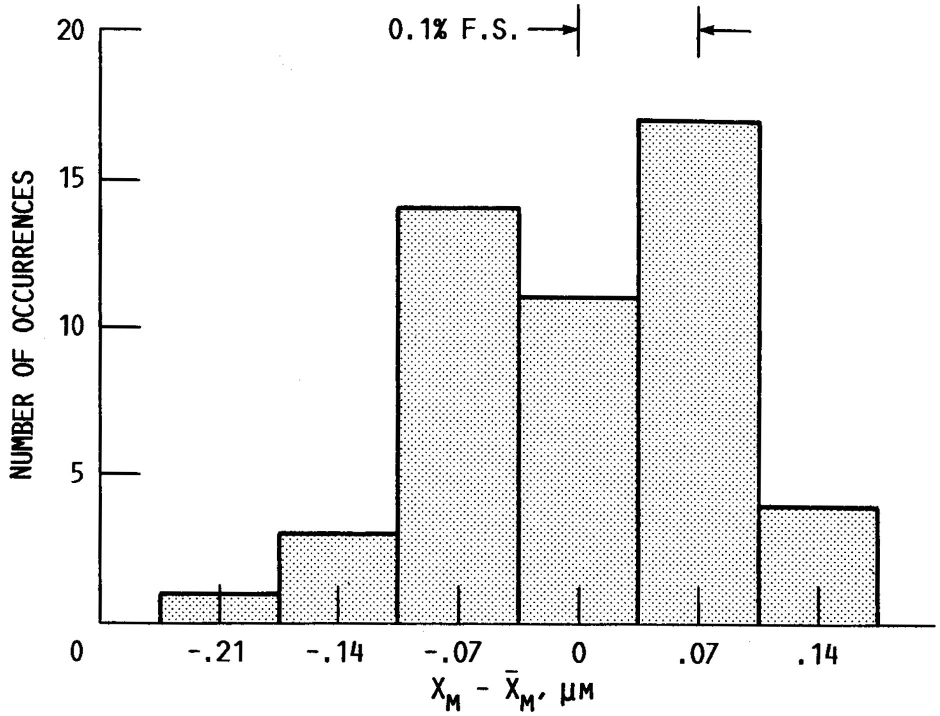

FIGURE 8.- VARIATIONS OF X_M PRODUCED BY DISCONNECTING AND RECONNECTING THE SENSOR.

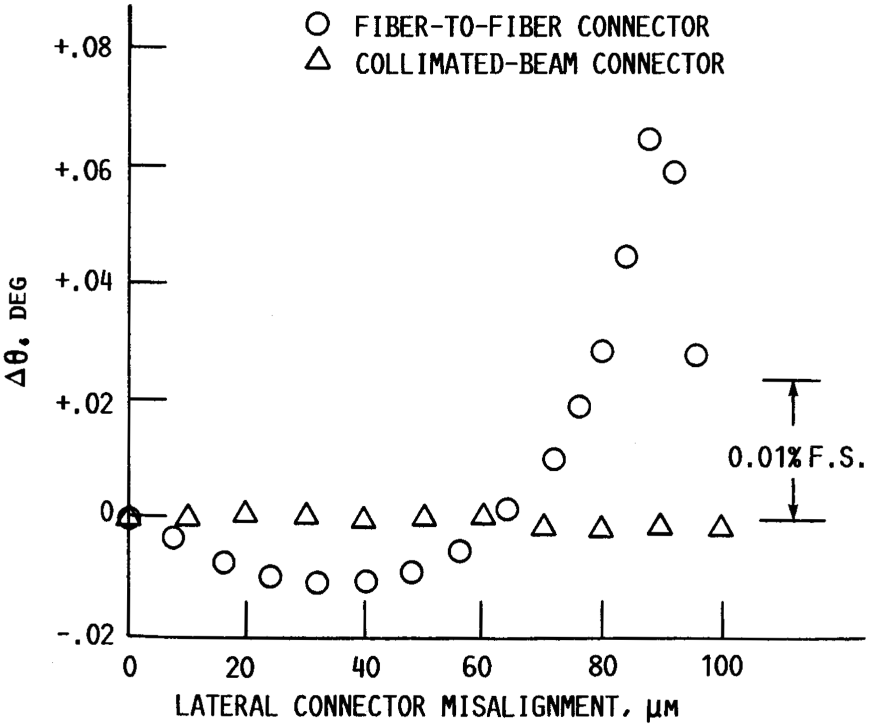

FIGURE 9.- EFFECT ON θM OF LATERAL MISALIGNMENT OF BOTH A FIBER-TO-FIBER CONNECTOR AND A COLLIMATED-BEAM CONNECTOR.

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