Available online at www.sciencedirect.com
SCIENCE DIRECT®
Sensors and Actuators A 127 (2006) 63–68
SENSORS AND ACTUATORS A PHYSICAL
www.elsevier.com/locate/sna

X-probe flow sensor using self-powered active fiber Bragg gratings

Charles Jewart[a], Ben McMillen[a], Sung Kwon Cho[b], Kevin P. Chen[a,*]

[a] *Department of Electrical and Computer Engineering, University of Pittsburgh, Pittsburgh, PA 15261, United States*
[b] *Department of Mechanical Engineering, University of Pittsburgh, Pittsburgh, PA 15261, United States*

Received 11 September 2005; received in revised form 1 December 2005; accepted 8 December 2005
Available online 24 January 2006

Abstract

A thermal X-probe sensor using self-powered fiber Bragg gratings (FBGs) has been developed to measure both magnitude and direction of two-dimensional gas flows based on convective heat transfer principles. The flow sensor employs two cross-mounted FBGs (X-probe), which are heated by light carried in the same fiber that contains FBGs. When the power light is turned off, the FBGs are used to measure the temperature of the surrounding fluids. When the power light is turned on, in-fiber diode laser light is leaked out of the fiber and is absorbed by the surrounding metallic coating to raise the temperature of the fiber gratings. The convective heat removal by incoming gas flows changes the temperature of the fibers and, as a result, the resonance wavelengths of the heated FBGs are shifted. The FBG sensor is calibrated for air flows of speeds from 0.3 to 20 m/s and a yaw angle from −45° to 45°, respectively. Air flow tests indicate the flow speed and the direction deduced from the sensors are in good agreement with the actual flow conditions confirming the feasibility of the present sensor.

Keywords: Bragg grating; Thermal sensor; Flow sensor; Optical heating

1. Introduction

Two-dimensional thermal flow sensors are widely used to measure both speed and direction of gas and liquid flows. At present, one of the conventional ways to measure flow fields is based on hot-wire anemometry [1]. Heat removal rate from electrically heated wires or films to the surrounding flow is a measure of incoming flow velocity. Recently, thanks to the advent of micro electro mechanical systems (MEMS) technology, numerous miniaturized flow sensors [2] have been developed. MEMS-based flow sensors adopting the thermal heat transfer principle typically consist of heated elements made of electrically conductive materials. To minimize heat conduction to the substrate, the heating elements are often placed on a thin membrane or suspended in the form of a free standing beam [3–8]. Similarly the convective heat transfer rate from the heating elements, which is normally balanced by a given electrical energy input, is closely correlated with the flow velocity. Although MEMS flow sensors as well as hot-wire anemometry offer important advantages, such as high sensitivity and fast response time, a number of drawbacks also limit their applications, especially in harsh environment including cryogenic fuel flow and corrosive flow rate measurement. Although miniaturized MEMS sensors are compact in size and compatible with CMOS technologies, the packaging of MEMS devices could be bulky and involve multiple metal leads for power supply and signal delivery. This becomes a more significant problem if a sensor network is needed to provide flow information in multiple locations. A large number of metal feed-through lines increase heat leakage and the potential of mechanical and electrical failure at high-*g* environments. A large number of electronic sensors and metal leads are also easily susceptible to electromagnetic interference, especially for the low signal output (in the millivolt range), because any ac current imposed upon them is rectified and appears as an erroneous offset.

Fiber sensors are well-known for harsh environment sensing. However, the functionality of traditional fiber Bragg grating sensing has been limited to temperature and strain sensing due to their total passivity. Recently, we demonstrated a new class of multi-functional active sensors based on self-powered fiber Bragg grating technology [9,10]. The self-powered active fiber sensor is electric-free and directly powered by optical energy. The energy sources provided to the sensor units are delivered directly through the optical fibers rather than by electric cable.

---

[*] Corresponding author. Tel.: +1 412 624 9675; fax: +1 412 624 8003.
E-mail address: kchen@engr.pitt.edu (K.P. Chen).

0924-4247/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.sna.2005.12.024

The sensing signal is detected by an in-fiber Bragg grating and transmitted back through the same fiber. This sensing configuration and energy delivery mechanism minimize both electrical and optical cabling; reduces packaging costs; enable sensors to operate in both conducting and non-conducting fluids as well as narrow tubes. By wavelength division multiplexing, many FBG sensors can be inscribed in a single fiber for multiple-point sensing with only one fiber feedthrough. More importantly, the electric-free flow sensors preserve all the intrinsic advantages offered by fiber-optical components. In the subsequent sections, we will present the design, optical powering configuration and testing results of the active two-dimensional FBG flow sensor.

2. Sensor principle

The operation of self-heated FBGs is similar to other thermal-based flow sensors. The main difference is that the output signal from FBGs is optical (resonance wavelength shift), not electrical. The configuration for an optically heated FBG sensor is presented in the experimental section of this paper. If a single FBG is initially self-heated by optical input and placed perpendicular to an incoming flow, the flow increases heat removal from the heated FBG sensor, thereby decreasing the temperature of the FBG sensor. Since the resonance wavelength shift in the FBG sensor $\Delta\lambda$ is correlated with the FBG sensor's temperature, the wavelength shift can resultantly be a measure of the incoming velocity of constant-temperature flows. However, if the flow comes to the sensor with an arbitrary angle, what the sensor measures is not the magnitude of the velocity U_0 but the effective velocity U_e, which can roughly be estimated to be the velocity component normal to the sensor axis.

In order to measure both magnitude and direction of incoming flows on a two-dimensional plane, two FBGs which are cross-aligned with a 90° angle are designed as described in Fig. 1. The outputs of resonant wavelength shift from the two FBGs can be used to determine the magnitude and direction of the incoming flow. The relationship among them can be derived from the energy balance on the FBG sensors. For simplicity, consider one of the two FBG sensors first. Under a steady-state condition, the absorbed thermal energy rate P in the FBG sensor is considered equal to the convective heat energy rate transferred to the flow:

$$P = hA(T_s - T_\infty), \tag{1}$$

where h is the convective heat transfer coefficient, T_s the temperature of the FBG sensor, T_∞ the fluid temperature which is considered constant in the present work and A is the surface area of the sensor which is equal to $\pi D_s L_s$. D_s and L_s indicate the diameter and the sensing length of the FBG sensor. The convective heat transfer coefficient h is expressed non-dimensionally by the Nusselt number Nu as follows.

$$Nu = \frac{hD_s}{k_f} = M + N Re^n \tag{2}$$

where Re is the Reynolds number, $Re = U_e D_s/\nu_f$, and n the empirical exponent (0.3–0.8), and M and N are the coefficients that are functions of the Prandtl number ($Pr = \nu_f/\alpha_f$) and T_s/T_∞. The subscript f indicates the film temperature defined by $T_f = (T_s + T_\infty)/2$. The fluid properties of the thermal conductivity k_f, the thermal diffusivity α_f and the kinematic viscosity ν_f are defined at the film temperature. As a result, the coefficients M and N are only functions of the sensor temperature T_s under the condition of T_∞ = constant.

The energy Eq. (1) can be rewritten substituting h from Eq. (2), as

$$P = M' + N' U_e^n \tag{3}$$

where $M' = \pi L_s k_f\ (T_s - T_\infty)M$ and $N' = \pi L_s k_f (T_s - T_\infty) N D_s^n/\nu_f^n$. The coefficients M' and N' are also only functions of the FBG sensor temperature T_s since all the fluid properties and the coefficients M and N are only functions of T_s under the condition of T_∞ = constant. Meanwhile, U_e is the effective velocity of which a first-order approximation can be used as the normal velocity component to the sensor axis. For example, the effective velocity for FBG1 sensor in Fig. 1b can be described by $U_0\cos(45^\circ - \theta)$, where θ indicates the yaw angle of the flow defined with respect to the X-probe axis. In reality, the relationship between U_0 and U_e is not so simple as numerous different empirical formulae have suggested to date [1]. Although the functional forms are different on a case by case basis, U_e is generally a function of U_0 and θ. Furthermore, if it is assumed that the resonant wavelength shift $\Delta\lambda$ in the FBG sensor is solely dependent on the sensor temperature T_s, Eq. (3) can be written in the following functional form:

$$P = M'(\Delta\lambda) + N'(\Delta\lambda) U_e^n(U_0, \theta). \tag{4}$$

Since the present X-probe has two FBG sensors, this relationship can be applied to each sensor bringing up two coupled equations as follows:

$$P_1 = M_1'(\Delta\lambda_1) + N_1'(\Delta\lambda_1) U_{e1}^n(U_0, \theta) \tag{5}$$

$$P_2 = M_2'(\Delta\lambda_2) + N_2'(\Delta\lambda_2) U_{e2}^n(U_0, \theta) \tag{6}$$

where subscripts 1 and 2 indicate FBG1 and FBG2, respectively. Eqs. (5) and (6) reveal that given the in-fiber absorbed light energy P the wavelength shift $\Delta\lambda$ is only dependent on U_0 and θ. Since the output from the sensor is $\Delta\lambda$, it is more convenient to use the following explicit forms rather than Eqs. (5) and (6):

$$\Delta\lambda_1 = F_1(U_0, \theta, P_1) \tag{7}$$

$$\Delta\lambda_2 = F_2(U_0, \theta, P_2). \tag{8}$$

Given power inputs P_1 and P_2, the functions F_1 and F_2 can be determined from calibrations where the wavelength shift $\Delta\lambda$ for each sensor is registered with varying the magnitude U_0 and direction θ for the known incoming flows. Once the calibrations are established, U_0 and θ of the unknown incoming velocity in real measurements can be determined by measuring the wavelength shifts $\Delta\lambda_1$ and $\Delta\lambda_2$ and equating Eqs. (7) and (8).

3. Sensor fabrication and experimental setup

To construct the optically heated X-probe, two optical fibers were mounted on a rotational stage with a cross angle of 90°,