PRECISE ANALOG CURRENT DRIVER FOR MICRO-MECHANICAL ACTUATORS BASED ON SHAPE MEMORY ALLOY (SMA)

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ABSTRACT

The aim of this paper is to propose an analog current driver topology specifically designed for mechanical actuators based on Shape Memory Alloys (SMAs). The use of SMAs in present actuators represents an alternative to electromagnetic actuators in a wide range of applications. The current driver described in the following paper, matched to a dedicated SMA actuator, is perfectly suitable as a powerful evaluation tool for supporting and spreading the diffusion of a new actuation concept in modern electro-mechanical applications.

INTRODUCTION

The shape memory alloys, also called SMAs, are metallic alloys that exhibit the shape memory effect: SMAs can be deformed at a low temperature but regain their original configuration when heated to a higher temperature.

Components made from SMAs can be designed to exert forces over a considerable range of motion, often for many cycles. For this reason, SMAs as actuators are used as alternatives to electromagnetic actuators in a wide range of applications, even if, for the most, SMAs are applied as simple mechanical switches operating in dual state condition (ON-OFF). The main reason of this is because of the strong non-linearity of these materials and the necessity to couple a position feedback sensor for managing the stroke; these two aspects influence the complexity of SMA actuators controllers despite of current traditional actuators.

In this paper, electric and mechanical characteristics of SMAs will be briefly introduced and a proper sensor-less electronic solution suitable to drive SMAs in continuous mode will be described, designed, and then implemented.

SHAPE MEMORY ALLOY

Shape Memory Alloys are metallic materials, mainly based on an alloy of nickel and titanium, having the ability to return to some previously defined shape or size when subjected to the appropriate thermal process. These alloys that be plastically deformed at low temperatures, and upon exposure to higher temperatures, they are able to regain their initial shape.

Their working principle is based on the reversible crystalline phase transformations that occur between the low temperature martensite (M) phase and the high temperature austenite (A) phase of the SMA. These two phases have different thermal, mechanical and electrical properties, owing to their different crystallographic structures. In the absence of applied stress, the M phase is formed without any observable change of geometry. When an external stress is applied to the SMA in the M phase, it causes a large inelastic strain in the SMA. When the SMA is heated to a higher temperature, the SMA reverts to the symmetric A phase via a phase transformation. This phase transformation is accompanied by a large force against the applied stress and recovery of the inelastic strain.

From the electric point of view, the electrical resistance of the material changes during the cooling process of the martensitic transformation, and during the heating process on the reverse transformation. This characteristic is fundamental for implementing a new actuator family where the position feedback is directly retrieved by the SMA resistance values. Figure 1 shows the relation between SMA resistivity and its induced temperature: the hysteresis curve indicates the high non-linearity of these materials.

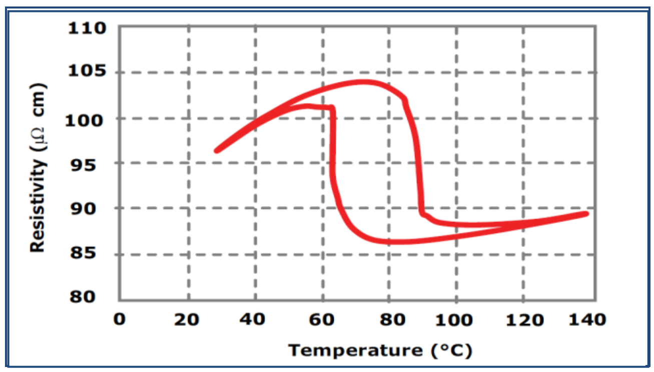

Figure 1. Resistivity of the material changes during martensitic transformation showing the hysteresis curve behavior. (Courtesy of SAES Getters)

A very important feature for defining the suitability of SMAs for a specific application is the shape memory effect stability during cycling. For this it's necessary to investigate the fatigue behavior in a wide range of operative conditions because the SMA lifetime depends on the heating current, actuation time, and required strokes under applied load conditions (Fig.2).

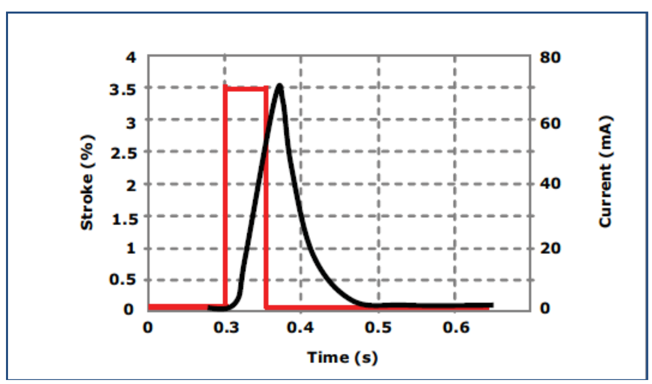

Figure 2. Stroke vs. Time [1st cycle, L=100mm, T=25°C, Max Curr.=70mA, Max Stress= 170 MPa] (Courtesy of SAES Getters)

Based on the above information, the possibility of having very light mechanical actuators based on SMA with small sizes and modest power consumption could enable the deployment of light-robotic applications.

For this reason, SMA wire samples of about 25µm diameter were chosen for a design of a dedicated mechanical micro-actuator and a constant current driver to match it. The wire samples have been provided by SAES Getters, one of the most important worldwide suppliers of Shape Memory Alloy materials.

The following table (Tab. I) reports the main characteristics of the chosen sample class compared with higher diameter ones.

TABLE I. SMA WIRE CHARACTERISTICS

SMA-wire diameter [µm]	Max Force [N]	Max Stroke	Suggesting operating Force [N]	Suggested operating Stroke
25	0.3	5%	0.1	<3,5%
50	1.2		0.3	
100	4.7		1.3	
150	6.2		2.7	

ANALOG CURRENT DRIVER

The possibility of a sensorless actuator makes the SMA eligible for a new way of actuation. This implies that the main feature of a SMA current driver is the high precision in the measuring of the electrical characteristics of the wire. Moreover, to avoid any noise, the control frequency must be higher than the audible range.

Starting from this specification, the design of the SMA driver is based on a very precise current generator with a variable output level modulated by a PWM signal at 25kHz. The current generator is constituted of an operational amplifier and a BJT, both opportunely selected to exploit their dynamic characteristics and regulate the current that flows in the load (i.e. SMA wire) with the maximum precision. The current generator control signal has been obtained by a reference voltage, opportunely divided and modulated by the PWM signal through a high speed analog switch.

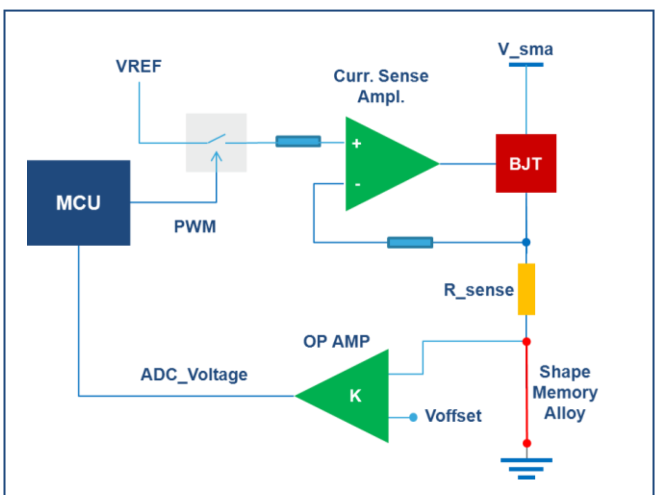

Figure 3: SMA current driver block scheme.

Once fixed, in order to obtain the SMA resistance value, the current on the shape memory alloy wire has been inserted in an operational amplifier stage that permits the capture of the small voltage variation on the SMA resistance in a very tiny time window. Therefore, the SMA voltage must be amplified and translated into an offset voltage, in order to be compliant with the voltage acquisition range of the MCU ADC.

To illustrate the previous description, the current generator block scheme is presented in Figure.3.

To implement a precise and stable control signal according to the requested speed and precision, the voltage reference TS824AILT-2.5 [1] and the analog switch STG3157 [2] have been chosen for their characteristics. A 25kHz PWM signal generated by a STM32F103 MCU [3] [4] [5] drives the STG3157 to modulate a PWM control signal with the desired level fixed by a resistance divider. The new generated signal precision is guaranteed by the STG3157 switching rate, while the precision value is mainly due to the stability of the TS824AILT-2.5 to temperature variations.

Based on the previous considerations, Figure 4 shows the schematic of the control signal generator for the current driver.

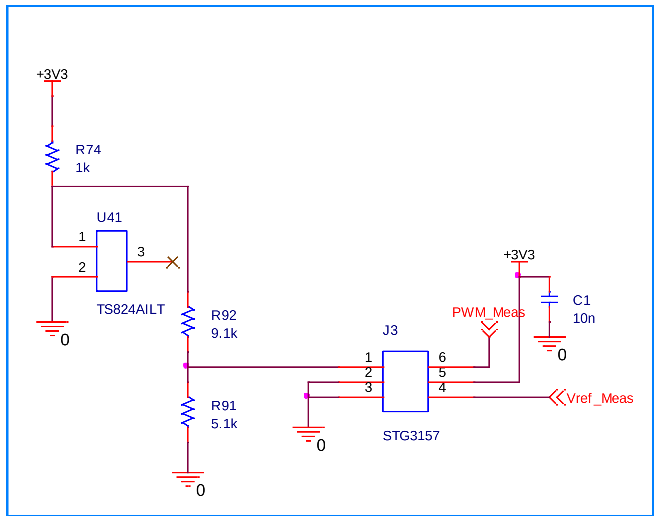

Figure 4: Current driver – control signal generator stage.

The 25kHz PWM control signal, generated by the stage just described, is provided as input to a current generator implemented by a closed-loop operational amplifier.

This second block implements a very precise current generator with the OPAMP TSV992 [6], that is suitable for this application for its performance in terms of gain bandwidth product because it guarantees an excellent speed response to 25kHz PWM control signal.

This driver stage based on TSV992 OPAMP, through a sense resistance, reads the current value, compares this with the voltage reference, and consequently, drives the BJT 2STR1230 to minimize the current error. For this operation, TSV992 is suitable for managing the 25kHz PWM signal generated by the control signal generator stage, and provides an output current signal free of distortion that may influence the next stage during the reading of the SMA resistance value.

Figure 5 represents the Current generator stage.

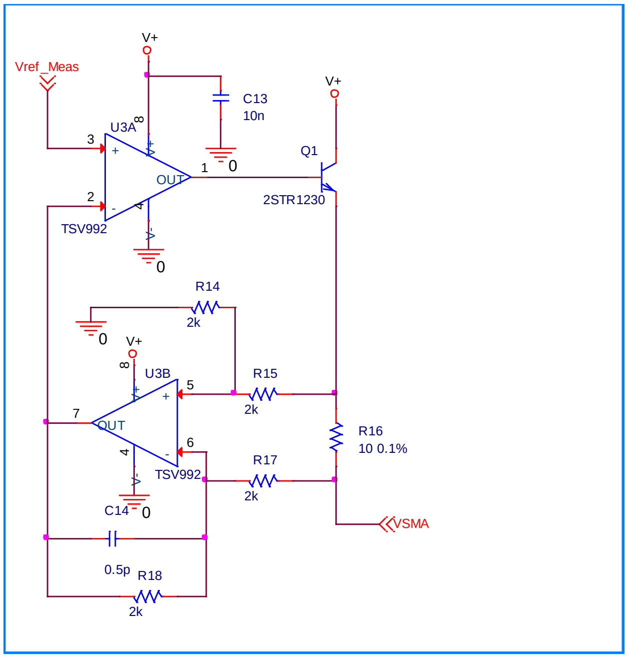

Figure 5: Current generator stage.

The SMA resistance data acquisition is a very delicate operation: it has to be accomplished by the MCU ADC with the highest precision in a time window of just 4µs, and the R-SMA variation is in the 1Ω-range with a maximum accuracy of ~1mΩ.

To have an efficient resistance data reading, starting from an applied stable and fixed current level, it's sufficient to measure the voltage upon the SMA wire with the desired accuracy. To reach this specification, the conditioning stage has been designed to amplify the voltage signal subtrahend an offset generated by a DAC. This offset is useful to select the right voltage range necessary to maintain the R-SMA variation in the ADC operative range. Due to the high gain requested and to the necessity to maintain the high slope of the signal during the measurement, the TSH72 [7] has been selected to implement the conditioning stage. The TSH72 is a dual OPAMP with video performances that perfectly fits with the specification of very large bandwidth and low distortion.

Finally, the MCU performs the acquisition through its ADC according to the desired time window and sets the suitable voltage acquisition range through its DAC.

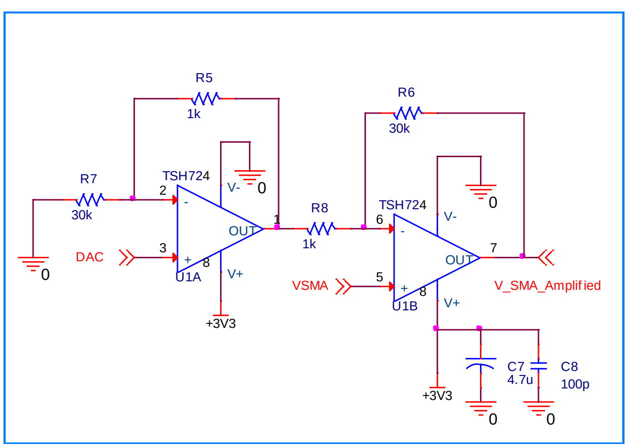

Figure 6: Measure conditioning stage.

A further sample and hold stage has been added to guarantee the signal integrity during the ADC acquisition (Fig. 7).

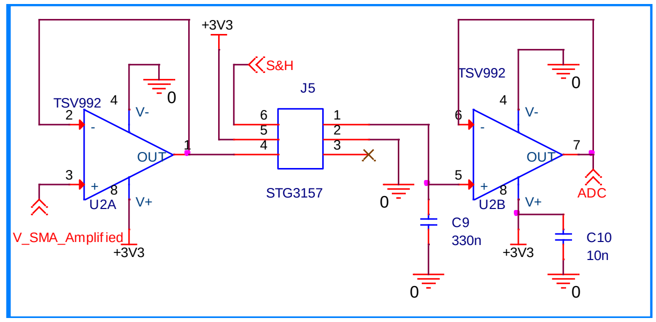

Figure 7: Sample and Hold stage.

Figure 8 shows the driving signal, generated by the current driver, applied to a constant resistance. In this case, a current of 90mA has been applied on a 33Ω resistance.

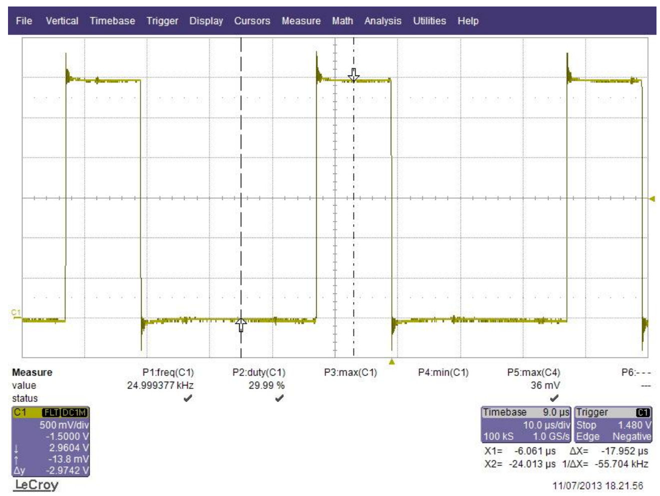

Figure 8: SMA current driver block scheme.

In the following paragraphs, a brief description of the main products is reported.

a) TSV992

The TSV992 is a dual operational amplifier belonging to ST's operational amplifiers family. It's a rail-to-rail OPAMP with an excellent speed/power consumption ratio and features an ultra-low input bias current. The TSV992 offers a 20MHz gain-bandwidth product, stable for gains above 4 with 100 pF capacitive load, while consuming only 1.1 mA maximum at 5 V.

These characteristics make the TSV99x family ideal for sensor interfaces, battery-supplied and portable applications, as well as active filtering.

The main characteristics of the TVS922 are

- Low input offset voltage: 1.5 mV max (A grade);
- Rail-to-rail input and output;
- Wide bandwidth 20 MHz;
- Stable for gain ≥ 4 or ≤ -3;
- Low power consumption: 820 µA typ;
- High output current: 35 mA;
- Operating from 2.5 V to 5.5 V;
- Low input bias current, 1 pA typ;

- ESD internal protection ≥ 5 kV;

b) TSH72

The TSH72 is a dual operational amplifier featuring high video performances with very large bandwidth, low distortion, and excellent supply voltage rejection.

Running with a single supply voltage from 3V to 12V, these amplifiers feature a large output voltage swing and high output current capable of driving standard 150Ω loads. A low operating voltage makes the TSH7x amplifier family ideal for use in portable equipment.

The TSH71, TSH73 and TSH75 belong to the same product family, and also feature standby inputs, each of which allows the op-amp to be put into a standby mode with low power consumption and high output impedance. This function allows power saving or signal switching/multiplexing for high-speed applications and video applications.

For the TSH72, the SOT23-5 package is suitable to economize both board space and weight.

The main characteristics of the TSH72 are

- 3V, 5V, ±5V specifications;
- 3dB bandwidth: 90MHz;
- Gain bandwidth product: 70MHz;
- Slew rate: 100V/ms;
- Output current: up to 55mA;
- Input single supply voltage;
- Output rail-to-rail;
- Specified for 150Ω loads;
- Low distortion, THD: 0.1%;
- SOT23-5, TSSOP and SO packages;

c) TS824-25

In order to implement a precise voltage reference stage for the two level control waveform, the TS824AILT-2.5 has been chosen for its characteristics. This is a low-power shunt voltage reference, housed in a SOT23-3 package. It features a very low temperature coefficient of 50ppm/°C as a maximum value, operating over the industrial temperature range (-40 to +85°C). It provides a 2.5V output voltage and is ideal for battery-operated equipment where power conservation and space saving are critical points for the application.

Its main characteristics:

- low Tc: 50 ppm/°C maximum
- 2.5V output voltage
- low operating current: 60µA max @ 25°C
- high precision at 25°C: ±0.5% and ±1%
- stable when used with capacitive loads
- industrial temperature range: -40 to +85°c

d) STG3157

The STG3157 is a high-speed CMOS analog single-pole double-throw (SPDT) switch or 2:1 multiplexer/demultiplexer bus switch manufactured using silicon gate C2MOS technology. It is designed to operate from a 1.65 V to 5.5 V supply, making the device ideal for portable applications.

The STG3157 features very low on-resistance (< 9Ω) at VCC = 3.0 V. The IN input is provided to control the SPDT switch and is compatible with standard CMOS output. Switch S1 is ON (connected to common port D) when the IN input is held high, and OFF (a high impedance state exists between the two ports) when IN is held low.

Switch S2 is ON (connected to common port D) when the IN input is held low and OFF (a high impedance state exists between the two ports) when IN is held high.

Additional key features are fast switching speed, break-before-make delay time, and very low power consumption. All inputs and outputs are equipped with protection circuits to protect against static discharge, giving them immunity from ESD and transient excess voltage.

Its characterics:

- High speed:tPD = 0.3 ns (max) at VCC = 4.5 VtPD = 0.8 ns (max) at VCC = 3.0 VtPD = 1.2 ns (max) at VCC = 2.3 V;
- Ultra low power dissipation:ICC = 1 µA (max) at TA = 85 °C;
- Low on-resistance; at VIN = 0 V:RON = 7 (max TA = 85 °C) at VCC = 4.5 VRON = 9 (max TA = 85 °C) at VCC = 3.0 V;
- Wide operating voltage range:VCC (OPR) = 1.65 V to 5.5 V single supply;
- TTL threshold ON control input at VCC = 2.7 to 3.6 V;
- Pin and function compatible with 74 series 3157;
- Latch-up performance exceeds 150 mA (JESD 17);

CONCLUSIONS

In this paper is presented a new current driver for SMA-based micro actuators. The requested specifications in terms of speed and accuracy have been accomplished by using devices from ST’s analog product family. In particular, the high speed OPAMPS TSV992 and TSH72, the voltage reference TS824AILT-2.5, and the analog switch STG3157 have been selected for their features and performances.

The results obtained by the measurements show that the designed platform allows an accurate control of the SMA actuator.

REFERENCES

[1] TS824AILT-2.5 – Datasheet - STMicroelectronics

[2] STG3157 – Datasheet – STMicroelectronics

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[4] STM32F101xx, STM32F102xx, STM32F103xx, STM32F105xx and STM32F107xx advanced ARM-based 32-bit MCUs, page 597/1093 - Reference Manual - STMicroelectronics

[5] ARM-based 32-bit MCU STM32F101xx and STM32F103xx firmware library - Firmware Library User Manual - STMicroelectronics

[6] TSV992 – Datasheet - STMicroelectronics

[7] TSH72 – Datasheet - STMicroelectronics

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