Constant Power Operation of a Two-Dimensional Flow Sensor

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Abstract—To compensate for changes in ambient temperature, thermal flow sensors are usually heated to a constant temperature above ambient temperature. This operating mode, however, requires an extra ambient-temperature sensor. Using a simple model, it is shown that for a two-dimensional thermal flow sensor, similar compensation may be obtained by using a constant heating power, thus eliminating the need for an ambient-temperature sensor. The flow sensor's interface circuitry consists of two thermal sigma-delta modulators that heat the sensor with constant power and dynamically cancel the flow-induced temperature gradient. The modulator's bit-stream outputs are then a digital representation of the heat distribution in the sensor. Wind tunnel tests confirm the validity of the sensor model used and show that both flow speed and direction may be accurately determined from the bit-streams, with errors less than $\pm 5\%$ and $\pm 3^\circ$, respectively, for flow speeds between 1 and 25 m/s.

Index Terms—Constant power operation, interface electronics, thermal flow sensor, thermal sigma-delta modulation.

I. INTRODUCTION

FLOW speed and direction may be determined by the use of two-dimensional (2-D) thermal flow sensors [1]–[4]. These devices utilize the fact that airflow over a heated plate will cool it asymmetrically, with the upstream portion of the plate being cooled more than the downstream portion. The resulting temperature gradient in the plate is aligned with the airflow, and its magnitude is a well-defined function of flow speed. The layout of a typical integrated 2-D thermal flow sensor is shown in Fig. 1 [1]–[4]. It consists of a square silicon chip (or membrane) in which a diode, four thermopiles, and four resistive heaters are integrated. The diode is used to measure the chip's average temperature, while the output of the thermopiles is used to measure the flow-induced temperature gradient in the chip.

To compensate for ambient-temperature variations, such sensors are usually operated in a *constant temperature difference* (CTD) mode [1]–[3]. Here, a control loop maintains the sensor at a constant temperature (known as the *overheat*) above ambient temperature. A second, off-chip diode is used to measure ambient temperature. The latter must be located close to the heated flow-sensor and, simultaneously, be thermally isolated from it. These conflicting requirements are difficult to achieve in practice. Furthermore, for an ambient-temperature-independent overheat, the temperature sensitivity of both diodes must

Fig. 1. Layout of a 2-D thermal flow sensor.

be well matched. This may be achieved by using the diode of an identical chip as the ambient temperature sensor [5]. However, this is an expensive solution since each flow sensor will then require two chips.

A 2-D thermal flow sensor may also be operated in a constant power (CP) mode, in which a constant heating power is dissipated in the sensor [4]. This eliminates the need for an ambient-temperature diode, thus greatly simplifying the realization of the complete flow sensor system. It will be shown that in CP mode, the sensor's output is also insensitive to ambient-temperature drift. Its response speed, however, will be somewhat increased, since changes in flow speed (and thus changes in the amount of convective cooling) now alter the temperature of the *entire* sensor.

In both CP and CTD modes, flow speed and direction may be determined by measuring the flow-induced temperature gradient. This may be conveniently done using thermopiles [1]–[4], which, being self-generating transducers, are intrinsically offset free. Their sensitivity, however, is process and temperature dependent, and will therefore contribute to the overall process and temperature dependence of the flow sensor's characteristics [6]. Alternatively, the heating power may be spatially distributed in the sensor such that any flow-induced temperature gradient is *cancelled* [7], [8]. Information about the flow is now contained in the distribution of heating power in the sensor. After [8], this null-balance mode of operation will be referred to as the *temperature balance* (TB) mode. The main benefit of this approach is that variations in thermopile sensitivity are now unimportant, since the thermopiles now function simply as null detectors.

This paper describes the behavior of an integrated 2-D flow sensor operated in the CP mode. In Section II, it is shown that,

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operation in this mode provides first-order compensation for ambient temperature variations. The sensor is operated in both CP and TB modes by incorporating it in the feedback loops of two thermal sigma-delta modulators [9], [10]. Each modulator dynamically cancels one component of a flow-induced temperature gradient in the sensor. The required interface circuitry is described in Section III. In Section IV the results of wind tunnel experiments are given and, finally, some conclusions are drawn.

II. AMBIENT-TEMPERATURE COMPENSATION

A detailed mathematical analysis of flow-sensors of the Fig. 1 variety is given in [1]. There it is shown that such sensors obey the following relationship, known as King's law [11]

$$P_{\text{tot}} = \left(A + B\sqrt{|\vec{U}|} \right) \Delta T \quad (1)$$

where P_{tot} is the total power dissipated in the heaters, ΔT is the overheat with respect to ambient temperature, and $\vec{U}$ is the flow velocity. The value of the constants A and B depends on flow geometry, and on material properties of the sensor and fluid, e.g., the latter's viscosity and thermal conductivity. It is usually assumed that A and B depend only weakly on ambient temperature. From (1), ambient-temperature independent operation may be obtained by keeping ΔT constant, i.e., by operating the sensor in the CTD mode.

The flow-induced temperature gradient $\delta\vec{T}$ in the sensor is given by

$$|\delta\vec{T}| = \sqrt{|\vec{U}|} \Delta T \quad (2)$$

$$\arg(\delta\vec{T}) = \arg(\vec{U}) = \phi \quad (3)$$

where S is a sensitivity constant that again depends on flow geometry and material properties, and ϕ is the flow direction, as indicated in Fig. 1. It should be noted that the direction of the temperature gradient depends *only* on that of the flow (3) and is thus inherently unaffected by ambient-temperature variations.

When the sensor is operated in the CTD mode, the overheat ΔT is held constant by a control loop. Then, for small ambient temperature variations, where S may be assumed constant, the relationship between flow speed and the temperature gradient will be independent of ambient temperature.

When the sensor is operated in the CP mode, P_{tot} is constant. From (1) and (2) the ΔT term may be eliminated, yielding

$$|\delta\vec{T}| = \frac{SP_{\text{tot}}\sqrt{|\vec{U}|}}{\left(A + B\sqrt{|\vec{U}|} \right)}. \quad (4)$$

Flow speed may thus be determined from the differential temperature vector $\delta\vec{T}$ in a substantially ambient-temperature independent manner. Once more, the temperature dependence of the various constants in (4) has been neglected.

In the TB mode, however, the flow-induced temperature gradient is *cancelled* by dynamically adjusting the heat distribution

Fig. 2. Block diagram of the north-south thermal $\Sigma - \Delta$ modulator.

in the sensor. This creates a heating power gradient $\delta\vec{P}$ across the sensor's thermal resistance R_s . Then, from (4)

$$\frac{|\delta\vec{P}|}{P_{\text{tot}}} = \frac{S\sqrt{|\vec{U}|}}{R_s \left(A + B\sqrt{|\vec{U}|} \right)}. \quad (5)$$

The flow-induced temperature gradient has thus been converted into a *differential-power* gradient, an electrical quantity that may be conveniently measured. Furthermore, in order to cancel the temperature gradient, the control circuitry only requires accurate knowledge of its *direction*. Orthogonally arranged thermopiles are near-ideal candidates for this task, due to their inherently offset-free and monotonic temperature-to-voltage characteristic.

It should be noted, however, that irrespective of the operating mode employed, the output of a thermal flow sensor will *still* require compensation for *large* changes in ambient temperature, due to the temperature dependency of the material properties of the fluid and sensor [6], [12].

III. OPERATION IN THE TEMPERATURE BALANCE MODE

The flow-induced temperature gradient $\delta\vec{T}$ in a 2-D thermal flow sensor may be decomposed into two orthogonal components, a north-south component δT_{ns} and an east-west component δT_{ew} . Each of these components may be cancelled by a thermal $\Sigma - \Delta$ modulator that drives the appropriate pair of heaters. A block diagram of the north-south modulator is shown in Fig. 2.

The modulator attempts to satisfy the condition $\delta T_{\text{ns}} = 0$ by periodically turning either the north or south heater "on" or "off," thereby balancing the sensor's asymmetric heat loss to the flow (modeled by the flow-dependent thermal resistances $R_{\text{flow},n}$ and $R_{\text{flow},s}$). When turned "on," each heater dissipates a constant power P_{ref} . Since one of the heaters is always "on," the sensor is operated in the CP mode. The heat pulses are low-pass filtered by the combination of the various thermal resistances and the sensor's thermal capacitance C_{th} , and so $\delta T_{\text{ns}} \approx 0$ provided the clock frequency greatly exceeds the filter's cutoff

Fig. 3. Normalized power differences as a function of flow angle.

frequency. Since $\delta T_{ns} \approx 0$, the modulators effectively operate the sensor in the TB mode. The bit-stream output b_{ns} of the flip-flop then represents $\delta P_{ns}/P_{ref} = (P_n - P_s)/P_{ref}$ i.e., the *normalized* north-south component of the power gradient $\delta \vec{P}$. In a similar manner, the normalized east-west component of $\delta \vec{P}$ is digitized by a second thermal $\Sigma - \Delta$ modulator that drives the east and west heaters.

The main advantage of this interface architecture is its simplicity; apart from the elements of the flow sensor, the only extra component required is a latched comparator. Also, P_{ref} does not need to be accurately stabilized, since the bit-stream outputs represent *normalized* power differences that from (5) depend only on flow speed and on sensor constants.

IV. RESULTS

A. Experimental Setup

Wind tunnel tests were carried out using a previously reported “smart” wind sensor chip [13] on which both a 2-D flow sensor and the thermal $\Sigma - \Delta$ modulators have been realized. In order to provide a performance benchmark, the wind sensor chip was mounted in the aerodynamic housing of a commercial wind sensor that also utilizes a silicon flow sensor [3].

The thermal $\Sigma - \Delta$ modulators were operated at a clock frequency of 10 kHz, and the heaters were driven by heat pulses with an amplitude (P_{ref}) of 300 mW. The bit-stream output of the modulators was externally low-pass filtered and decimated. The filter used consists of a Sinc² filter, followed by a 10-point moving-average filter. The equivalent noise bandwidth of the combined filters is about 0.3 Hz.

B. Results of Wind Tunnel Experiments

Measurements were made at flow speeds of approximately 2, 8, and 18 m/s. The exact flow speed in the wind tunnel was measured with a reference anemometer. To simulate changes in flow direction, the sensor was rotated through 360°. At a constant flow speed, the normalized power differences $\delta P_{ns}/P_{ref}$ and $\delta P_{ew}/P_{ref}$ may be approximated by sine and cosine functions of flow direction ϕ , as shown in Fig. 3. The normalized power differences are then given by

$$\frac{\delta P_{ns}}{P_{ref}} = A_{ns} \sin(\phi + \varepsilon_{ns}) + a_{ns} \quad (6)$$

$$\frac{\delta P_{ew}}{P_{ref}} = A_{ew} \cos(\phi + \varepsilon_{ew}) + a_{ew}. \quad (7)$$

The amplitude A is a function of flow speed; the offset a is due to thermal asymmetry in the sensor; and the angle ε is a constant phase shift. The latter reflects the fact that the sensor’s reference axis was not aligned with the reference axis of the measurement system.

The amplitude A_{ns} is shown in Fig. 4 as a function of the square root of flow speed. The measured data agrees well with a fitted curve based on (5), thereby confirming the validity of the sensor model. The curve is a monotonic, nonlinear function of the square root of flow speed, in contrast with the linear response obtained when the same sensor is operated in a CTD mode [10]. In the TB mode, however, the output sensitivity is significantly larger at low flow speeds; this is because the sensor is always heated with the maximum available power, resulting in a larger overheat at these speeds.

From (6) and (7) the amplitude A and flow direction ϕ may be expressed as a function of the measured data pair δP_{ns} and δP_{ew} and the constants a and ε [1]. The latter are obtained by

Fig. 4. Amplitude A_{ns} versus square root of wind speed.

Fig. 5. Errors in the computed flow speed and direction versus flow angle.

calibrating the sensor. By inverting (5), flow speed may be determined from the computed amplitude.

Using this procedure, flow direction and speed were computed using the data obtained during the wind tunnel tests. The errors in the computed amplitude and direction are shown in Fig. 5. It may be seen that the calibrated sensor is accurate to better than $\pm 5\%$ and $\pm 3^\circ$ in flow speed and direction respectively, over the speed range 1 to 25 m/s. These results

are essentially *identical* to the specified performance of the commercial wind sensor (which operates in the CTD mode) [3].

V. CONCLUSION

From theoretical considerations, it has been shown that compensation for ambient-temperature drift may be obtained

by operating a 2-D thermal flow sensor in either the constant temperature difference (CTD) or constant power (CP) modes. The latter mode, however, has the advantage that it does not require an external ambient-temperature sensor.

Operation in the CP mode may be achieved by a simple electronic interface consisting of two thermal sigma-delta modulators. These operate the sensor in a temperature balance (TB) mode in which a flow-induced temperature gradient in the sensor is cancelled by the spatial distribution of a constant heating power. The modulator's bit-stream outputs are then a direct digital representation of the power distribution in the sensor.

Wind tunnel measurements were carried out using a "smart" wind sensor chip on which a 2-D flow sensor and the thermal sigma-delta modulators have been co-integrated. The measurement results confirm the validity of the mathematical model used to describe the sensor. After calibration, flow speed and direction were determined from the decimated output of the modulators, errors in the results were less than $\pm 5\%$ and $\pm 3^\circ$ respectively. This performance is equivalent to that of a similar commercial wind sensor, which, however, operates in the CTD mode.

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