Hot Wire Anemometric MEMS Sensor for Water Flow Monitoring

Massimiliano Melani1, Lorenzo Bertini2, Marco De Marinis2, Peter Lange3, Francesco D’Ascoli1, Luca Fanucci1
1 Department of Information Engineering, University of Pisa, Via Caruso, 56122, Pisa, Italy
2 SensorDynamics AG, Via Giuntini 25, I-56123 Navacchio (Pisa), Italy
3 Fraunhofer Institute for Silicon Technology ISIT, Fraunhoferstrasse 1, D-25524, Itzehoe, Germany

Abstract

This paper presents an application based on a hot wire anemometric sensor in MEMS technology in the field of water flow monitoring. New generations of MEMS sensors feature remarkable savings in area, costs and power respect to conventional discrete devices, but as drawback, they require complex electronic interfaces for signal conditioning to achieve high performances and a high reliability. This anemometric sensor implementation has been developed with ISIF, a Platform SoC, aiming to fast prototype a wide range of sensors thanks to its high configurable resources.

The presented system achieves good performances with respect to commercial devices, featuring resolution of ±0.35% up to ±1.76% with repeatability roughly ±1% respect to the full scale (0-250 cm/s). Furthermore the proposed system, thanks to the compact size of the sensor, its robustness and its low costs can represent a solution for diffusive monitoring in water distribution networks.

1. Introduction

Mass flow sensors are widely employed in measurement systems whose application field ranges from industry (e.g. in process control for dosing reagents and combustibles, in cooling and purification plants) to domestic monitoring of potable water. Such wide and particular application fields brought to a consequent development of tailored typologies of flow sensors which differ each other for the operating measurement principle. However they typically consist in expensive and cumbersome devices, which sometime induce perturbations in the measurement line.

For the above mentioned issues, in the last few years, the academic and industrial research is tended towards the development of integrated flow sensors which offer the noticeable advantage of cost reduction, due to the large scale production, and can open the way to a progressive measurement devices miniaturization [1].

Furthermore, thanks to the recent developments in silicon micromachining technology, both the sensing elements and the conditioning electronics can be integrated in micro electromechanical devices (MEMS) featuring a drastic reduction in cost, area, and power, leading to harder disturbances rejection due to the thigh interconnection reduction. The scaling down of the sensor size also allows faster response to be obtained and guarantees a higher reliability, reducing movable structures thanks to more compact designs.

In literature we can find several examples of measurement methodologies for flow detection based on different physical principles according to the particular environment and to the requested specifications (fluid characteristic, measurement interval, desired timing of the response). Some sensors perform flow detection through a pressure variation in the measuring line obtained with porous sections or different section size in the line (Venturi effect). Other sensors exploit area variation, fluid dynamic turbulences, or mechanical turbine wheel [4]. All above mentioned sensors perform an “intrusive” measurement, since they induce a perturbation in the flow under test due to the considerable interaction between the sensor and the fluid itself (e.g. a pressure loss). These devices usually require a consistent effort in setting up the sensing equipment on the line under test.

Another class of “non-intrusive” sensors performs the measurement without affecting the flow under test, basing their interaction on energy transfer, (thermal, ultrasonic or electro-magnetic) [1-3]. These sensors avoid moving structures thus resulting more compact and robust and easier to manufacture, best nating the requirements for micromachining tooling. On the other hand electromagnetic sensors, in order to achieve good sensitivity, require a sufficient magnetic induction that is no so easy to provide in integrated inductances, while technological problems arises with devices for emitting and receiving ultrasounds, especially when they are in water. Thermal
sensors embody optimal candidates for MEMS integration thanks to their thickness, good sensibility and simple structure. In particular this paper focuses on hot wire anemometers. In literature we can find several examples of integrated anemometers, in particular targeted for microflow detection [5-7].

This paper presents the development of an anemometric hot wire sensor application in MEMS technology for water flow monitoring in potable water pipes for typical range of speed flow (from low flow up to few m/s) using the ISIF platform [8], a mixed signal system-on-chip concepted to speed up and ease a Platform Based Design Flow for optimized sensor interfaces. In section 2 the proposed sensor operating principle is depicted, in section 3 ISIF architecture is disclosed, while in section 4 implementation details are provided. Results are displayed in Section 5 and finally conclusions are drawn and next steps are hinted.

2. Physical description of proposed sensor

A thermal anemometer refers to sensors that measure total heat loss from some heating elements (e.g. resistors) cooled by the fluid. This heat loss is related to the flow rate of the fluid and increases or decreases with regard to the flow speed. The anemometer principle features three main different operating modes: constant current, constant power, or constant temperature. The former two operating modes feature simple circuit implementation while the latter one maintains a fixed value of the sensing resistor thus achieving more robustness respect to changes of the temperature of the fluid itself [2].

![Figure 1: MAF sensor scheme](image)

The proposed sensor is equipped with two complete half-bridges (figure 1) composed by a couple of heater resistances ($R_h$) and a reference resistances ($R_t$) lodged on a thin membrane. This MAF (Mass Air Flow) sensor was originally designed for automotive but is also suitable for all applications of flow control of gaseous and fluid media. The design of the MAF sensor is based on standard MOS semiconductor batch processes, available for high volume, low cost production at FHG/ISIT.

The primary sensor of this measurement tool is a heated wire ($R_h$ of 50.0 ±0.5Ω) that is exposed in a flow. A second sensor ($R_t$ of 2000 ±30Ω) is used to measure the ambient (fluid) temperature. It is worth noting that the reference resistances are interdigitated to provide the two half bridges the same reference [10].

As the fluid passes over the hot wire, it carries away heat. The heat loss depends on the flow rate, the heat capacity of the fluid, and the temperature difference between the wire and the fluid. Since the heat capacity of the fluid is known and the temperatures are monitored in real-time, the flow rate can be determined from the heat loss (related to the electrical resistance of the wire via the Ohm’s law) and the temperature coefficient of the wire. The wire resistance $R_h$ is a function of temperature according to (1), with $R_0$, the heater resistance at reference temperature $T_{ref}$ (ambient). Implementing constant temperature operating mode the temperature of the heated wire ($T_h$) relative to the ambient temperature ($T_{ref}$) is kept constant by a Wheatstone bridge [2]. The current $I$ (or voltage $U$) which is needed therefore, is proportional to the mass flow.

$$R_h = R_0 \left[ 1 + \alpha (T_h - T_{ref}) \right]$$

However, there are deviations from a linear dependence according to the “King’s Law”. The King’s law takes account for the different contributions to the heat transfer through the boundary layer by convection and conduction with flow and is empirically described in (2).

$$I^2 R_h = U^2 = (T_h - T_{ref}) (A + Bv^n)$$

The voltage drop (U) is used as a measure of velocity ($v$). The constants A, B and the exponent n are empirically determined and ambient specific. This nonlinearity must be compensated by a special signal conditioning. For the measurement of the direction of a flow the heating resistors are arranged twice on a chip in a way that they are adjoined closely in parallel. The fluid picks up heat at the first resistor and transfers this to the second resistor. The results are different cooling effects on the two resistors. This difference can be taken for the measurement of directionality.

The thin wires are deposited on a thin membrane, which is a stack of three layers – Siliconnitride, Silicondioxide and Siliconnitride. These layers are formed in LPCVD (Low Pressure Chemical Vapor Deposition) processes, which generate highly stoichiometric layers without contaminants and high long-time reliability. The membrane is formed by anisotropic KOH etching and shows only slightly tensile stress, which results in high mechanical stability. Beyond this, the membrane enables a high thermal isolation of the heated wires to the chip edges. The membrane with the wires is subsequently
covered with a Siliconnitride layer formed in a Plasma Enhanced CVD process. This final passivation is known to be inert against most environmental detrimental effects and is also biocompatible. For the application in water the backside cavity is filled with a flexible organic material with significant lower heat conduction as water. This assures an explicit signal from the front side, and prevents uncontrolled fluctuations on the backside. In addition an enhanced stability against water pressure is achieved. The resistors are made of Titanium and completely covered with a nanolayer of Titaniumnitride to eliminate any reaction of Titanium with adjacent media. The Ti/TiN resistors show no drift due to electrical or temperature stress. Production of this chip is done in a Standard MOS-line. Thus it can be manufactured in quantity with guaranteed uniformity, a factor that is critically important to manufacturers. A schematic cross-section of the device is given in figure 2.

ISIF (Intelligent Sensor Interface) is a mixed-signal SoC conceived to speed up a Platform Based Design Flow, which significantly reduces the time needed for design space exploration and system architecture validation.

In figure 3 ISIF block diagram is described: an analog front end for sensor driving, signal acquisition, and basic analog conditioning; a digital DSP section based on LEON core; and peripherals for communication with external devices, memories and buses (AMBA APB/AHB). ISIF platform has been developed by SensorDynamics AG in collaboration with Pisa University and it is implemented on 0.35µm BCD6 STMicroelectronics technology into a single chip with area occupancy of 72mm² [8].

An input/output test bus is provided to supply stimuli and to probe output signals for each block. This system also features separated analog and digital power supplies for noise margin improvement and a JLCC approach for handling the digital bits used for analog block configurations, featuring safe communication between digital and analog sections.

The digital hardware section is based on the LEON core CPU, a 32-bit RISC SPARC-V8 compliant architecture, which features hardware multiplier and divider, interrupt controller, memories busses and peripherals for external communication. The digital signal processing section is composed by dedicated IPs optimized for low power consumption such as modulator and channel demodulators, a 6 DAC controllers, filters (FIR and IIR) and sine wave generator. These IPs are connected each other by hardware but can be also accessed at their input or output by software.

The CPU potentiality joined with the flexibility and configurability of the DSP section allows designers to implement ad-hoc algorithm for the target sensor, combining hardware processing with software routines [9]. The digital section is completed by standard IPs such as timers, watchdog SPIs (Serial Peripheral Interface), UARTs (Universal Asynchronous Receiver Transmitter) CACHE, ROM RAM and EEPROM memories.
The industrial requirements are pushing towards hardware solution, especially for safety applications, on the other hand digital IPs require detailed and exhaustive analyses to guarantee complete reliability and for proper parameter settings in order to achieve high performances with reasonable area (thus reduced number of trimming bits). Furthermore the presence of non-linearity and parasitic often invalidate the design exploration making a right first time silicon difficult to achieve.

To meet these requirements ISIF platform includes a library of software peripherals (e.g. filters, controllers) with an exact matching with hardware devices. The LEON CPU, thanks to its good signal processing features, guarantees flexibility and required computational power for real-time software IPs implementation.

These features help the designers to carry on a quick and exhaustive design space exploration changing analog settings, interconnecting digital IPs and even instantiating new ones finding the fittest solution in interfacing a target sensor, both in term of area and performances.

It is worth noticing that ISIF platform is not tended towards a solution with best performances but aims to provide an accurate emulation of a complete hardware interface optimized for the target sensor. In the final ASIC device, software routines can be quickly replaced by corresponding hardware IPs with low risks and costs for redesign, minimizing time to market.

4. Implementation of MAF anemometer

In this section an ISIF implementation with the MAF sensor in water is described.

The MAF driving scheme is depicted in figure 5. The input channel is configured to operate as instrument amplifier and the signal is acquired between the heater resistance and the reference resistance which are connected in a standard Wheatstone bridge structure. Further analog stages perform low pass filtering and gain adjustment.

The digital section decimates the ΣΔADC output and low-pass filters. Closed loop is implemented by software-emulated IPs which feature reference subtraction, PI controller and feedback actuation directly to supply the two bridges. Since the driving scheme for this anemometric sensor keeps constant temperature [2], the digital output of the PI controller, which represents the voltage supplied to the two bridges, is proportional to the water flow. This output signal requires further filtering (with an IIR filter down to the bandwidth of 0.1 Hz) in order to improve the sensitivity. The system, thanks to ISIF high configurability, also provides the monitoring of a commercial magnetic water flow sensor (Endress and Hauser Proline Promag 50) for comparing and calibrating the MAF sensor and a temperature sensor for tracking thermal flow variation.

\[
Ca(HCO_3)^- \rightarrow CaCO_3 + CO_2 + H_2O \tag{3}
\]

In figure 6 the board set-up for the evaluation of the MAF sensor with ISIF is depicted; particular attention has been used for MAF sensor contacts for avoiding water infiltration in the wet ambient, furthermore the board was protected by complete plastic coverage.
Secondly, a proper assembly for the sensor housing is essential to protect the contacts from leakage current and corrosion problems in the water aggressive environment.

The first problem (figure 7) can be overcome adopting a pulsed voltage driving technique instead of continuous sensor biasing in conjunction with reduced overtemperature of the heating element respect to water (compared to air environment). Due to the extremely thin membrane technology (2 µm thickness including the passivation layer) the response times are reasonable short, even in water, this prevents significant heating of the device and ambient.

A first prototype has been developed and is shown in figure 9: the sensor is placed onto a ceramic board with glob-top glue to protect wire bonding in order to prevent water creeping underneath. The ceramic is housed in a stainless-steel pipe for insertion in the potable water tube. The sensor head is set parallel to the flow and its profile has been smoothed to introduce low perturbations in the flow, minimizing turbulence on the sensing elements.

5. Results

The proposed system has been fully tested in a water station for city distribution in Tuscany near the Arno river in Vinci in collaboration with the local responsible water supplier Acque s.p.a.. The whole set-up consisted in a dedicated line for the measurements, derived from conventional water lines, in which pressure and water speed could be fine tuned. The line was also equipped with a commercial high resolution magnetic water meter (Promag 50) and with a transparent section for monitoring the water flow and the correct position of the sensor in the tube (figure 10).

The system has been tested to cover a typical range of flow speed for a water station ranging from 0 to 250 cm/s with pressure variance form 0 up to 3 bar with peaks of 7 bar. The flow direction was clearly detected and the resolution is in the range of ±0.75 cm/s to ±4 cm/s (worst-case) that is ±0.35% up to ±1.76% with repeatability roughly ±1% respect to the full scale.

Compared to commercial devices, as for example magnetic system like Promag 50 (resolution lower than ±0.5% respect to full scale), this implementation features a slightly higher noise but dramatically reduces the cost of more than one order of magnitude, thus representing a solution for diffuse water distribution monitoring. The proposed system achieves the same accuracy of the turbine wheel devices with cost reduction and improved reliability since no mechanical moving parts are exposed in water. Furthermore the sensor proved no corrosion or
pollution on the surface after several months of test and no deposit of calcium carbonate.

6. Conclusions

A hot wire anemometer in MEMS technology for water flow monitoring has been presented. This application has been developed and supported by the ISIF (Intelligent Sensor Interface). ISIF is a powerful Platform On Chip, developed by SensorDynamics AG in collaboration with the University of Pisa, in 0.35 µm BCD technology, aiming to fast prototype a wide range of sensors.

The presented system shows good performances with respect to commercial devices, featuring resolution of ±0.35% up to ±1.76% with repeatability roughly ±1% respect to the full scale, achieving considerable costs reduction.

A prototype has been developed: a steel pipe equipped with a sensor head, which is inserted into water, and fulfills the following requirements: contacts robustness, no water infiltration through the sensor board, smooth pipe profile. These devices have been tested with respect to mechanical resistance against pressure, pollution of the surface, corrosion of electrical contacts and drift in resistance values. Furthermore thanks to the compact size of the prototype and its robustness it can be inserted in the water tube without stopping the flow directly with insertion in pressure techniques.

Nowadays water monitoring is limited only to key points in the distribution network, due to the high cost of reliable equipment and their difficult connection to the pipes (e.g. need to stop water flow). The presented measurement system, thanks to the easy insertion, the good resolution and the low cost, features a precise measurement water sensing equipment that can be widely diffused all over the water distribution channels: allowing also any malfunction behavior (e.g. water loss in tube), more usual in peripheral part of the networks, to be immediately localized and isolated. The proposed application has been patented on the Italian Patent Office.

7. Next steps

Starting from the proposed system implementation with ISIF, a proper asic for MAF sensor interfacing can be designed, optimizing area and power consumption, with very low risk. Furthermore proper miniboard can be developed to house the conditioning electronics directly in the pipe close to the sensor to reduce parasitics and to increase resolution.

The dedicated asic, currently in fab, features advanced low power techniques with deep sleep mode for a considerable power saving allowing the whole system to be supplied by rechargeable batteries (4 alkaline AA) that guarantee autonomy of one year for a typical sensor usage.

8. Acknowledgements

The authors wish to thanks Acque Engineering s.p.a., in particular Damasco Morelli and Francesco Branchitta for fruitful discussions and precious technical support.

9. Reference