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NOVEL INSTRUMENT FOR AERODYNAMIC PRESSURE MEASUREMENTS WITH EXCHANGEABLE MULTISENSOR MODULES

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Abstract: *Aerodynamic properties of objects such as aircraft, road and railway vehicles, wind turbines etc. are crucial for their operation, and must be tested during their development. In the case of large stationary objects such as bridges and buildings, aerodynamic effects are also important, and must be assessed. Key equipment for performing aerodynamic tests are multichannel pressure measurement instruments. In this work we present an innovative instrument intended for this purpose, and discuss some important aspects of its development. Main advantages of the instrument are its modularity, which is achieved by means of easily exchangeable multisensor modules, miniature dimensions, which are enabled by the development of specialized chips with multiple monolithically integrated sensing elements, novel hardware architecture capable of synchronous measurement on all pressure channels, and high measurement performance enabled by advanced signal processing. The design of multisensor modules, which consist of the developed chips and accompanying electronic circuitry in a compact sealed enclosure, will be described in more detail.*

Keywords: *multisensor, pressure measurement, instrument.*

1. INTRODUCTION

Aerodynamic testing of road and railway vehicles, aircraft and wind turbines is a necessary step in their development. It is also performed on stationary objects such as bridges, buildings and other architectural structures, in order to assess the influence of wind. Such tests can be performed in a controlled environment (wind tunnel) or in the open space, by using specialized multichannel pressure measuring instruments, which are commonly called pressure scanners. In this paper we

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present the design of a novel instrument for aerodynamic pressure measurements, which offers several advantages over the existing ones, including modularity and miniature dimensions, high measurement performance, and the capability of synchronous measurements on all pressure channels. A unique MEMS multisensor chip with multiple monolithically integrated sensing elements enables high-performance pressure sensing and high channel density in a miniature package. Modularity is enabled by the development of compact multisensor modules exchangeable by the user, and also the specially designed miniature instrument housing. Synchronous measurements and high measurement throughput are achieved through the advanced hardware architecture that eliminates multiplexing of pressure sensor signals by having a separate signal path for each pressure channel. High measurement performance of the instrument is enabled by using advanced signal processing techniques.

In this paper, the main focus will be on the design of the multisensor module, which consists of four MEMS multisensor chips and accompanying electronic circuitry in a compact sealed enclosure.

2. MAIN CONCEPTS

In order to be suitable for applications that require placement in limited spaces (within structural parts of tested objects or inside of scale models), modern electronic pressure scanners must be of miniature dimensions. In addition to this requirement, a modular construction that enables a user to change the measurement range by exchanging sensor modules was also implemented in this work. This approach resulted in the instrument design shown in Figure 1. The main parts of the instrument are the signal processing unit and two exchangeable multisensor modules. The overall dimensions of the instrument are approximately 110 mm × 35 mm × 30 mm (excluding pressure ports and electrical connectors).

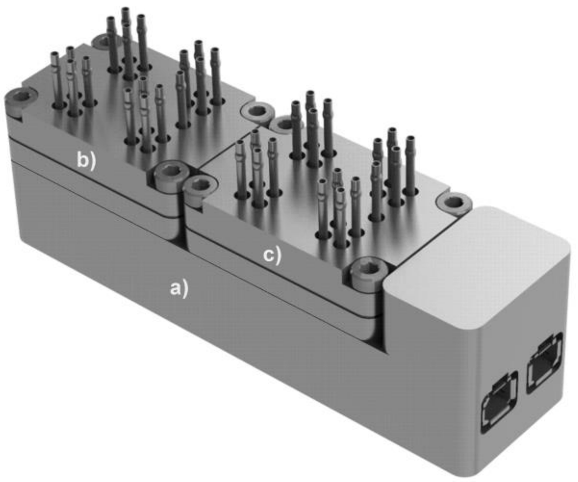
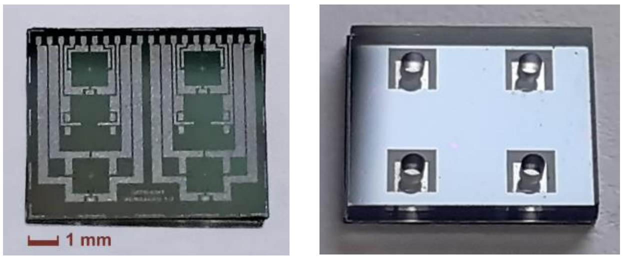


Figure 1. Visualization of the instrument for aerodynamic pressure measurements: a) signal processing unit, b) and c) multisensor modules

A key component for the realization of the instrument is the dedicated MEMS multisensor chip, developed and fabricated at the Institute of Chemistry, Technology and Metallurgy (ICTM), University of Belgrade. Apart from enabling the instrument's main functionality, it is crucial for achieving high pressure channel density without sacrificing the measurement performance. It contains four MEMS piezoresistive pressure sensing elements, two temperature sensing elements, and the accompanying electrical connections. Photographs of the fabricated chip are shown in Figure 2. Its pressure range is 100 kPa, but it can be made for other ranges, so to suit different measurement needs. A more detailed description of the multisensor chip is given in [1].



a) b)

Figure 2. MEMS multisensor chip: a) top side, b) bottom side with anodically bonded glass plate

The hardware architecture of the multisensor instrument for aerodynamic pressure measurements represents an important next step in the development of such instruments, as it has a separate signal path for each of the pressure measurement channels. This is accomplished by using a separate signal conditioning circuit and analog-to-digital converter per channel. The absence of parasitic effects, which inevitably exist in conventional designs based on analog signal multiplexing, enables achieving higher sampling rates (up to the order of 10^3 samples per channel per second). Another significant advantage of this architecture is the capability of fully synchronous pressure measurement on all channels. This is important for performing aerodynamic experiments with unsteady flow fields and transient phenomena [2,3]. The instrument's hardware architecture is described in more detail in [4].

Digital signal processing is another important concept included in the instrument's design. After performing analog-to-digital conversion of the sensor signals, digital signal processing is applied on each pressure channel's measurement data in order to perform sensor correction. The correction is based on mathematical modeling and computer algorithms, and it greatly reduces the temperature dependence and non-linearity of the pressure sensing elements. In this way, the achievable measurement uncertainty can be significantly lower than 0.1 %FS in the temperature range of interest for the intended application (from 0°C to 50°C). Digital signal processing also enables the implementation of self-diagnostic features.

The communication between the instrument and the rest of the measurement system is via a high-speed digital interface (Ethernet). There is also a connector for the power supply, with the synchronization input and some other optional signals. Thus, there are two miniature connectors on the signal processing unit, as illustrated in Figure 1.

3. MULTISENSOR MODULE

A simplified block diagram of the multisensor module is shown in Figure 3. Four MEMS multisensor chips (shown as violet rectangles) are placed in a sealed enclosure. Each of the pressure sensing elements (shown as blue squares with the letter P inside) has a pressure port through which the connection to an external pressure source is established. In this application, the measured pressure is differential, so it is measured as a difference between the pressure applied through the pressure port and a reference pressure. For that purpose, there is an additional pressure port (not shown in the diagram), that brings the reference pressure inside the module's enclosure. In this way, each pressure sensing element has the corresponding external pressure on one side of its diaphragm, and the common reference pressure on the other side, resulting in differential pressure measurement.

Apart from the pressure sensing elements, there are also temperature sensing elements on the multisensor chips (shown as yellow squares with the letter T inside), which are used for temperature compensation. This is necessary because semiconductor-based piezoresistive pressure sensors exhibit parasitic temperature dependence.

As all the mentioned sensing elements behave as resistive electrical networks, sensor excitation (here in the form of constant voltage) must be provided in order for them to generate the output signals. The signals from all the pressure sensing elements are brought directly to the multisensor module's connector. They are digitized and processed in the signal processing unit of the instrument.

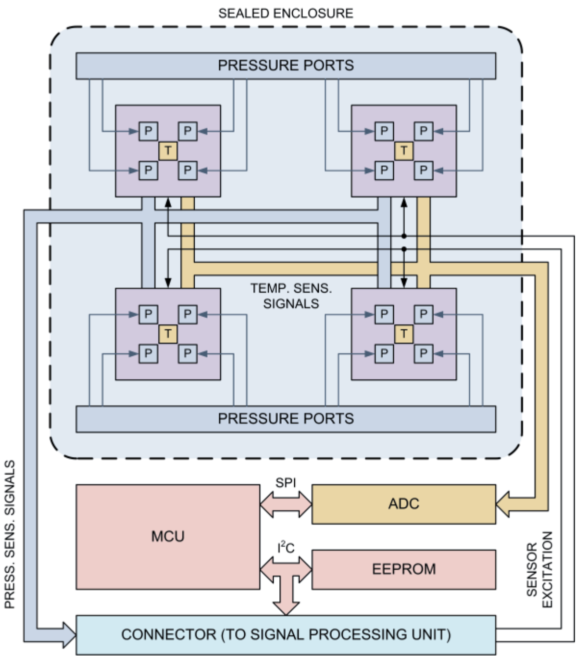


Figure 3. Simplified block diagram of the module

The signals from the temperature sensing elements are digitized and processed in the module, by using the analog-to-digital converter (ADC) and the microcontroller (MCU) [5], respectively. This yields the temperature values that correspond to the four multisensor chips. The built-in EEPROM contains calibration data, as well as other information necessary for module identification, operation and adjustments. These data are read-out and used by the signal processing unit. Both the EEPROM and the MCU are accessible through the multisensor module's connector, using the I^{2}C interface.

A photograph of the main parts of the realized multisensor module prototype is shown in Figure 4. The mechanical assembly consists of the top and bottom part of the module's enclosure (both made of metal), and the rubber gasket for sealing of the enclosure. Shown in the top left corner of Figure 4 is the inside of the top part, with mounted multisensor chips and the circuit board for establishing electrical connections between the chips and the module's electronic circuitry. In the bottom left corner of Figure 4 is the bottom part of the enclosure with the gasket. The module's electronic circuitry (shown on the right) is realized in the form of a printed circuit board that consists of two 6-layer rigid parts and a 2-layer flexible part. The purpose of the flexible part is to avoid connector misalignment and mechanical stresses due to assembly and fabrication tolerances. The external appearance of the realized module prototype is shown in Figure 5.

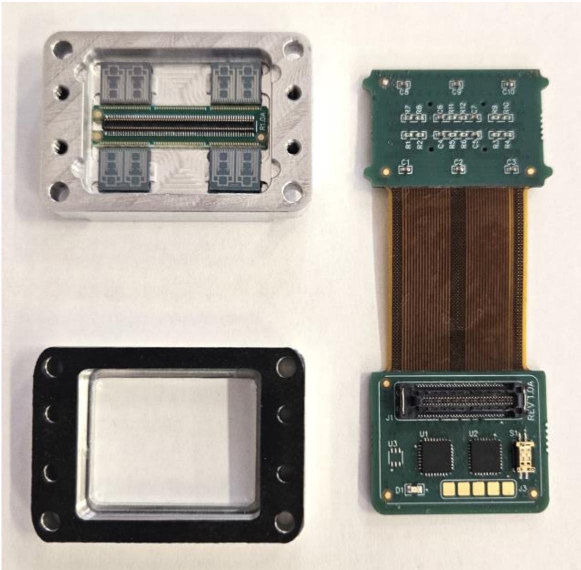


Figure 4. Photograph of the realized multisensor module prototype: main parts

Figure 5. Photograph of the realized multisensor module prototype: external appearance

4. CONCLUSION

In this paper we presented the main features of the novel instrument for aerodynamic pressure measurements (pressure scanner). Compared to the existing instruments, it has several advantages, including modularity, miniature dimensions, and the capability of synchronous measurements on all channels. After the overview of the main concepts of the instrument's design, a description was given of the exchangeable multisensor module. The design of the module and the realization of the prototype were complex and multidisciplinary tasks, posing significant challenges in the fields of semiconductor sensor technology, component packaging, electrical and mechanical engineering. Similar can be said for the rest of the instrument's hardware, i.e. the signal processing unit, where a high level of functionality and performance must be achieved in a miniature package. The activities towards that goal are currently in the final stage. Apart from that, the software development, including advanced signal processing, communication and other functions, is also an important aspect of this work, and it is currently in progress.

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