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Investigations of the Shape Memory Alloy actuator applied in a current sensitive switch

Abstract

The main goal of this paper is to present results of investigations of the Shape Memory Alloy (SMA) actuator applied in a current sensitive switch. The SMA muscle wire actuates the electric micro switch, breaking the electrical circuit. The prototype stand of the switch, automatically breaking the circuit when overcurrent appears, was designed. The stand consists of a prototype switch construction and a measuring system, allowing for various investigations. The measurement methodology and selected results of the performed experiments are also presented. Finally, the authors try to answer the following question: is it possible to use the SMA actuator as a main drive in a current sensing switch?

Keywords: SMA, Shape Memory Alloy, actuator, current sensing actuator.

1. Introduction

Shape Memory Alloy Actuators are modern mechatronic components which transform electrical energy into mechanical one. The biggest advantage of SMAs is a relatively high force achieved with a very small size of the actuator. The available force/volume ratio is very high, outstanding all the other actuator types.

The SMA actuators are controlled by thermal energy which can be generated in multiple ways. The most popular way is current heating solution. The current flows through the SMA material causing its heating in accordance with the Joule-Lenz Law. This way of actuating the SMA is very convenient because it requires only the simplest electrical power supply to start the process.

The SMA behavior is very difficult for control because the thermo-mechanical characteristic describing their behavior is highly nonlinear with a hysteresis loop. The theoretical, basic thermo-mechanical characteristic of SMA material is shown in Fig. 1. The SMA material does not change its state as a whole – each particle does it separately. Hence, until the whole piece is transited, there are still some martensite and austenite particles in it. The proportion of the number of transited and non-transited particles is called the internal phase transition ratio. The characteristic presents the internal phase transition ratio (called martensite friction ξ) vs. the applied temperature.

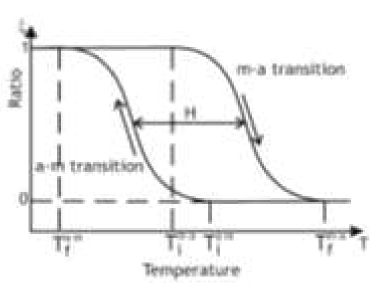

Fig. 1. Thermo-mechanical SMA characteristic [1]

2. Experimental setup and measurement layout

The prototype stand consists of a mechanical construction of the current sensitive switch and a measurement system allowing for various experiments and investigations. The mechanical construction was designed and modeled in Autodesk Inventor environment. There are two main mechanical components: a base and a moving arm. The mechanical parts were printed in 3D printing technology using *3D Kreator Motion* printer. *The Flexinol® 150LT Muscle Wire* is used as an SMA actuator. Its properties and examinations are presented in [12]. It is connected between the base and one side of the moving arm. The current flows through the SMA actuator and the electrical switch, which can be mechanically switched on and off by the moving arm. The opposite force (for SMA actuator) is generated by a mechanical spring. When the current flows through the SMA actuator its temperature increases according to the Joule-Lenz Law. When the temperature achieves the activation value (it happens for the current called *the static switch off current*) the SMA actuator shrinks and the arm breaks the circuit. Then the SMA actuator starts to cool down and the spring tries to stretch it back to the nominal length. If the current is smaller than the static switch off current, the circuit is closed and the current flows all the time. The mechanical construction of the measurement stand is presented in Fig. 2.

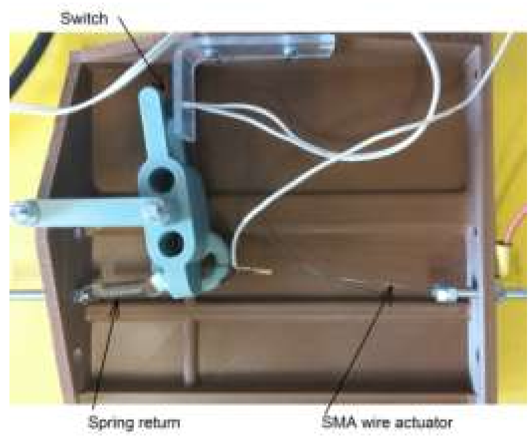

Fig. 2. Mechanical construction of the measurement stand

The prototype stand is equipped with a measuring system consisting of the following main components: power supply unit, data acquisition card (DAQ) and infrared camera. All the devices are controlled via a PC computer. The measurement software was developed in the LabVIEW environment. The functional scheme of the measuring system is shown in Fig. 3.

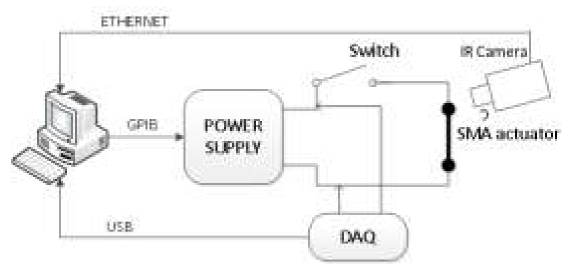

Fig. 3. Functional scheme of the measuring stand

The power supply unit used in the system is GW Instek PSH-2036. It is able to work in the constant current or constant voltage mode. It has an additional important ability – it can switch automatically between the modes due to the variable load resistance (see Fig. 4).). As a data acquisition card the National Instruments my DAQ card was used. It measures the power supply output voltage for recognizing the state of the circuit. The circuit is in one of two modes: switched on (current flows) and off (open circuit). For the open circuit, the power supply unit switches into the voltage mode and delivers the preset voltage. For the switch on state, the voltage delivered by the power supply unit (in the current mode) is much smaller, adjusted to keep the set current in the circuit with variable resistance (it varies with the transition state). Voltage measurement allows calculation of the SMA resistance (in the switch on state) as well as the detection of the switch off state (when the voltage is equal to the preset one).

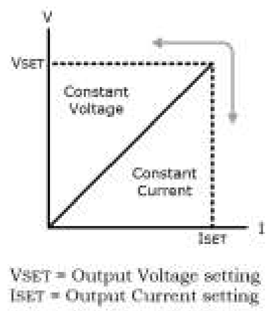

Fig. 4. Constant voltage/current modes of PSH-2036 power supply unit [9]

3. Software structure in LabView

The measuring system is controlled by a PC computer with a dedicated application developed in LabView environment. The software structure is divided into three separate loops: main loop, power supply loop, file loop. The main loop maintains the measurement process, communicates with DAQ card and controls the other loops. Loops are organized in the so called “producer-consumer” structure, where the main loop is producer, pushing data into queues when necessary. The power supply loop is a consumer loop, it waits for messages from the main loop queue. If the message arrives, it performs the order. There are three possible actions realized by the power supply loop: IDLE (wait), START (configure output voltage value and switch on the power), MEASUREMENT (switch the value of output current). The power supply loop maintains the communication process with the power supply unit using short messages called SCPI (Standard Commands for Programmable Instruments). Example action – START and program configuration is presented in Fig. 5. The message consists of two elements “State” and “Current value”. State defines which action is realized. In Fig. 5, Action START is presented. So action START sends three commands into the power supply device: set up the voltage as 9 V, set up the current value given in “Current value” element of the message and switch on or off the output of the device.

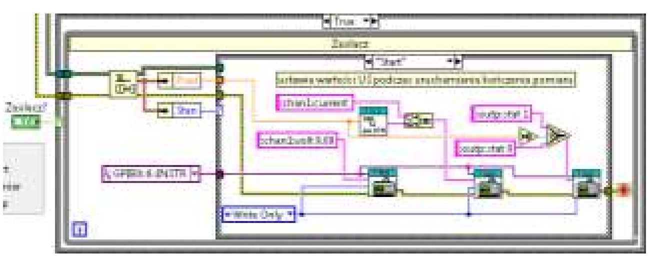

Fig. 5. Power supply loop code

The second consumer loop is a data file loop which collects measurement data in a string format and saves the data to the text file with the preset file name and structure. The file structure is different for various measurement types but the loop structure is the same. The file loop performs two actions: SAVE – TRUE case substructure, which saves data to file and COLLECT – FALSE case substructure, which just collects the measuring data in a shift register, as presented in Fig. 6.

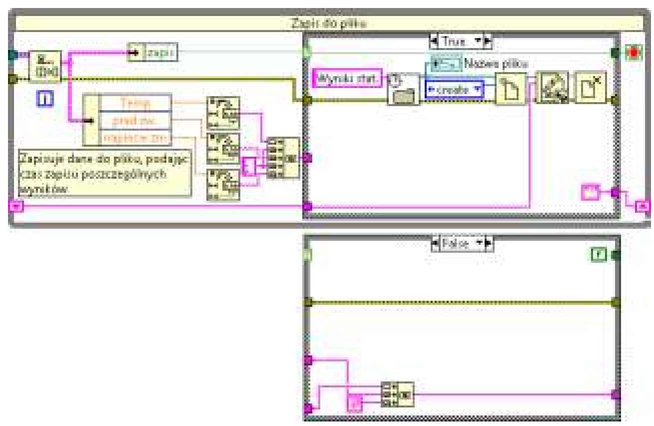

Fig. 6. File loop with two actions: SAVE (above), COLLECT (bottom)

Similarly to Fig.5, the file loop reacts on the message delivering the Boolean value called “Save”. If its value is False (means no save,) the data (measured values of temperature, current and voltage) is added into the internal memory of the structure called a shift register. If its value is True (means save), all the collected data is saved into the text file. The name of the file includes actual date and time.

There is another saving structure in the main loop which collects the raw data directly from the DAQ card into the file. The structure is called Functional Global Variable (FGV) and stores the voltage values in each measurement series and saves the series in a file. The FGV structure (save case) is shown in Fig. 7. The FGV collects the temperature and voltage data, and realizes three actions: clear the data buffers (c), add data into buffers (b) and save the buffers into text file and clear after all (a).

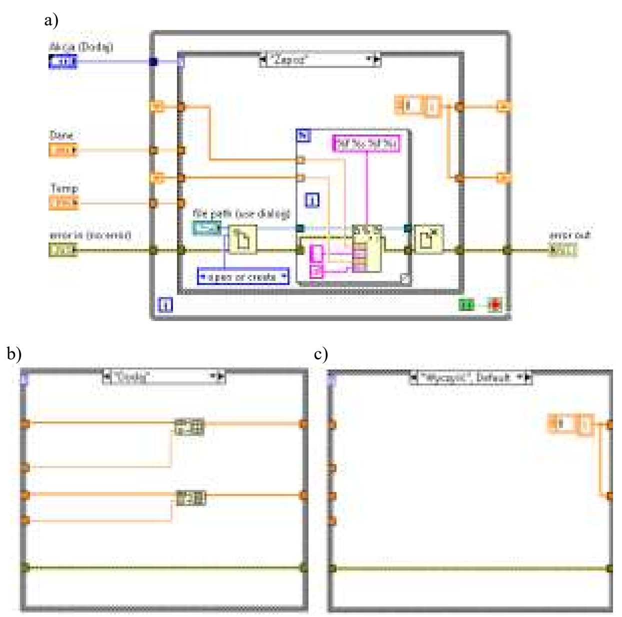

Fig. 7. Save DAQ data into file FGV, a) Save action, b) Add data into buffer case, c) Clear buffer case

Other important functionality of the control software is circuit state detection. It is realized as an FGV as well. This FGV remembers the previous voltage value and compares it with the actual one. If the difference is higher than the preset threshold value, the circuit must be off, if not, the current flows through the actuator.

On the other hand, the data acquisition process starts before the power supply unit switches on the output power. This FGV detects this fact as well. The adequate code is presented in Fig. 8.

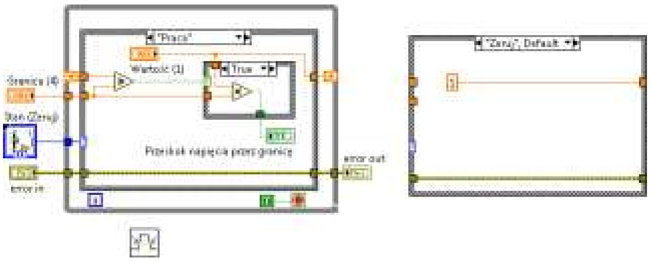

Fig. 8. Brocken circuit detection using FGV

FGV shown in Fig. 8 is used to detect the state change of the circuit. It performs two actions: resets the internal memory into the nominal value, compares the difference between the actual and previous value with the threshold value and saves the actual value as the previous one for next call.

4. Measurements

A wide program of experimental measurements was planned and performed. Measurement experiments can be divided into two basic kinds: static and dynamic measurements.

A static measurement means recognition of the steady state parameters of the switched on circuit. Series of static measurements made for increasing levels of the set current enable determination of the *static switch off current,* which is the lowest value of the current flowing through the SMA wire, which opens the circuit by SMA actuation. Knowledge of this value is necessary for dynamic measurements. Four kinds of dynamic measurements were made:

- Switch off measurements
- Switching sequence measurements
- Exploitation measurements
- Destroying measurements

4.1. Static measurement

The series of static measurements were made by increasing the supplying current from zero to *static switch off current* step by step, each time by a small value of the current called dA. A time delay after each current enhancement allows achieving the thermally steady state of the SMA. The series of measurement were repeated three times to check the repeatability. The set up parameters were: dA value, step time. In typical SMA measurements, this kind of measurement is taken in two ways: for increasing and decreasing current value, to determine the hysteresis curve shown in Fig. 1. In our case, the increasing branch was enough, because the goal of this experiment was to determine the lowest value of the current causing switching off the circuit. Figure 9 presents exemplary, full series of static measurements. For every set value of the current (horizontal axis) there are three measured or calculated values: resultant voltage (Uzm), SMA actuator resistance (RSMA) and its temperature (Temp). The measurements were made when the temperature was stabilized. The resistance of the SMA wire was calculated basing on the Ohm's law. During the experiment the SMA temperature increased from ambient temperature to 78°C. The reached *static switch off current* value is 1.15 A (at this current the SMA actuator brokes the circuit).

The virtual instrument panel for static measurements is shown in Fig. 10. It presents the set up page and the data page.

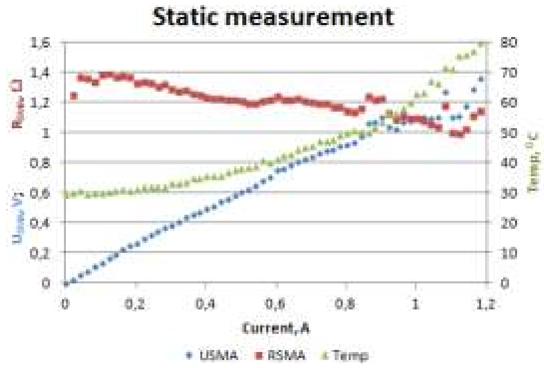

Fig. 9. Results of static measurement series

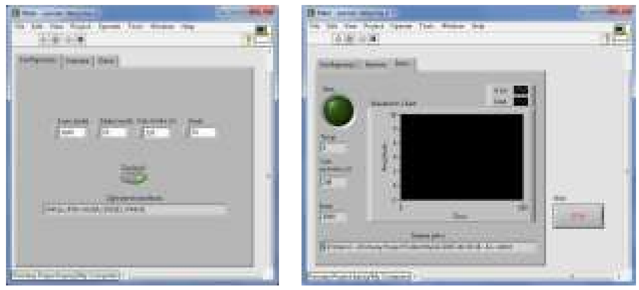

Fig. 10. Panel view of static measurement virtual instrument

4.2. Switch off measurement

The switch off measurements were made to investigate the SMA reaction to a step increase in the current from zero to high current value which causes the switch off in the circuit. The measurement was made with the static measurement software using one measurement step with a high current value. The exemplary curve is presented in Fig. 11. It is necessary for determining the indicatory time for the next measurement. It can be noted that the SMA actuator responds with a significant delay in this case.

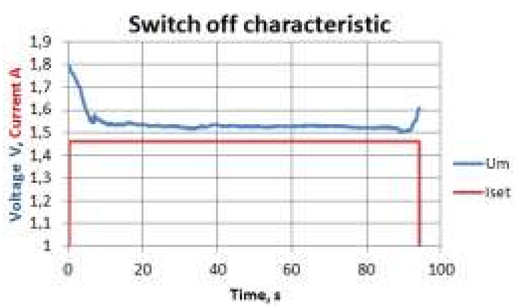

Fig. 11. Switch off measurement result

4.3. Switching sequence measurement

In this experiment, the constant, high value of the supply current heats the SMA actuator and breaks the circuit. After the SMA wire is cooled, it contracts and allows automatic switch on of the circuit. Several switch on and switch off sequences were observed and time delays between them were measured. The *static switch off current* was taken into account as the lowest possible value of the heating current, but the measurements were taken with a three times higher current value. Exemplary resultant characteristics are shown in Fig. 12. The first switch on time was longer than the other times in the sequence due to the initial temperature of the SMA.

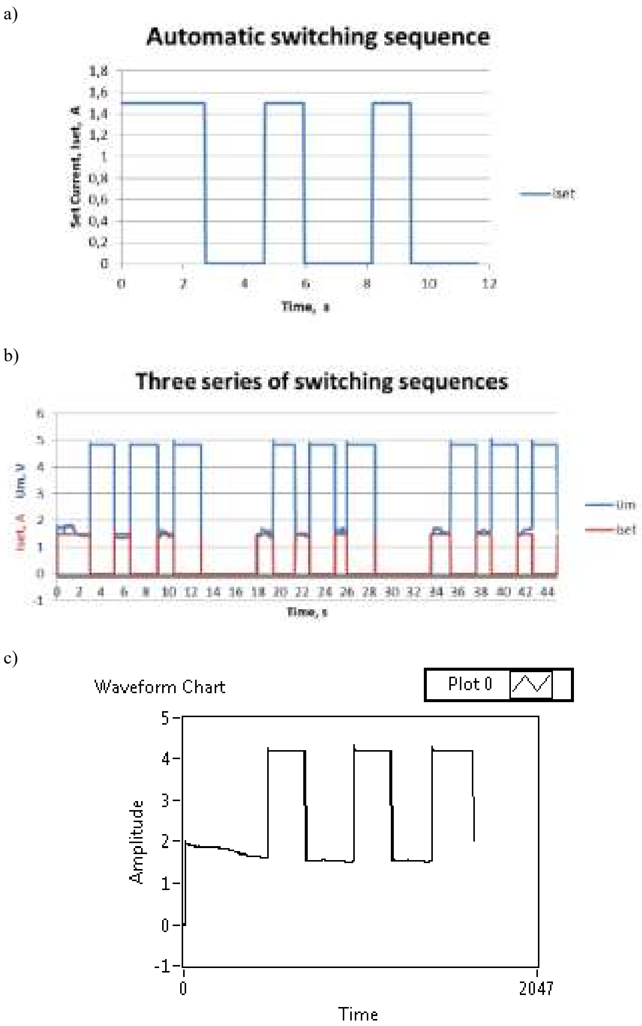

Fig. 12. Switch off measurements examples. a) One measurement series, b) full measurement with three measurement series and delay times, c) real voltage measurement series directly acquired by DAQ

The temperature changes in the range of 50 to 78°C. It is the width of the thermo-mechanical hysteresis loop for this SMA wire.

During the operation there are three important times that can be observed and measured:

- first switch off time, when the SMA actuator temperature increases from ambient to switch off temperature,
- cooling time, when the SMA temperature decreases from switch off to switch on temperature,
- cyclic heating time, when the temperature rises from switch on to switch off temperature.

The second and third times are repeatable in a measurement series. The first time depends on the ambient temperature and is much longer than the other ones.

In Fig. 12b, the full measurement with three measurement series is presented. The delay time between the series was taken into account as well. The lowest value of the delay time which enables decreasing the SMA temperature to the ambient one was investigated.

The virtual instrument panel for this experiment is shown in Fig. 13. It presents the entire view of the control panel.

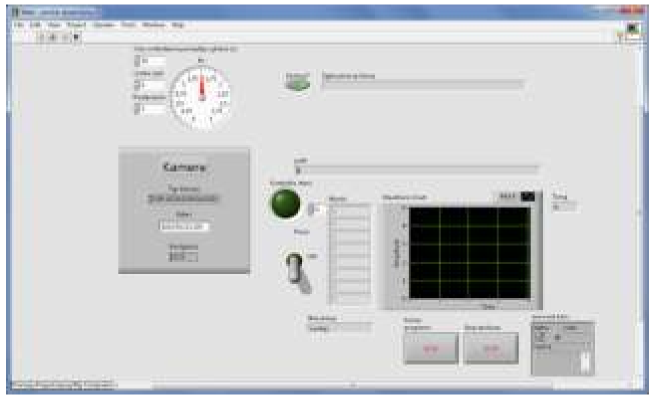

Fig. 13. View of the dynamic measurement control panel

4.4. Exploitation measurements

The idea of the exploitation measurement is similar to the switch off measurement. The only difference is that before forcing the switch off current the wire is already preheated with a smaller value of the current. The preheating current values were 25%, 50%, 75%, 85% of *static switch off current* value. It is a simulation of the normal way of circuit exploitation. The preheating current increases the temperature of the SMA actuator above the ambient one and - as a result - causes faster first reaction. The experiment has two important parameters: the preheating current value and the preheating time. The idea of the measurement is illustrated in Fig. 14.

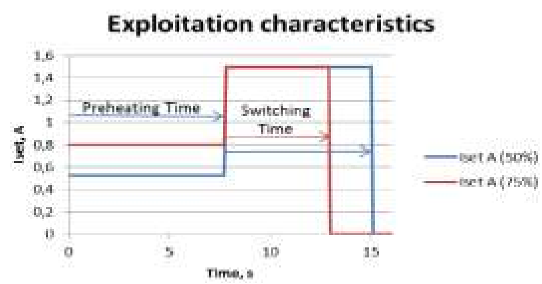

Fig. 14. The idea of exploitation measurements

The results of several measurements were statistically processed and presented in Fig. 15. The minimal, maximal and average switch off time for each preheating current is presented. The switching time depends strongly on the preheating current value, which was easy to predict. It is interesting that the measured time dispersion for several repetitions of the experiment is lowest in the middle, and much higher on the both sides of the curves.

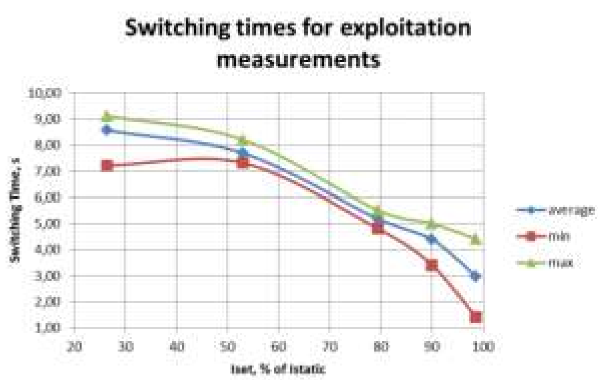

Fig. 15. Results of the exploitation measurements

The exploitation measurements were controlled in LabVIEW using the switch off measurement panel as a subvi (subroutine). In the first step, the SMA is preheated by a preset period of time, and then the dynamic measurement procedure is run as a subvi.

a)

b)

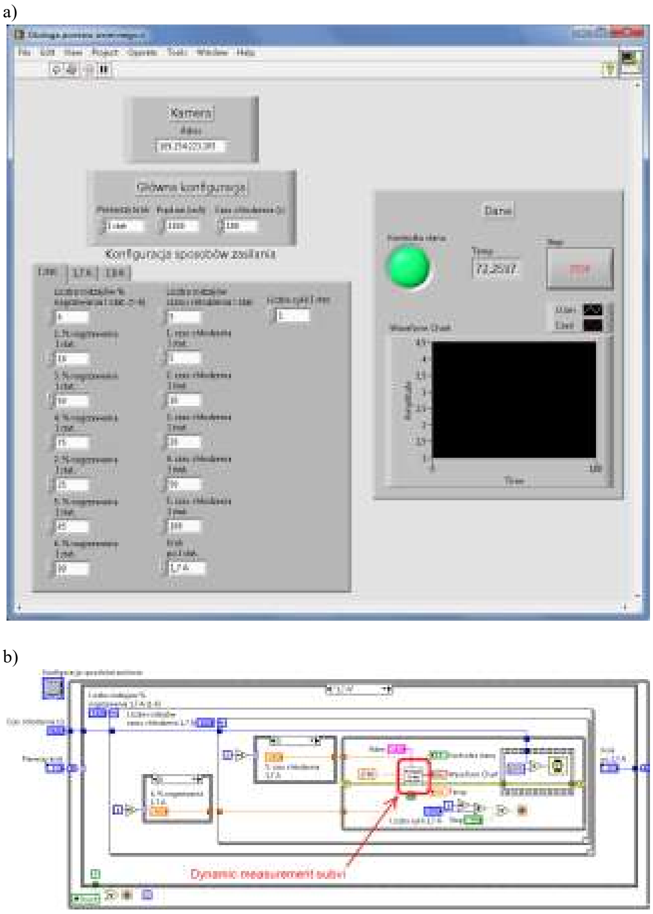

Fig. 16. Exploitation characteristic software. a) Virtual instrument front panel, b) Code diagram with dynamic measurement subvi pointing

4.5. Destroying measurements

Two kinds of destroying measurements were taken. In the first step, the switching sequence was made using a very high current. The current was about 13 A which is 12 times bigger than the static switch off current (about 1.15A). This experiment did not destroyed the SMA actuator. The device worked correctly, and the only difference was that the switch on times were very short while the switch off times were exactly the same as for the switching sequence measurements.

To destroy the SMA actuator, it was necessary to force the permanent short circuit. As a result, the thermal destruction of the SMA wire was achieved. There are two steps of destroying the SMA actuator. The first is just a Shape Memory Effect (SME) damage, which happens for overheating the SMA. It is difficult to be achieved because no visible changes in the actuator can be observed. Additional measurements are necessary to confirm missing Shape Memory Effect. In our case, the effect was obtained for a long lasting short circuit with the current about 4 A. If the overheating is significant and long lasting, it burns and mechanically destroys the SMA wire. The mechanical damage happens when the temperature achieves the melting point and the mechanical spring breaks up the SMA actuator. In our case, this measurement was not possible to be made because such a high temperature caused melting effect on the plastic moving arm (Fig. 17).

Fig. 17. Moving arm melting effect

5. Concluding remarks

The measurement stand was designed and realised to allow a wide range of experiments and measurements. The simple measurement methodology and helpful control system in LabVIEW were proposed and tested in practice. The methodology of voltage measurement instead of current measurement was implemented. The experiments covered various types of measurements: static measurements, different types of dynamic measurements and finally destroying measurements.

The examined SMA actuator behaviour strongly depends on two main factors: mechanical load and ambient temperature. The first of them is well described in literature [11]. On the prototype measuring stand, the mechanical load was tuned by the tension of the mechanical spring. This parameter strongly influenced the static switch off current value thus it could be adjusted in a wide range. The second one results from the current heating value according to the Joule-Lenz law. The SMA starting point is ambient temperature, but the flowing current just increases the SMA actuator temperature. If the ambient temperature changes, then a different current is necessary to achieve the same, desirable effect. All the measurements were made in the laboratory class with almost constant ambient parameters; the temperature was about 25°C. So the temperature influence was not taken into account.

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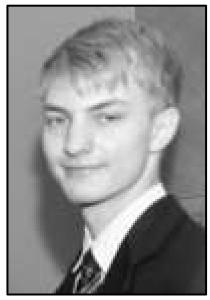

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