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SciVerse ScienceDirect
Procedia Engineering 15 (2011) 989 – 993
Procedia Engineering
www.elsevier.com/locate/procedia

Advanced in Control Engineering and Information Science

Study on an Intelligent Optical Fibre Displacement Sensor

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Abstract

Laser interferometry measurements are difficult to use in industrial environments for expensive, and optical fiber sensors based on intensity are sensitive to the service voltage and thermal drifts of the surrounding medium. To help to solve these problems, an intelligent intensity optical fiber sensor based on two-circle reflective coaxial bundle is presented. The structure of the sensor and measurement system are designed with auto- zeroing and auto-compensation, and its sensitivity, noise level, and drift compensation are calculated to offer quantitative guidance for the design and implementation of the sensor.

Selection and/or peer-review under responsibility of [CEIS 2011]

Keywords:Optical fibre sensor; Compensation; Intelligent

1. Introduction

High-precision noncontact displacements measuring have been explored to reach the sub-nanometric resolution, in order to satisfy the need in nanopositioning and nanomanipulation fields [1]. The systems are mostly based on the optical sensors. The advantages of the optical sensors are noncontact measurement, no added mass or modification of the structure being measured, compactness, wide bandwidth, simplicity, high resolution [2]. Two distinct ways are used to measure relative displacements using an optical sensor: either by interferometric technique or by intensity modulation technique. The most efficient systems are based on interferometry but they need expensive equipments [3]. In addition, these systems function using the Michelson technique which relies on the interference between an optical reference wave and a signal wave reflected from the object under investigation. However, these methods are sensitive to fluctuations of the refractive index of the air and are difficult to apply in industrial conditions subjected to variations in temperature [4], this problem is solved by measuring all the environmental parameters (atmospheric pressure, temperature, water vapor rate, carbon dioxide rate) with specific sensors and calculating the refractive index value using semi-empirical equations[4]. The

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doi:10.1016/j.proeng.2011.08.183

reflective intensity modulation technique is the simplest noncontact method to obtain high resolution. In these sensors, light is transmitted through a bundle of fibers onto the target. The reflected light is received by another set of fibers, and is finally measured by a photodiode. Another noncontact solution is the capacitive gauge. Nowadays commercial systems report resolution as good as 0.01nm over a 100um range in static case and 0.02nm with a 10 kHz bandwidth in dynamic case [5]. However the interferometric technique and the capacitive gauge remain expensive. Although the reflective intensity modulation technique has a simple principle and many outstanding advantages, some authors have researched on that[2,4,6], their results are not satisfactory for the two-circle reflective coaxial fiber bundle displacement sensor.

In this paper, an intelligent optical fiber displacement sensor with measuring service voltage and temperature is presented. The structure of the intelligent optical fiber sensor and measurement system is designed. Its sensitivity, noise level, and drift of the sensor are analyzed.

2. Description of the systems

2.1. Principle of operation

The ratio of the two group receiving fiber bundle can compensate for the optical fiber displacement sensor in theory, eliminate interference factors affect on the output result, and ensure the accuracy of the measurement [7].

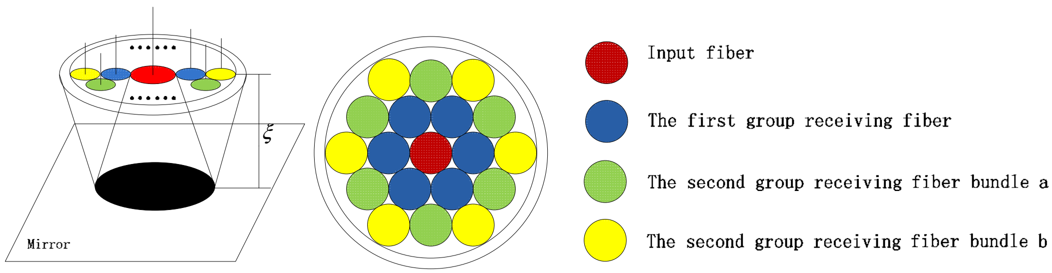

Fig. 1 The principle of a fibre optic based sensor and arrangement of the fiber bundle

The principle (Fig.1) of intensity modulated optical fibre displacement sensors is documented [8]. The intensity of two groups receiving fiber bundle can be obtained respectively.According to the probe arrangement of the two-circle coaxial fiber bundle (Fig.2), Based on the assumptions [7], that is

$$M(\xi) = \exp\{\frac{-3\cdot d^2}{a_0^2[1+\zeta\tan\theta_c(2\xi/a_0)^{3/2}]^2}\} + \exp\{\frac{-2\cdot d^2}{a_0^2[1+\zeta\tan\theta_c(2\xi/a_0)^{3/2}]^2}\} \tag{5}$$

Where a_0 is the fiber core radius, θ_c is the maximum entrance angle of the emitting optical fiber, ζ is the coupling coefficient of the optical field, ξ is the target distance, d is distance between the input fiber and any fiber of the first group receiving fiber bundle.

Eq. (5) shows that, when the fiber structure parameters d 、 a_0 、 θ_c are certain, the optical fiber output characteristic $M(\xi)$ is only relation to the distance ξ between the optical fiber end face and the reflector, and it is independent of the light source intensity, the reflectivity of the reflector, the fiber loss coefficient and the light intensity coupling to the optical fiber from the light source.

2.2. The elements of the sensor

The configuration of the System is shown in Fig. 3,To remove noise from the probe of the surrounding medium, the output voltage of the filter is adjusted to zero by the zero module when the power of the light source is off. The measurement of the service voltage and temperature is used to compensate the drift to improve displacement measurement accuracy.

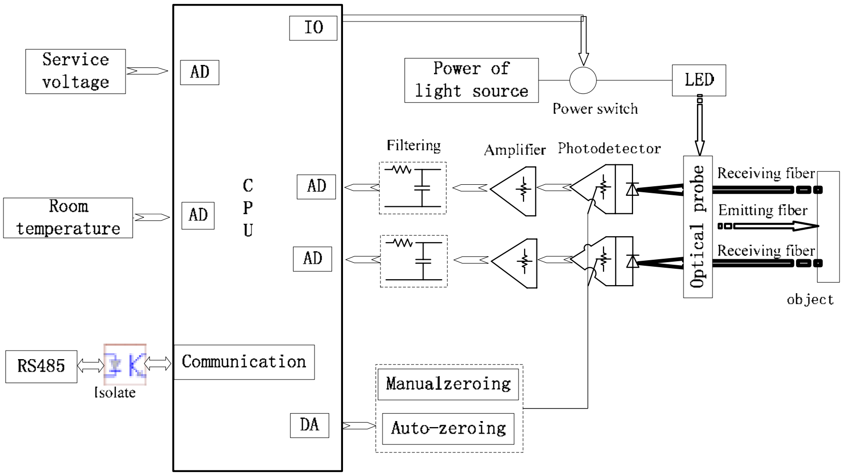

Fig.3 The configuration of the System

3. Standard calibration of the sensor

3.1. Sensitivity

The sensitivity of a single receiving fibre is defined as $S_1 = dV_1 / d\xi$ and $S_{2,3} = dV_{2,3} / d\xi$, where $V = 6GR_f S_p P_{sr}$. Fig. 5 shows the increasing slopes of the sensitivity $S = dV_M / d\xi$ versus ξ relationships. $V_M = V_{2,3} / V_1 = G_{2,3} R_f S_p (P_{sr3} + P_{sr2}) / G_1 R_f S_p P_{sr1}$, where $G_{2,3}$ and G_1 is the gain, S_p the sensitivity of photodiodes, R_f is the load resistance of the photodiode. The sensitivity increase drastically with an increase in ξ, reach a peak value, and then gradually decrease.

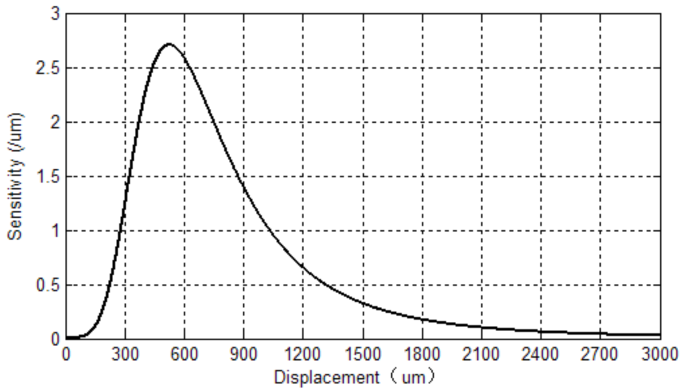

Fig. 5 Optical fibre displacement sensor sensitivity curve and $G_{2,3} = G_1$

3.2. Noise Level of the Sensor

Theoretically, the dominant natural noises to be considered in this system are the shot noise and the Johnson noise [9]. The shot noise i_{sh} is generated from a current flow at p–n junctions in semiconductor elements and is described by:

$$i_{sh} = \sqrt{2eIB} \tag{6}$$

where e is the electron charge, I the current and B the equivalent noise bandwidth given by $B = 1/(4\tau)$, where τ is the time constant of the filter. Johnson noise voltage v_J is generated from the resistance and can be expressed by:

$$v_J = \sqrt{4kTRB} \tag{7}$$

Where k is Boltzmann's constant, T is absolute temperature and R is the resistor.

Since the noises generated from different elements are mutually independent, the total noise of the system can be calculated by the square root of the sum of the square of noises of individual noise sources. The N_1 of a single receiving system is given by:

$$N_1 = G_1\sqrt{(i_{sh1}R_f)^2 + v_{J1}^{\ 2}} / S_1$$
$$N_1 = \sqrt{12eBS_p f_1(\xi)R_f^{\ 2} / P_e + 4kTR_f B / P_e^2} / [6R_f S_p df_1(\xi) / d\xi] \tag{8}$$

where $P_{sr1} = f_1(\xi)P_e$. And the total noise level of the system can be calculated by:

$$N_{total} = \sqrt{N_1^{\ 2} + N_{2,3}^{\ 2}} \tag{9}$$

Eq. (9) also shows that N_{total} is inversely proportional to P_e, B, so enhancing these factors is essentially effective for improvement of the displacement resolution.

3.3. Sensor drift

The stability or drift of the sensor is a problem in practical applications. The drift of the sensor is mainly affected by the thermal variations of the mechanical system and opto-electronic components. A number of modifications are in hand to further improve this figure.. Alayli, Topcu, Chassagne, Viennet [10] propose compensation of the thermal influence on the sensor, the calibration shows a short term accuracy of $\pm 3.5nm$ and a long term accuracy of $\pm 12nm$.

According to the reference [10] and considering the supply voltage drift, The error can be calculated in Table 1. The model [10] is very useful to take into account the effect of the temperature and the service voltage on the optoelectronic components of the sensor, which can be used to compensate on the intelligent sensor to improve accuracy.

Table 1. Drift error of the experimental sensor

Characteristic	Single receiving fiber	Twin receiving fiber
Thermal drift	$0.82\% / {}^{o}C$	$1.17\% / {}^{o}C$
Supply voltage drift	$0.002\% / V$	$0.0007\% / V$

4. Conclusions

This paper presents the results of a two-circle reflective coaxial fiber probe for non-contact intelligent displacement measurements. By taking the ratio of tow receiving signal, the sensor is independent of source power fluctuation and target reflectivity variation. The sensitivity, resolution and drift of the sensor are analyzed and calculated. The model of the drift on the sensor can be compensated to improve accuracy. Certain disadvantages still exist in its present form: the system bandwidth was limited by the low-pass filters and medium pollution affects on the sensitivity and linear range of the sensor.

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