11th International Conference on Electrical, Electronics and Computer Engineering (IcETRAN), Nis, 3-6 June 2024

On the Design of a MEMS Multisensor Instrument for Aerodynamic Pressure Measurements

Miloš Frantlović
Department of Microelectronic Technologies,
University of Belgrade – Institute of Chemistry, Technology and Metallurgy – National Institute of the Republic of Serbia
Belgrade, Serbia
frant@nanosys.ihtm.bg.ac.rs
0000-0002-6015-8489

Žarko Lazić
Department of Microelectronic Technologies,
University of Belgrade – Institute of Chemistry, Technology and Metallurgy – National Institute of the Republic of Serbia
Belgrade, Serbia
zlazic@nanosys.ihtm.bg.ac.rs
0000-0003-1797-6248

Milče Smiljanić
Department of Microelectronic Technologies,
University of Belgrade – Institute of Chemistry, Technology and Metallurgy – National Institute of the Republic of Serbia
Belgrade, Serbia
smilce@nanosys.ihtm.bg.ac.rs
0000-0002-3420-0823

Ivana Jokić
Department of Microelectronic Technologies,
University of Belgrade – Institute of Chemistry, Technology and Metallurgy – National Institute of the Republic of Serbia
Belgrade, Serbia
ijokic@nanosys.ihtm.bg.ac.rs
0000-0002-1397-5996

Predrag Poljak
Department of Microelectronic Technologies,
University of Belgrade – Institute of Chemistry, Technology and Metallurgy – National Institute of the Republic of Serbia
Belgrade, Serbia
predrag.poljak@nanosys.ihtm.bg.ac.rs
0000-0001-9810-8957

Dušan Nešić
Department of Microelectronic Technologies,
University of Belgrade – Institute of Chemistry, Technology and Metallurgy – National Institute of the Republic of Serbia
Belgrade, Serbia
nesicad@nanosys.ihtm.bg.ac.rs
0000-0002-8046-5697

Miloš Vorkapić
Department of Microelectronic Technologies,
University of Belgrade – Institute of Chemistry, Technology and Metallurgy – National Institute of the Republic of Serbia
Belgrade, Serbia
worcky@nanosys.ihtm.bg.ac.rs
0000-0002-3463-8665

Dragan Tanasković
Department of Microelectronic Technologies,
University of Belgrade – Institute of Chemistry, Technology and Metallurgy – National Institute of the Republic of Serbia
Belgrade, Serbia
dragant@nanosys.ihtm.bg.ac.rs
0000-0003-2606-219X

***Abstract*—In this paper we present the concept of a novel MEMS multisensor instrument for aerodynamic pressure measurements, and discuss the main aspects of its design. Designing of such instrument is a complex task, especially because of high requirements regarding miniaturization, measurement performance, the number of pressure measurement channels, and other features. The main goal of the presented work is to address these requirements in an innovative way. A novel multisensor chip, which has been designed and fabricated, is an important step towards further miniaturization and higher measurement performance of aerodynamic pressure measurement instruments. Multisensor modules, which contain the multisensor chips and accompanying connections and circuitry, enable modularity and reconfigurability of the instrument. The novel hardware architecture has a separate signal path for each of the pressure channels, and is capable of synchronous pressure measurement on all channels. Digital signal processing enables high measurement performance, and can be used to implement fault detection capabilities. The final goal of the presented work is to combine these concepts into a high-performance and innovative instrument for aerodynamic testing, which is a useful tool for several scientific and industrial fields.**

***Keywords*—MEMS, multisensor, instrument, pressure**

This research was supported by the Science Fund of the Republic of Serbia, Grant No. 7754287, MEMS Multisensor Instrument for Aerodynamic Pressure Measurements – MEMSAERO. It was also supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia, grant number 451-03-66/2024-03/200026.

I. INTRODUCTION

Aerodynamic testing of various objects and structures is important for several scientific and industrial fields, from fluid dynamics research to architecture and civil engineering. It is performed on moving or stationary objects, from vehicles, wind turbines, bridges and buildings to sports equipment. Such tests enable optimization of various characteristics, including energy efficiency, and can be beneficial for some emerging concepts and technologies, such as smart buildings and smart cities. Aerodynamic testing requires pressure measurement to be performed at a multitude of points on aerodynamic surfaces or other features of the tested object. Typically, the air pressure from the measurement points is transferred by flexible tubing to one or more multichannel sensing devices. Such sensing devices are called pressure scanners, because their early implementations were based on one pressure sensor and a multiplexing valve that sequentially connects individual pressure channels to the sensor. Aerodynamic tests are often carried out in well-controlled measurement conditions (wind tunnels), but some other measurement scenarios require aerodynamic experiments to be performed in the open space (e.g. buildings, bridges, wind turbines, a racing car on the track etc.). In both cases, it is often necessary to place the measurement equipment within very spatially constrained structural parts or objects. Apart from the need for miniaturization, such applications require high accuracy in a wide temperature range, fast channel scanning, and a large number of channels. These requirements make further development of pressure sensing instrumentation very challenging. The main objective of the research presented here is to address these requirements in an innovative way. A high level of miniaturization is achieved through the development and fabrication of the novel micro-electromechanical systems (MEMS) multisensor chip with a matrix of integrated sensing elements. New instrument architecture is developed in order to enable synchronous and high-throughput pressure measurement on all channels, which can provide a better insight in some unsteady aerodynamic effects. Reconfigurability is achieved by using two multisensor modules exchangeable by the user. High measurement performance is to be achieved through advanced mixed-signal hardware and digital signal processing.

II. Concept

The multisensor instrument for aerodynamic pressure measurements is envisaged as a miniature, modular, and reconfigurable device. Its main parts are the signal processing unit (within the instrument enclosure), and two exchangeable multisensor modules, as illustrated in Fig. 1.

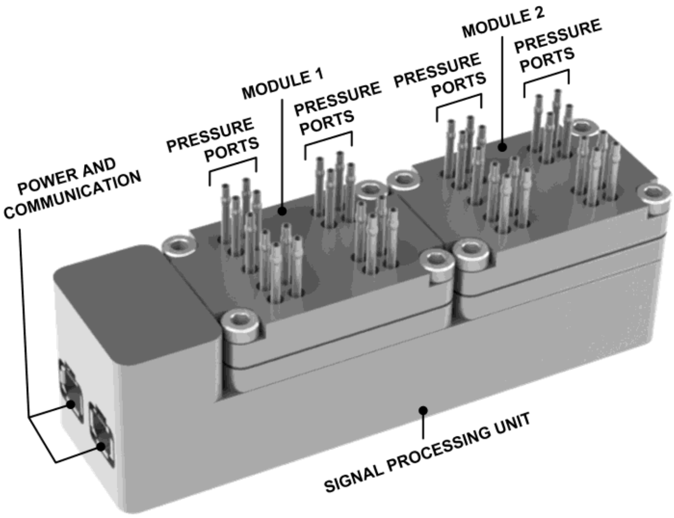

Fig. 1. 3D rendering of the multisensor instrument for aerodynamic pressure measurements.

A. *MEMS Multisensor Chip*

Modern instruments for aerodynamic pressure measurements are typically based on silicon piezoresistive MEMS pressure sensors. Several advantages of such sensors, including their reliability, low cost, and good measurement performance, proved as very beneficial in this application, and their small size has made it possible to use a dedicated sensor for each pressure channel, so the multiplexing valve is not needed. Pressure scanners of the current generation also have one or more temperature sensors built in the pressure sensor housing, for the purpose of temperature compensation.

As an important step towards higher integration, higher performance, and further miniaturization of aerodynamic pressure measurement instruments, a novel dedicated piezoresistive MEMS multisensor chip with a matrix of integrated sensing elements has been developed at the Institute of Chemistry, Technology and Metallurgy (ICTM). It was possible to accomplish this in an efficient and economical manner due to the ICTM’s extensive expertise and long experience in the field of silicon piezoresistive MEMS pressure sensors [1–3]. Although reports on chips with multiple pressure sensing elements exist in the literature [4], the concept and the intended application of the developed chip are quite different.

The photograph of the chip is shown in Fig. 2. The chip contains four piezoresistive MEMS pressure sensing elements, two resistive temperature sensing elements, as well as conductive traces and wire bonding pads for electrical connections. The temperature sensing elements enable temperature sensing directly on the chip. Thermal coupling between the monolithically integrated pressure and temperature sensing elements is much better compared to the case of sensors made as separate components. This is significant for temperature compensation of the pressure sensing elements. Better matching of characteristics of the pressure sensing elements on the same chip is another important advantage. The multisensor chip is described in more detail in [5].

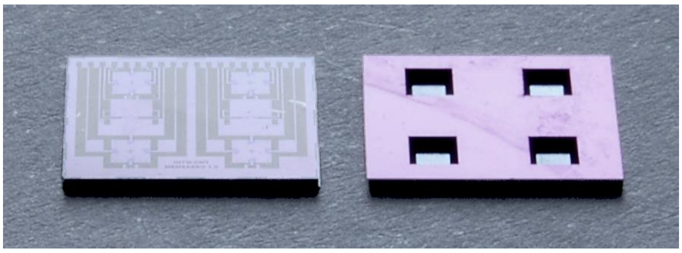

Fig. 2. Photograph of the multisensor chip: top side (left) and bottom side (right).

B. *Multisensor module*

The multisensor module consists of four MEMS multisensor chips mounted in a dedicated, specially designed sensor package, which ensures suitable operating conditions, and also contains electronic circuitry, including a non-volatile memory that stores multisensor parameters. A block diagram of the module is shown in Fig. 3. The module has pressure ports on one side, and all the needed electrical and mechanical connections on the other side. The main advantage of the modular concept is the simplicity of instrument reconfiguration through the exchange of multisensor modules, which can be done by the user.

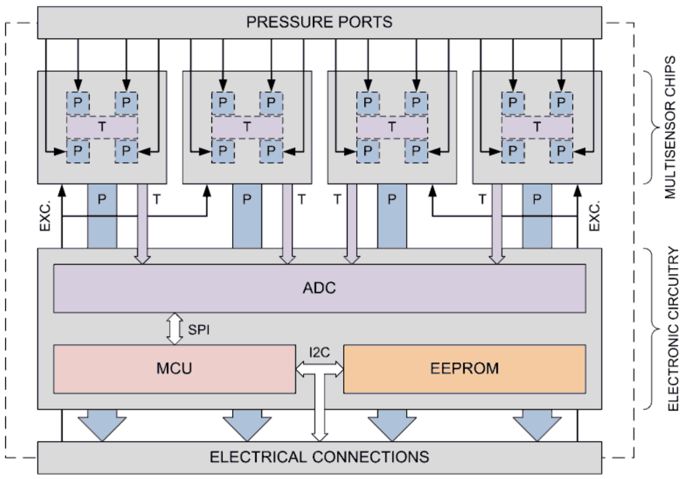

Fig. 3. Block diagram of the multisensor module.

C. Hardware Architecture

The architecture of the multisensor instrument for aerodynamic pressure measurements, shown in Fig. 4, is fundamentally different from the conventional ones, as it eliminates the multiplexing of sensor signals. There is a separate signal path for each of the pressure channels, which includes signal conditioning and analog-to-digital conversion. Digital signal processing is also performed separately for each channel. The main advantage of this architecture is that it enables fully synchronous pressure measurement on all channels (as explained in the paragraph about the analog front-end). In aerodynamic experiments that involve unsteady flow fields and transient phenomena [6], such as turbulences, this feature can be utilized to obtain spatially coherent measurements from a multitude of pressure taps across the tested structure. This architecture also offers some other advantages. Parasitic effects that may be introduced by multiplexing of sensitive analog signals are eliminated. Since there is no settling time after channel switching, the overall measurement throughput can be significantly higher. As the pressure channels do not share the same signal path, the instrument can be reconfigured in order to use different combinations of sensors (within multisensor modules), with different pressure ranges or different electrical characteristics.

The signal processing unit is the main sub-system of the instrument, to which the multisensor modules are connected, and it also provides the connections to external equipment. It consists of the high-performance analog front-end module and the data processing and communication module.

The analog front-end module is a separate printed circuit board with two main functions: 1) analog-to-digital conversion of differential voltage signals from all pressure sensing elements in multisensor modules, and 2) sensor excitation of all sensing elements. Regarding the analog-to-digital conversion, two confronting requirements had to be fulfilled: high-performance and high-throughput measurements on all pressure channels simultaneously, and keeping the used space at minimum for miniaturization. This is achieved by using synchronized simultaneously sampling 8-channel 24-bit analog-to-digital converters (all the signals are sampled at the same time, and the digital data are transferred sequentially via the SPI interface). Sensor excitation is programmable, in order to adapt to different multisensor chips and modules. To minimize the power supply noise, the analog front end board is equipped with an ultralow-noise voltage regulator, and the digital communication signals are isolated from a noisier external power domain by level translators.

The data processing and communication module is a separate printed circuit board with the following functions: 1) control of the front-end module (including the connected multisensor modules), 2) acquisition of the measurement data from all the pressure and temperature channels, 3) processing of the measurement data, 4) communication with external equipment, 5) sending of the measurement data by using a suitable communication interface and protocol, 6) power supply and power management. The functions from 1) to 5) are performed by a dual core ARM Cortex-A7 microprocessor, with an integrated ARM Cortex-M4 microcontroller core used for real-time tasks [7]. The Cortex-A7 cores are intended to be used with the Linux operating system, which makes software development and maintenance much more efficient.

D. Digital Signal Processing

There are multiple aspects in which digital signal processing can be beneficial for this application, including measurement accuracy and stability, detection and correction of various anomalies, extracting additional data etc.

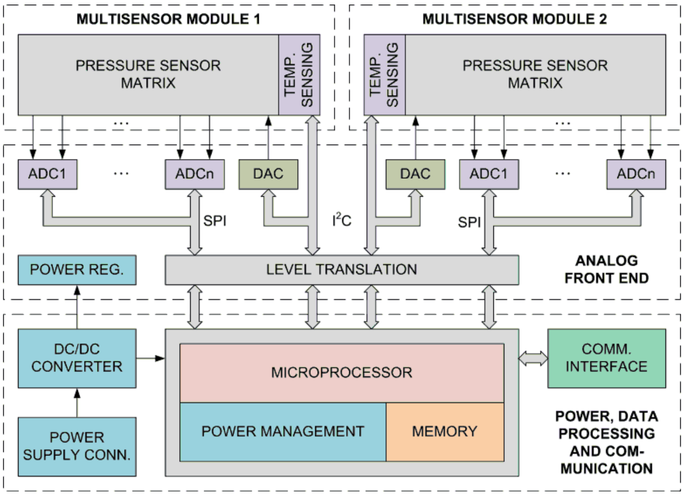

Fig. 4. Architecture of the multisensor instrument for aerodynamic pressure measurements (simplified block diagram).

Introduction of digital signal processing has led to vast improvements of sensor correction performance, resulting in much lower measurement uncertainties. In this case, estimations based on our first pressure measurement results indicate that the pressure measurement uncertainty significantly lower than 0.1 %FS can be achieved. A diagram showing the calibration function (pressure indication as a function of both the output voltage of a pressure sensing element, and temperature) of one of the pressure sensing elements is given in Fig. 5.

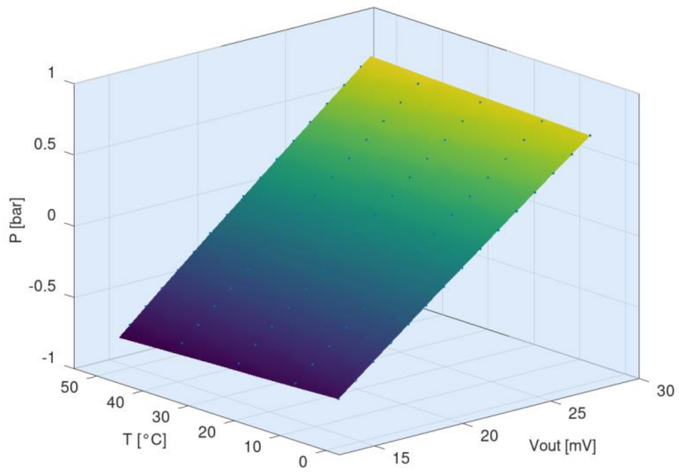

Fig. 5. Calibration function of a pressure sensing element.

Aerodynamic measurements can be significantly impaired by the failure of individual pressure sensing elements. Therefore, a fault detection capability is an important additional feature of the instrument. In order to facilitate fault detection, auxiliary measurement channels are built into the instrument's hardware, in addition to the pressure and temperature channels. At a later stage of our research, it is planned to use these channels, together with the pressure and temperature channels, to detect a fault and isolate a faulty sensing element on a multisensor chip.

III. Conclusion

In this paper we discussed several important aspects of the design of the novel MEMS multisensor instrument for aerodynamic pressure measurements, which is in development at ICTM. The main goal of the presented work is to address the increasingly high requirements for such instruments in an innovative way. After the Introduction, a brief overview was given of the instrument's overall concept. Subsequently, the concept and design of the main modules and building blocks of the instrument were described, with the emphasize on the specific problems to be solved and innovative aspects of the chosen solutions. The novel multisensor chip is an important step towards higher integration, higher performance, and further miniaturization. Its realization is a significant scientific and technological result. Apart from being a housing of multisensor chips and accompanying connections and circuitry, the multisensor modules enable simple reconfiguration of the instrument, which can be done by the user. The novel hardware architecture is fundamentally different from the conventional ones, as it has a separate signal path for each of the pressure channels. It enables fully synchronous pressure measurement on all channels, and thus can be used to obtain spatially coherent pressure measurements from a multitude of measurement points. Digital signal processing enables high measurement performance and, together with dedicated hardware resources, can be used to implement fault detection capabilities.

The development of the MEMS multisensor instrument for aerodynamic pressure measurements is a complex task, which is still in progress. Its final goal is to combine the design concepts presented in this paper into a high-performance and innovative instrument, which is a useful tool for several scientific and industrial fields.

References

[1] Z. Djurić, M. Matić, J. Matović, R. Petrović, N. Simičić, "Experimental determination of silicon pressure sensor diaphragm deflection", Sens. Actuators 1990, 24, pp. 175–179.

[2] N. Simičić, D. Tanasković, Z. Djurić, Ž. Lazić, R. Petrović, J. Matović, M. Popović, M. Matić, D. Totovski, "Investigation of impurity distribution for pressure sensor piezoresistors", J. Serb. Chem. Soc. 1993, 58, pp. 951–957.

[3] M. M. Smiljanić, V. Jović, Ž. Lazić, "Maskless convex corner compensation technique on a (1 0 0) silicon substrate in a 25 wt% TMAH water solution", J. Micromech. Microeng. 2012, 22, 115011.

[4] J. Zhang, J. Chen, M. Li, Y. Ge, T. Wang, P. Shan, X. Mao, "Design, fabrication, and implementation of an array-type MEMS piezoresistive intelligent pressure sensor system", Micromachines 2018, 9, pp. 104.

[5] Ž. Lazić, M. M. Smiljanić, D. Tanasković, M. Rašljić Rafajilović, K. Cvetanović, E. Milinković, M. V. Bošković, S. Andrić, P. Poljak, M. Frantlović, „Development of a MEMS multisensor chip for aerodynamic pressure measurements", Eng. Proc. 2023, 58, 52.

[6] T. Wolff, J. R. Seume, "Modeling the transient aerodynamic effects during the motion of a flexible trailing edge", Journal of Physics: Conference Series, 2016, 753, 8, 082038.

[7] STMicroelectronics, "Arm® dual Cortex®-A7 800 MHz + Cortex®-M4 MPU, 3D GPU, TFT/DSI, 37 comm. interfaces, 29 timers, adv. analog, crypto", STM32MP157C/F datasheet - production data, November 2022.