Design of Temperature Matrix with Direction Sensitivity

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ABSTRACT

The paper describes design of an anemometric sensor system for measurement of velocity and direction of airflow over a chip. A CMOS transistor has been used as the temperature sensor. Temperature “heater” has been designed as an integrated resistor. The direction of airflow is computed from the orthogonal arrangement of temperature matrix. The matrix is composed of two pairs of temperature sensors connected with the “heaters”. Each sensor contains 9 NMOS transistors. The transistors work in the mode of strong inversion (overthreshold area). The airflow is cooling the "heaters" and is heated at the same time. Two output voltages from the analogue part represent the vector of airflow in x and y axes. The angle and velocity of the airflow are computed from these output voltages. The computation is performed in the digital part. WinSPICE and MATLAB have been used for design and simulation. Models have been used for design and modelling.

Keywords: anemometry, airflow, temperature, microsystem, CMOS sensors

1 INTRODUCTION

The latest knowledge of microelectronic technology is used at development of new types of sensors for measurement of physical and biochemical quantities.

Development of new microsystem technologies has opened new application areas of microsystems. Miniature dimensions enable expansion of their applications, e.g. in medicine. Pressure and temperature microsensors keep their dominant position in applications. In the process of design of the systems working with non-electric quantities, system of models is used. According to the type and way of quantity conversion models in one or more energy domains are used. In that point it differs from standard electronic elements. Electronic elements and integrated circuits are designed for operation in electrical energy domain. Modeling and simulation of properties of electronic elements represent standard steps of design of the elements. The microsystem may represent a very complex system with complicated energy relations.

Modeling and simulation of the properties of the microsystem can be a very difficult problem. There are being developed more and more sophisticated software packages with the aim to improve modeling of properties of the designed microsystem.

For design of a direction sensitive matrix, the anemometric principle may be used. Its operation is based on cooling of temperature sensors of different type. Sensitivity of the sensors is derived from temperature equilibrium in steady state, when electrical energy delivered to the sensor is the same as heat energy lost for cooling of the sensor. The energy loss depends on velocity of flow of the cooling medium. Power delivered for the sensor heating is used for the flow velocity measurement. Sensors using this principle are "hot-wire" sensors (probe is not suitable for integration), thermistors (high sensitivity, not suitable for integration). Another group of sensors using the anemometric principle are p-n junctions (low sensitivity for air velocity), MOS channel (suitable for integration and miniaturization), metal or integrated thermocouples [1] and other types of integrated temperature sensors.

The core of the system is composed of 4 "heaters" with 4 temperature sensors. The sensors serve for temperature measurement of the "heaters". The heaters are heated over the level of ambient temperature $\boldsymbol{\vartheta_o}$. The air flows over the chip with velocity **v.** The flow direction forms the angle $\boldsymbol{\varphi}$ with the **x**-axis**.** As simplification let us consider the 1D space, i.e. the **x**-axis. The flowing air cools the first heater by $\Delta\vartheta_1$ and at the same time it itself is heated by $\Delta\vartheta$. Then the heater has the temperature $\vartheta_1=\vartheta_H-\Delta\vartheta_1$. ϑ_H is the temperature of the heater at no airflow. The heated air flows over the chip to the second heater. The second heater is cooled less, i.e. it has the temperature $\vartheta_2=\vartheta_H-\Delta\vartheta_2$. Then it holds for the temperature of the heaters $\vartheta_2>\vartheta_1$. The slower the airflow is, the higher the temperature gradient $\Delta\vartheta$ is. The system sensitivity decreases with increasing velocity. If the direction of airflow is opposite then the heaters are cooled in the reversed order. Then it holds $\vartheta_2<\vartheta_1$ for the temperature of the heaters. When designing a matrix for measurement of the angle of the airflow in the range up to 360^o it is necessary to design 2D orthogonal system – see figure 1.

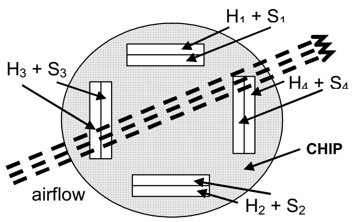

Figure 1: 2D orthogonal sensor matrix.

Measurement of direction of wind flow is based on decomposing of flow velocity vector into x and y components and their measurement by means of several identical sensors.

The sensor system is completed with analog and digital parts. The analog part ensures amplification of differential voltages. The differential voltages are generated by the difference of output voltages of temperature sensors placed in one axis (x or y). Differential amplifiers are placed inside the chip. The error caused by temperature fluctuation influenced by different air heating is minimal in relation to the output voltage. This error can be compensated, for example, using the mode of constant chip temperature (i.e. feedback control of constant average chip temperature).

Analog signals are processed in the digital part. Signal processing, computations, control of signal transmission and other functions are controlled by a microprocessor. This design of the equipment gives possibility to form external multiplex bus at output terminals. It is possible to connect an external memory or other circuits to the bus. The arrangement of the whole system is shown on figure 2.

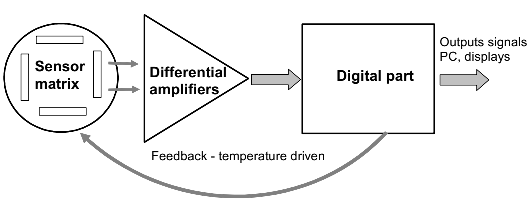

Figure 2: Measuring anemometric system.

Modern technologies of microsystem production are progressive, however often expensive in comparison with standard CMOS technologies. They require frequently non-standard technological steps. Presented anemometric system has been designed using CMOS technology. The sensor system has not high demands on speed of electronic circuits. Libraries of the CADENCE design system available at the university have been used for design.

To determine the flow direction, we must use four identical temperature sensors and heaters by means of which we can measure v_x and v_y components of the flow vector. For the measurement we can use the temperature gradient implemented using two temperature sensors S_1 (temperature υ_1) and S_2 (temperature υ_2) – see figure 3.

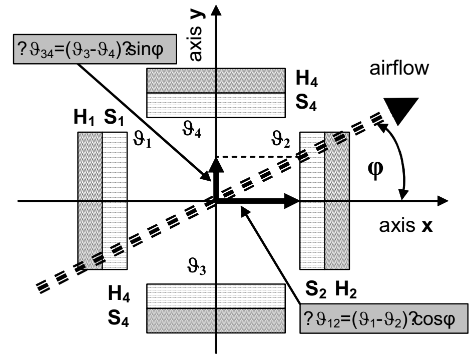

Figure 3: Two-dimensional direction of sensor arrangement.

Different surface cooling by the airflow causes the temperature gradient. Heater H_1 is cooled more than heater H_2, because the air is heated by the heat of H_1 and cooling of H_2 is reduced. Sign of the temperature difference changes when direction of the flow is changed by 180^o. A simple direction sensitive sensor can be designed using two heaters and sensors placed symmetrically. The temperature difference $\Delta\vartheta_{12}=\vartheta_1-\vartheta_2$ is measured for the purpose. For the flow vector having angle φ (see figure 3), the direction sensitivity in x-axis and y-axis may be expressed as

$$\text{X-axis: } \Delta\vartheta_{12} = (\vartheta_1 - \vartheta_2)\cos\varphi \tag{1}$$

According to sensor arrangement showed in figure 3, it is possible to measure flow direction up to 180^o. The range of measurement can be increased up to 360^o using two orthogonal couples of heaters and temperature sensors - see figure 3. Sensitivity of the sensors in axes **x** - see equation (1), sensitivity in the axes y is

$$\text{Y-axis: } \Delta\vartheta_{34} = (\vartheta_3 - \vartheta_4)\sin\varphi \tag{2}$$

According to the presented relations we can obtain table of signs for single-valued determination of angle φ. Sensors S_1 thru S_4 measure temperature of the heaters ϑ_1 thru ϑ_4. Output sensor voltages V_1 thru V_4 correspond to measured temperatures. Voltage difference $V_{12}=V_1-V_2$ corresponds to temperature difference $\vartheta_{12}=\vartheta_1-\vartheta_2$. The velocity of airflow over the chip can be computed from the equation

$$|v| \approx (V_{12}^2 + V_{34}^2)^{1/2} \tag{3}$$

2 SENSOR SYSTEM DESIGN

2.1 Mathematical model of the system

The temperature sensors S1 thru S4 are designed as matrices of 9 NMOS transistors. The operating points are set in the area of strong inversion (overthreshold mode of the transistor). The temperature dependence of mobility of charge carrier is dominant there. It causes decrease of drain current of

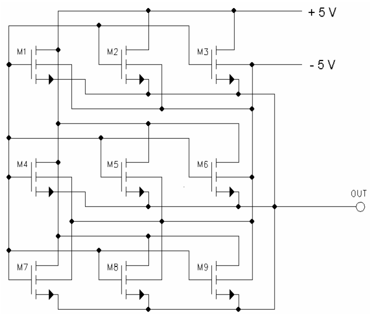

Figure 4: One NMOS temperature sensor.

the transistor in dependence on increasing temperature at constant voltage on the gate. Connection of one temperature sensor is shown on figure 4. There are 4 temperature matrices on a chip. They constitute 2 pairs with mutually orthogonal geometrical layout. Differential amplifiers process the output signals. The differential output signals are sent to the digital computational part. It serves for computation of the direction of airflow using goniometric functions. The connection allows to compensate influence of the environment temperature and responses to fast dynamic changes. Simulation of properties of temperature sensor has been realized on different levels. Used design flow is illustrated on figure 5.

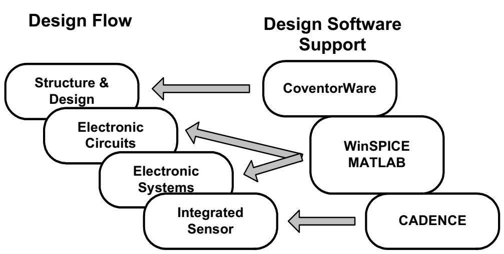

Figure 5: Design flow.

It is necessary to use models on system level for correct complex functioning of the designed sensors. On lower levels, further types of models can be used: models on the level of individual energy domains, physical models, etc. In the design process, there can be used equivalent models that operate with quantities from various energy domains. Modeling and simulation on various sensor levels are utilizes for optimal sensor design [2].

Behavior of a sensor or sensor block can be described by differential equations whose form is dependent on physical nature of corresponding sensor activity. Mathematical modeling of a sensor is a powerful tool in assessing its performance. Mathematical models are utilized for equivalence generation. Physical laws are applied to these models. Results are models with simple lumped parameters. Mechanical and thermal elements can be converted in this way to equivalent electric connection. For solving this electric model, well-known and elaborated methods for electric circuits can be used.

Thermal, mechanical and electric behavior of the structure has been modeled in the process of design of the temperature sensor. There have been modeled temperature flows over the structure, distribution of thermal field, and mechanical behavior of the structure at temperature changes. Equivalent models with electric parameters have been created. The CoventorWare software tool has been used for modeling of mechanical and electric parameters.

Different structure models were used for the design. Analytic model of the structure was used for WinSPICE simulation. The MATLAB program was used as well.

HARD model of the system has been realized for verification of the basic functions. This model illustrates characteristics and behavior of the designed sensor model.

2.2 Design of temperature matrix with direction sensitivity

The analog part contains sensitive temperature sensors, circuits for signal processing, power temperature sensors, power stages, invertors and differential amplifier. In the analog part, the design of velocity measurement and flow direction measurement are treated separately. This enables to simplify microcomputer program for display control and calculation of the absolute values of the flow velocity. Block diagram of the analog part is shown in figure 6.

The sensors S_1 and S_2 are used to determinate the velocity vector components, i.e. to determinate the flow velocity direction. The sensors measure angle of the flow. Velocity vector component in x direction is represented by V_1-V_2 difference signal; velocity vector component in y direction is represented by V_3-V_4 difference signal. Principle of the "constant power supply" has been used for the flow velocity measurement.

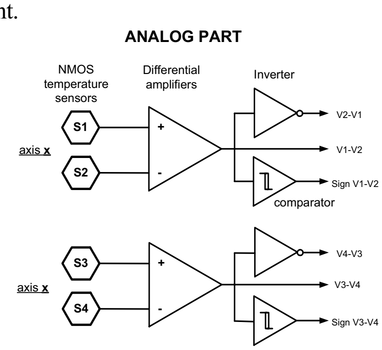

Figure 6: Block diagram of the sensor part for measurement of velocity and flow direction.

Digital part for the velocity measurement is composed of an A/D converter and a data transmitter, for direction measurement there is used an A/D converter, a microcomputer - see figure 7. For flow direction measurement, the analog multiplexer is used to switch over the signals for difference signal processing in the microcomputer. It enables to choose an appropriate signal for the microprocessor according to the level of the control signal

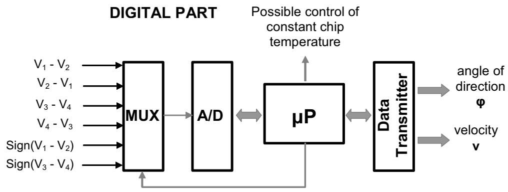

Figure 7: Block diagram of the digital part of the system.

at the microprocessor inputs. Microcomputer controls the system and data processing. One controls the whole measurement of flow direction, provides correct data processing and calculation of φ angle.

3 REACHED RESULTS

In the process of measurement of transfer characteristic there have been primarily measured transfer characteristics of sensor part with output signal V_2-V_1 and V_4-V_3.

There have been simulated output values of individual differential amplifiers with the output voltage V_{OUT} in dependence on temperature difference between individual sensors from the sensor pair ($\Delta\vartheta_{12}=\vartheta_1-\vartheta_2$) for S1 and S2. Similarly there have been performed simulations for the sensor pair S3 and S4. Simulated dependencies of output voltage of the differential amplifier in dependence on the difference of temperatures of sensors S1 and S2 are illustrated in figure 8. Sensor S2 is less cooled by airflow than the sensor S1. Temperature gradient emerges between the sensors. It is function of flow velocity. The course of the simulated temperature gradient can be simulated. It is obvious from the characteristic that the system is most sensitive for small velocities of the airflow.

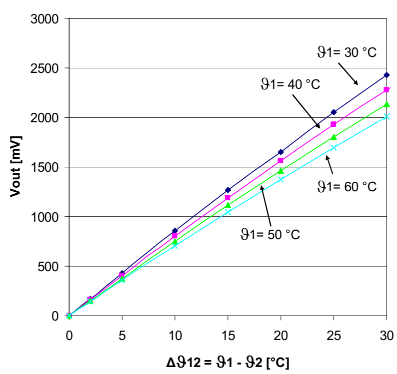

Figure 8: a) simulated output voltage of the diff. amplifier

Based on the results presented in figure 8, it is possible to derive a model for simulation of output voltage from the differential amplifier in dependence on flow velocity. The reached results are shown in figure 9. In the process of measurement of airflow direction, the measurements have been done with the step of 30° rotation.

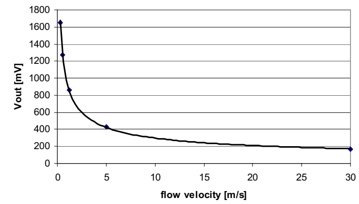

Figure 9: Output voltage of the differential amplifier vs. airflow velocity.

4 CONCLUSION

Anemometric system with integrated temperature probe has been designed. The temperature probe is composed of 4 temperature heaters and sensors. Each sensor contains 9 NMOS transistors. The transistors work in the area of strong inversion. Axes of 2 sensor pairs are perpendicular. The heaters are warmed by electric power. The airflow cools the heaters. From the emerging temperature gradients of both sensor pairs, the airflow velocity and direction are computed.

The real circuit model of intelligent structure has been realized and tested. With the appropriate setup the system is able to measure with resolution of 1°. The accuracy and reproducibility of flow velocity measurement has been evaluated to be 4 per cent and has been the same as accuracy and reproducibility of measurement of airflow direction. The system is able to measure airflow higher than 0.5 m/s. The digital part can be extended with a RS 232 interface to a PC.

Different structure models have been used for the design. Analytic model of the structure has been used for WinSPICE simulation. The MATLAB program has been used as well. Mechanical properties of the structure have been modelled using the CoventorWare program.

The measurements have been realized in a wind tunnel with airflow. Maximal reachable airflow velocity is 30 m/s.

5 ACKNOWLEDGEMENTS

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