Multichannel Laboratory Equipment for Measurement of Smart Concrete Material Properties

Ladislav Machan, Pavel Steffan
Department of microelectronics
BUT, FEEC
Brno, Czech Republic
email: machan@feec.vutbr.cz, steffan@feec.vutbr.cz

***Abstract*— “Smart Concrete” materials are cement-matrix composites prepared according to the final application. Strain properties can be used to measure the deformation of concrete structures (bridges, beams, pillars) or for weighing-in-motion of road vehicles. This article describes novel laboratory equipment which is designed for multichannel dynamic and long-period material stability measurements.**

Keywords—smart concrete; dynamic measurement; long-period measurement

I. INTRODUCTION

One of the most common structural materials used in engineering construction is cement and its mixtures (concrete and mortar). Cement is slightly conducting material, but its electrical conductance, Electromagnetic Interference (EMI) shielding effectiveness and wave absorbing property are very poor. In order to increase the ability of cement materials to transfer electrons, additional conductive fillings and loadings have to be added. Smart Concrete (SC) could be considering to be a material of the future. Due to its attractive features, SC can be used as a strain-sensing element.

The strain-sensing properties are achieved by a proper volume amount of conductive filler. In this system, the matrix is made of cementitious material with small amount of silica fumes, fly ash, and fine aggregates [1]. Different conductive fillers were tested considering the best strain-sensitivity / material price ratio. Existing research proved carbon black and graphite particles to be the best choice in terms of price. The best strain-sensitivity is achieved near the percolation threshold of filler particles [2].

Strain properties of the composite can be evaluated by impedance changing. The impedance changing sensitivity regarding deformation can be widely affected by a proper choice of concrete admixtures [3]. Generally, in many types of mixtures, the real component is not much affected by the deformation, on the other hand, the imaginary component is, and it can be used to detect the changes [4]. A novel mixture with carbon black filler has a different behavior. The real part of impedance is strongly affected by deformation and can be used for measurements. This property is profitable with regard to the future usage. Measuring principle can be simplified and power supply requirements reduced. Conventional DC techniques for resistance measurements cannot be used. Electrode system of sensing element would be damaged by electrolytic corrosion in this case. Square-wave AC technique with an excitation frequency of 1 kHz and an excitation voltage of 1 V_{p-p} were experimentally set [5]. In the light of new knowledge about materials, a necessity to a simple, relatively inexpensive and portable device has been raised. Considering the needs of laboratory measurements, some requirements on a new device were established:

- AC square-wave measuring principle of resistance.
- Excitation frequency 1 kHz and voltage of 1 V_{p-p}.
- Eight independent measuring channels for multiple element sensing applications.
- Shunt sensing and bridge-based measuring option.
- Four additional channels for sensing temperature and humidity.
- Integrated memory storage device compatible with PC and File Allocation Table (FAT32) system for data logging.
- Battery powered.
- Suitable for a long-period measurements.
- Water and dust proof case.

In Section 2, there is a description of the device. The block diagram is described in Subsection A and B. Subsection C is focused on measuring principle. In Subsection D, there is a mechanical design discussed. The measuring automation and data processing is described in Subsection E. In Subsection F, there are discussed the results of development and final measurement parameters. In Section 3, there is a conclusion which summarizes the results of work.

II. DESCRIPTION OF THE DEVICE

According to the aforementioned requirements, a block diagram of the instrument has been suggested.

A. The block diagram of device

The diagram is shown in Figure 1. The device function is based on 16-bit MSP430F5529 microcontroller, which uses Reduced Instruction Set Computing (RISC) architecture [6]. This microcontroller can be “in circuit” programmed via Joint Test Action Group (JTAG) interface. Interface also allows real-time debugging of firmware, which ensures all device functions.

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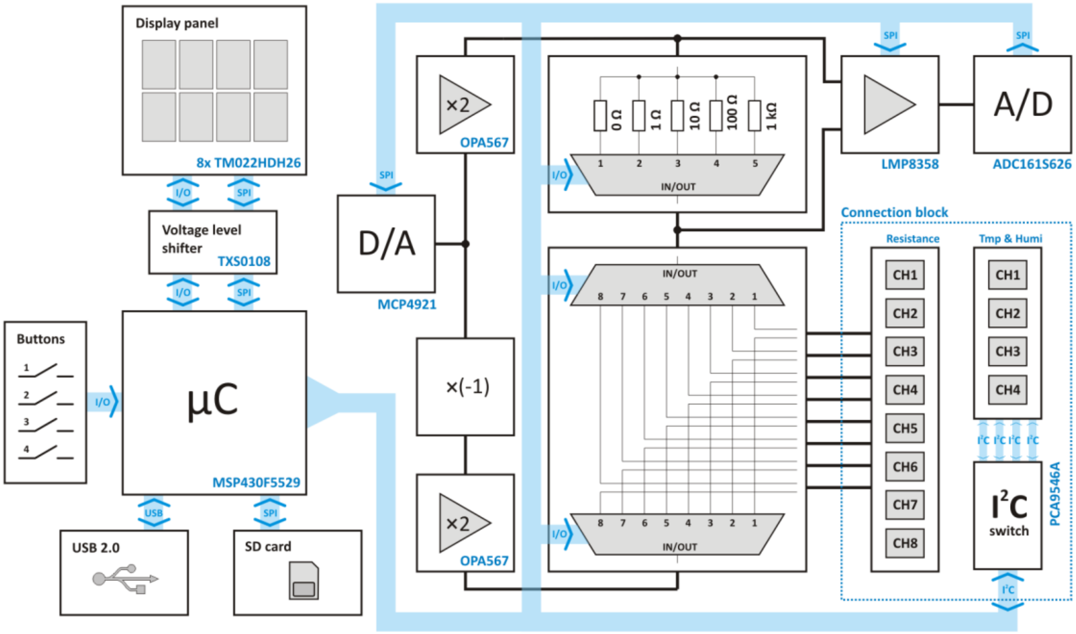

Figure 1. The principial block diagram of proposed device

The device is equipped with a Secure Digital (SD) card, which can be inserted into a side slot, for saving the measured data. SD card communicates with the microcontroller via Serial Peripheral Interface (SPI) interface. A special feature of used microcontroller is built in Universal Serial Bus (USB) interface connection for transferring the measured data into PC. Microcontroller contains complete physical layer of USB communication device. All higher layers of protocol are implemented in the firmware of device. There are two basic regimes of operation. When a measurement is running and measured data are periodically stored into memory, USB device works in Communications Device Class (CDC) mode (virtual COM port emulation in operating system). By this way, it is possible to view a response of measured system in real-time. Specialized software developed together with device is able to receive this data and display it in a graph. It is possible to view a response of measured system real-time by this way. The second mode of USB operation is used when a measurement is stopped and SD card is not used for storing data. This mode is called Mass Storage Class (MSC). SD card is transparently accessible for operational system of PC via USB device in this case. User can download measured data which are stored on SD card in standard FAT32 file system. This behavior is common e.g. for today‘s Smartphones and contributes to user comfort of the device. There is no need to open the housing of device and remove the SD card from the slot for downloading measured data to PC.

B. Supply voltage supervising

The aforementioned USB is not used for device supplying and internal accumulator charging. The main supply voltage is obtained from build-in lead-acid battery 6 V, 12 A/h. This large-capacity battery is able to supply the device a long time thereby enabling long-period measurements. USB bus supplying capability is 5 V / 500 mA. The usage of USB bus for charging this type of battery would not be effective. The battery charging is provided by external “fast-charger” through a build-in connector.

The supply voltage supervising is maintained by a group of supply blocks depicted in Figure 2. All supply voltage supervising blocks are based on linear regulation principle. No switch current blocks were used to minimize the noise and ripples in supply strings. This configuration is not such a power effective, but a quiet supply is a big benefit for this application. Supply system of the device consists of a digital supply string, high power analog supply string and low power analog supply string. Digital supply string contains 3.3 V and 5 V voltages. All digital blocks uses 3.3 V voltage levels (microcontroller, SD card, D/A converter). Higher voltage 5 V is used for signal relays, Liquid Crystal Display (LCD) backlight and voltage level shifter block as an option for possibility to connect an older type of display. High-power analog string is used to supply a pair of high-power operational amplifiers OPA567. Noise sensitive analog or mixed-mode parts are supplied via low-power analog string. There are supply and reference voltages for virtual ground definition.

Printed circuit board is designed considering low-noise layout rules. Analog and digital parts of device are separated into two boards. Noisy digital components are spatially separated from noise-sensitive analog blocks in this way. For even better noise properties, it is possible to cover analog board by shielding box. Special attention was paid to the design of ground surfaces. Each supply string has own ground surface shielding. All grounds are connected in one point to avoid noise induction via ground loops.

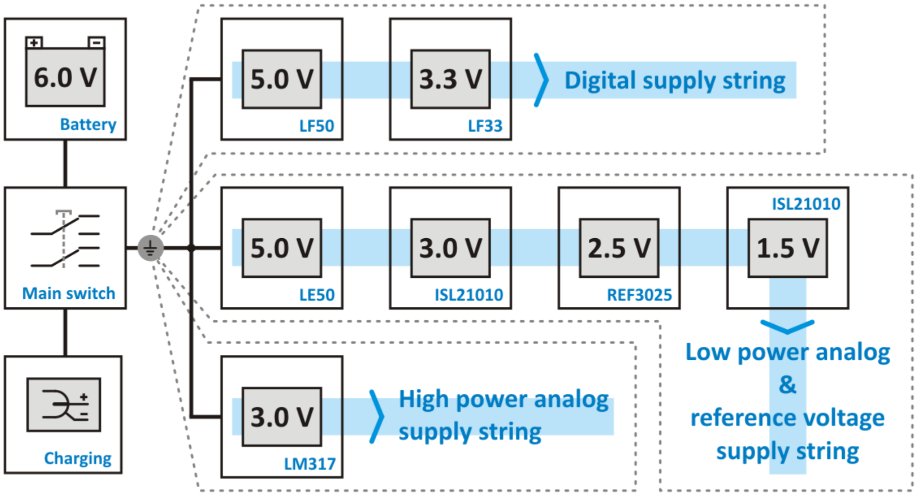

Figure 2. Supply voltage supervising blocks

C. *Measuring principle*

Excitation signal is digitally generated by D/A converter MCP4921. Output signal is amplified by the pair of high-power operational amplifiers OPA567 connected in push-pull configuration. One of them is connected as non-inverting amplifier while the other is inverting. Voltage gain of both amplifiers is 2. Supply voltage of amplifiers is 3 V and virtual ground is shifted to the middle of dynamic range by voltage reference 1.5 V. Output current from amplifiers is internally limited (short circuit protection) and a shift of virtual ground enables the flow in both directions via electrical load. Shunt resistors are in series with load and can be (1 from 5) selected by the program of microcontroller. Shunts are switched by small signal relays, considering low-noise design. Measured sample of material is connected as an electrical load via digitally controlled channel selection switch. Channels are switched (1 from 8) by small signal relays, too. There are two modes of operation which can be selected by proper combination of channel and shunt switches. The first measuring mode uses two-wire load connection. Current flowing through the load causes voltage drop on the shunt resistor. Voltage drop on the shunt resistor is amplified by precision instrumentation amplifier LMP8358 with digitally switchable gain (10, 20, 50, 100, 200, 500 and 1000). Output voltage from this amplifier is sampled by 16-bit successive approximation A/D converter ADC161S626. Samples are taken only in steady states of square-wave excitation signal. Resistance is calculated from a known value of selected shunt resistor, gain, excitation voltage and result from A/D converter. In this mode, eight channels can be used simultaneously one by one.

The second measuring mode offers the possibility of four-wire bridge connection of load. This type of connection helps to reduce temperature and humidity drift of measured material. In an ideal case, temperature and humidity changes act on all four elements of bridge in the same way and the effect on measurement vanishes. This mode does not use a shunt resistor (0 Ω shunt is selected). Proper setting of channel switch allows using four channels for bridge excitation and four channels for differential voltage sensing. Differential voltage is amplified by LMP8358 and processed by the same way as in the case of the first mode. Usage of the second "bridge mode" is under development at this time. A problem arises in the field of technological preparation of measured samples. There is a need to use four material elements with similar value of resistance, in bridge connection. In the meantime, production repeatability is not sufficient considering absolute value of resistance.

In the case of the first "shunt mode", temperature and humidity cause a drift in measured value. There are four additional digital channels which allow connecting temperature and humidity sensors, in the block diagram (Figure 1). Sensors can be connected via I^{2}C serial interface. For example SHT21 from Sensirion Company is a suitable type. Addressing possibilities of serial bus are extended by hardware I^{2}C switch PCA9546A. Data from sensors can be used for numerical compensation of drift.

D. *Mechanical design*

Dynamic measurements of samples bring problems such as dusty environments, mechanical vibrations, EMI interferences and temperature stress. Mechanical design of a device is based on requirements for battery powered laboratory instrument which must be robust and environmentally resistant. The device is build-in IP68 standard plastic case with transparent cover (Figure 3). Under cover, there is a very well readable display panel. Four control buttons are placed from the front. The opposite side is equipped with eight connectors for measuring probes and four connectors for digital sensors. On the left side, there is the main switch and a connector for charging. The right side includes a water and dust proof USB connector with a rubber plug.

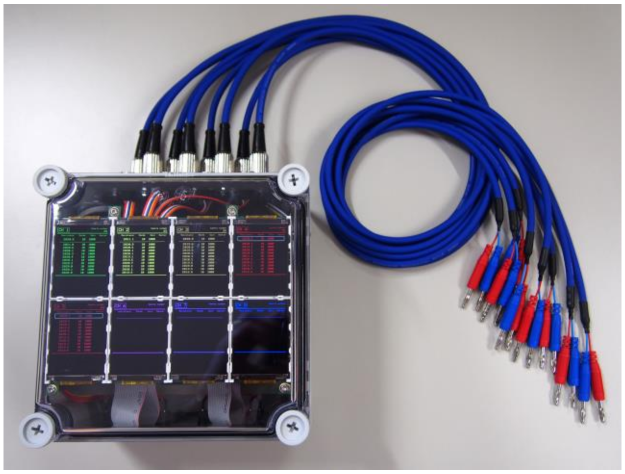

Figure 3. Mechanical design of device

E. *Measurement automation and data processing*

User can start to measure with predefined configuration by pressing the proper button. First, it is possible to choose a measurement mode (shunt or bridge), number of logged channels and measuring period. Measuring range and the gain of instrumentation amplifier is set automatically for each sample. Measuring can be paused and started again or stopped. When measurement is stopped a file with data log is saved with a specific name. During measurements, it is possible to add a marker to log by pressing a button. This feature is useful for better orientation in data log. Output of measurement is in standard ".csv" format. It can be easily processed for example in Microsoft Excel. An example of processed output data log from dynamical measurements is depicted in Figure 4.

F. *Results and final measurement parameters*

An example of processed output data log from dynamical measurements is depicted in Figure 4. This measurement was realized under conditions:

- constant temperature and humidity,
- concrete block size: 300 x 300 x 500 mm,
- automatic range and gain select,
- measurement duration: 2.5 hours,
- three channel mode,
- sample rate: 1s,
- cyclic press loading:
    - 3x 4.4 MPa till 16.6 MPa.
    - 1x 4.4 MPa till 33.3 MPa.
    - 3x 4.4 MPa till 16.6 MPa.
    - 1x 4.4 MPa till 22.2 MPa.
    - 3x 4.4 MPa till 16.6 MPa.
    - 3x 4.4 MPa till 27.8 MPa.
    - 3x 4.4 MPa till 16.6 MPa.
    - 1x 4.4 MPa till 44.4 MPa (destruction).

Sampled data were recalculated from absolute resistance values to relative changes of resistance during loading. Absolute values were compared with the output of professional impedance analyzer Agilent E4980A and absolute error of proposed device is 0.2%. This result is sufficient with regard to the current state of research. There is a possibility for the future improvement. On the basis of known internal temperature, the temperature drift of shunt resistor value can be numerical compensated.

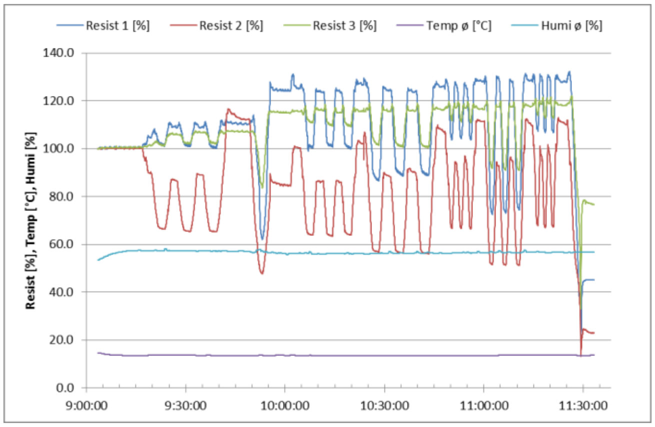

Figure 4. Processed data output – 3 channel dynamical measurement

III. CONCLUSION

A development of new laboratory instruments was presented in this paper. The overall structure, including suggested block diagram, realization and design of the printed circuit boards, was described. The precision LCR meter E4980, which does not enable the multichannel measurements, can be replaced by this low-cost device.

This instrument is currently used for laboratory measurements and characterization of smart concrete panels at department of microelectronics.

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