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Design and Implementation of Experimental Set-up for Property Assessment of NiTiNol Shape Memory Actuator Springs

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ABSTRACT
This study aims to design and implement an experimental set-up to make property assessment of NiTiNol Shape Memory Actuator Springs. Having the right material characteristics for Nickel Titanium based alloy, shortly named in industry as NiTiNol, is very important at determination of application areas and performing simulations with analytical and numerical models. An experimental set-up having load cell and sensitive displacement measurement device has been prepared to determine SMA basic characteristics. In addition to this experimental set-up, a control and power unit is used to reach at aimed control values. Measurement has been performed using a spring, which is made of NiTiNol material as shape memory alloy. SMA spring undergoes deformation with weight effect and it returns to original shape by heating with electrical current. The effect of the current data and different geometrical properties of springs used in experiment on the heating time, displacement. Properties such as wire diameter, spring diameter and number of turn of the spring have been obtained experimentally and numerically during heating and cooling processes.
Keywords- Shape Memory Alloy, SMA, Linear actuator, Nickel Titanium Alloy, NiTiNol, Spring Design

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I. INTRODUCTION

SMAs are newer types of metal alloys that consist of two or more different materials of a particular chemical composition. The main characteristic of these alloys is the **S**hape **M**emory **E**ffect (**SME**), meaning that they have the ability to return to their initial shape in case that heat treatment is applied to them. The plastic deformation of such alloys begins at low temperatures, and after the alloy is exposed to high temperatures, it returns to its initial form.

Internally responsive SMA, the reversible solid-solid, diffusionless thermos-elastic phase transformations between an austenitic phase and martensitic phase are causing amazing phenomenon like SME and Superelasticity (SE). Advantage to recover initial shape when warmed is related to SME, and property to recuperate larger strains than other materials (up to 8%) during mechanical loading-unloading is related to SE.

Superelasticity is the ability to elastically deform to higher than normal levels when mechanically deformed, nearly to 11%, between the Af and Md temperatures. Most metals only have the ability to elastically deform less than 1% strain. While in this temperature range, SMA material results in a phase transformation from austenite to detwinned martensite. Upon unloading, the martensite phase becomes unstable and transforms back to its original austenite phase [1].

With simple words SMA shows its superelasticity when load is removed and shape memory effect is being activated with heating or cooling. It is generally accepted that SMA's are controlled superelastic materials.

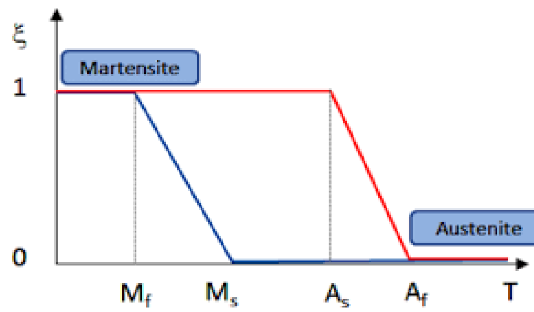

Figure 1. Transformation of SMA [2]

The fascinating properties of Shape Memory Alloys (SMA) have inspired engineers all over the world ever since their discovery. The reason for their attractiveness lies in the fact their microstructural changes when subjected to temperature or magnetic field changes. NiTiNol is an alloy of roughly 50% Nickel and 50% Titanium. It was named after its chemical components and its founders: Ni (Nickel) + Ti (Titanium) + NOL (Naval Ordinance Lab). The most important characteristics of this smart material, shape memory effect and superelasticity, make NiTiNol unique from other engineering metallic alloys. Other frequently used elements are iron and chromium (to lower the transformation temperature), and copper (to decrease the hysteresis and lower the deformation stress of the martensite).

The implementation of SMA wires coupled with a simple DC control system can be used to drive small objects without the addition of relatively heavy motors, gears, or drive mechanisms. In a thermomechanical system, SMAs can be used as combined sensors and actuators where they can sense the changes in external stimuli and monitor certain desired functions. The unique characteristics of SME and SE discussed earlier have made SMAs the material system of choice in applications ranging from sensing and control, vibration damping, biomedical, automotive and aerospace areas [3].

II. EXPERIMENTAL SET-UP OF SMA SPRING

2.1. Design Of Experimental Set Up

The schematic of the experimental setup designed and developed for position control of the SMA wire actuator is shown in Figure2. It consists of the SMA spring with load cell against a weight load along with Balluf linear transducer, programmable power supply and Parallax Data Acquisition tool (PLX-DAQ). The dimension and properties of the SMA spring are given in Table. The load cell is used to measure the generated load during phase transformation. The output of the load cell is conditioned using the load cell signal conditioner to provide output in the range of 0- 10 V to the data acquisition system. The displacement sensor measures the displacement due to SMA contraction. The programmable power supply delivers power to the SMA in the constant current mode.

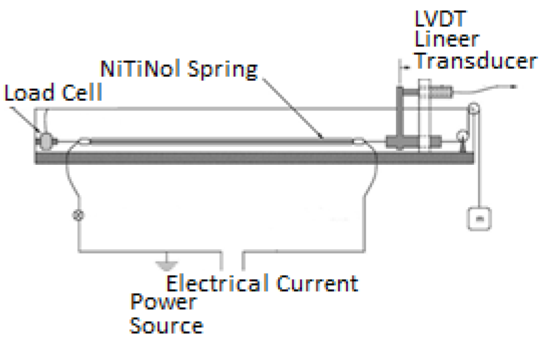

Figure 2. The Schematic of the Experimental Set Up [4]

2.2 Properties Of Linear Transducer-

The BTL6 Micropulse transducer is used in different systems or any kind of machine where change in a position is needed to be measured. In a system, it is used with any kind of microcontroler, PLC or Arduino. It consists of waveguide and aluminum housing. Moving part is made with magnet and it is moving along the housing and constantly measuring the position. The most important characteristics of this sensor are listed in following table.

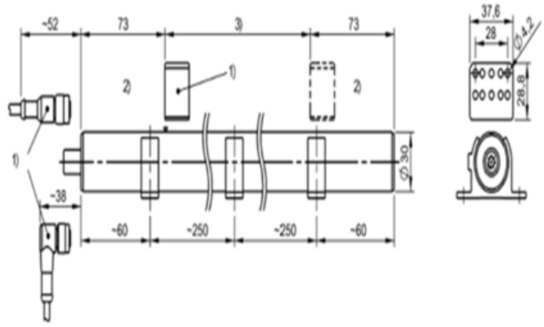

Figure 3. The BTL6 Micropulse transducer

2.3 Properties of Load Cell-

This load cell sensor is used for change up to 5 kg of weight (force) into an electrical signal. Electrical resistance which is directly proportional to strain is also measurable with this load cell. Aluminum-alloy is used in straight bar load cell and is also accomplished to read a capacity of 10kg. Four strain gauges are combined in a Wheatstone formation. Detailed properties are showed in Table 2.

Table 1. Properties of linear transducer

Input Current Range	Max. of 70 mA
Output Range	0 → 10 V
Overall Width	60mm
Stroke	150 mm
Brand	BALLUF
Minimum Operating Temp.	0°C
Maximum Operating Temp.	70°C
IP Rating	IP67
Overall Height	37 mm
Supply Voltage	20 → 28 V dc
Housing Material	Anodised Aluminium
Overall Depth	296mm

Weight connected to the test device causes extension in spring and this deformation is measured by the displacement sensor. The force that opens the spring is also measured by the load sensor and the deformation force - displacement curves are plotted using Parallax Data Acquisition tool (PLX-DAQ) software add-in for Microsoft Excel which collects data from microcontrollers and puts the numbers into columns. PLX-DAQ provides analysis of collected numbers from sensors

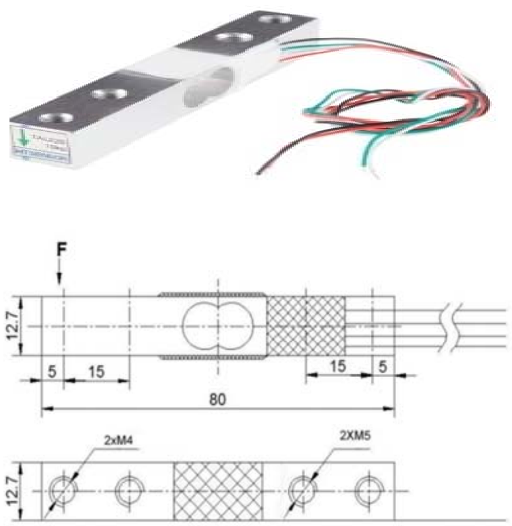

Figure 4. Load cell

Table 2. Properties of Load Cell [5].

Type	TAL220- PARALLEL BEAM LOAD CELL
Capacity	5 kg
Excitation Voltage	5-10 V dc
Operating temperature range	From -10ºC to +55ºC
Compensated temperature range	From -10ºC to +40ºC
Electrical connection	4 color wire
Material	Aluminum Alloy
Defend grade	IP 65

Table 3. Analytical results

Definitions	**Analytical Value**
Load (P, N)	11.7
Deflection (δ, mm)	1.47
Spring Diameter (D, m)	0.0082
Wire Diameter (d, m)	0.00175
Number of Active Turns (n)	16
Spring's Length (L, m)	0.46
Shear Stress (τ, GPa)	0.0405

2.4. Experimental Study

The designed shape memory spring's mechanical behavior was tested using an experimental setup, made as a thesis project in department of Mechatronics Engineering in Marmara University. This study consist of two experiments to show the effect of current and load to displacement and time needed to extend and compress the spring. [6,7]

Table 3 shows the mechanical properties of the spring used in first experiment, which was analytically designed before. Table 4 show us analytical results of designing SMA spring. To occur 1.47mm deflection by using 11.7N load, we need following characteristic properties of SMA spring.

The SMA spring is connected to the experimental set up with several weights ranging from 1 kg, to 2 kg weights. The SMA spring, activated with current of 2.5A is than showing its shape memory effect and going back to first position. Displacement measured with micropulse transducer and displacement calculated analytically were compared. Micropulse transducer has maximal stroke of 150 mm. Compared data are presented in table 3. It was observed that there was a difference of 3% between the two data. This difference is due to the resolution and repeat accuracy characteristics of the micropulse transducer (Resolution ≤10μm, repeat accuracy ≤10μm) and changes in the internal structure of the SMA spring during heating and cooling operations.

Figure.5 demonstrates change of deflection depending on load. It is shown that there is a linear increase in deflection with change of load. After first experiment, where one spring is analyzed, it is decided to compare springs with different geometrical properties, which have a great influence to behavior of the spring.

In second experiment effect of current, load, different geometrical properties to SMA spring behavior is tested.

Table 4. Change of deflection depending on the load

Load (P, N)	Deflection (δ (mm)	
	Experimental Results	Analytical Results
9.81	1.25	1.22
10.79	1.38	1.34
11.7	1.51	1.47
12.7	1.63	1.58
13.7	1.75	1.71
14.7	1.88	1.83
15.6	2.01	1.94
16.7	2.14	2.08
17.6	2.25	2.19
18.6	2.38	2.32
19.62	2.51	2.44

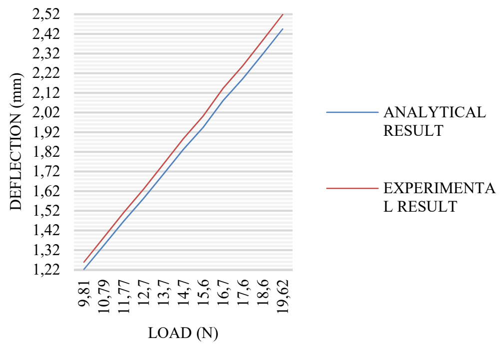

Figure 5. Change of Deflection Depending on a Load

Firstly, currents of 2, 2.5 and 3A are applied to spring designed before and result is showed in following diagram. Spring is extended with 330gr weight. Measured displacement is 42mm. Heating cause compression in spring (spring is going back to its first position), but because weight is not removed complete recovery does not occur. Displacement of spring after heating while loaded with weight is 15 mm. After removing weight spring recover completely which means that used spring is not proper for this system. Effect of current in this case is reflected to speed of recovering. As it can be seen from Figure6, speed of recovering is directly proportional with intense of current; with higher current recovering process happen faster and is also almost linear in this case. SMA spring needs time to heat up and with higher current time is lower.

When it is about geometrical properties of this two springs, it is noticed that length and diameters of spring and wire are enlarged for approximately 30% which will be considered in analyzing the effect of this variables. Linear increment in time needed to complete the whole process of extending and heating is seen. First spring's process is being completed in 60 seconds while second spring's time is around 90 seconds. It is observed that there is linear dependence between geometry properties and time.

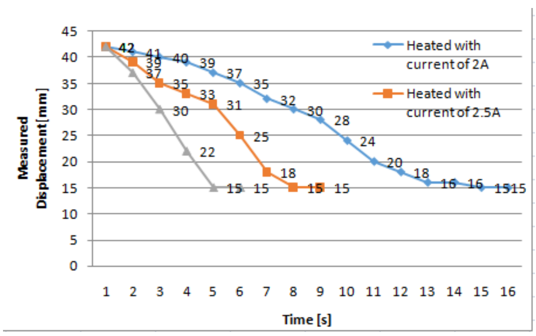

Figure 6. Time-Displacement Diagram

Following diagram is also Time – Displacement diagram but it shows the effect of geometry to displacement, while same load and current is applied. Geometrical properties of spring 1 and spring 2 are presented in following table.

Table 5. Geometrical properties of Spring 1 and Spring 2

Properties	Spring 2	Spring 1
Length [cm]	2.2	3.2
Diameter of spring [cm]	0.6	0.8
Diameter of wire [mm]	0.6	0.8
Number of turns	19	8

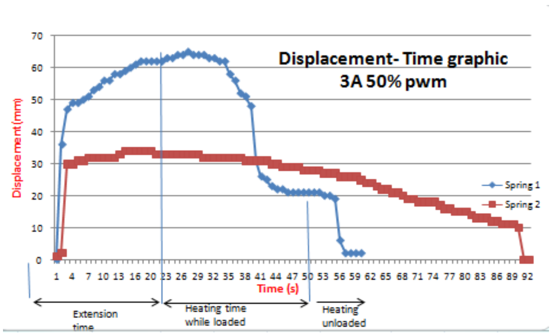

Figure 7. Time- Displacement Diagram

Next goal is to see how each of these geometrical properties is affecting the spring's behavior. Larger wire diameter will make the spring stronger and this is because making the wire diameter larger also makes the spring's coils tighter which reduces the spring index. The opposite effect is done when making diameter smaller, the spring index increases so it isn't as tight and it is under less stress. This adjustment will not only affect spring's force but it will also affect its elastic limit like it does when adjusting the outer or inner diameter. When it is needed the outer diameter to be stronger it must be made smaller. Tighter coils have a smaller index, which gives more force. The way this affects the elasticity of spring design is because springs with reduced spring indexes are under more stress than springs with average or large indexes. Springs with larger diameter need more time to heat up but are better in case when large strokes are needed. As it is said smaller diameter is increasing the strength of spring so with higher loads diameter should be decreased.

Figure 8 shows comparison of speed of extending two springs with different geometrical properties while same load is applied. Using displacement and time values taken from sensors speed of extending is calculated. From diagram, it is seen that in both cases 3 seconds are needed to heat up the spring and to reach the maximum value of the speed, which is after that point lowering. Spring 1 with bigger diameter is extending faster and reaches bigger and needed displacement faster but is also harder to control. Its time of stabilizing is almost two times bigger than for other spring so can be used in systems with not so high level of precision.

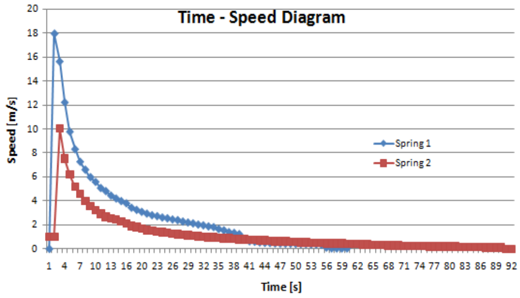

Figure 8. Time- Speed Diagram

III. CONCLUSIONS

In this study, using all the advantages of superelastic mechanical properties of NiTiNol (Nickel-Titanium Alloy), Shape Memory Alloy spring is designed and experimentally tested for optimization processes. Displacement, load and time values are taken from sensors integrated in experimental set up system. The experimental data obtained and the analytical data were compared in the first experiment and comparison of two designed springs with different geometrical properties is made in the second experiment. Results are found to be mutually successful. Main goal is to see the effect of electrical current and change in diameters and number of coils to behavior properties of the spring and following conclusions are obtained:

- Speed of recovering is directly proportional with intense of current; with higher current recovering process happen faster and is also almost linear;
- Springs with larger diameter need more time to heat up but are better in case when large strokes are needed. As it is said smaller diameter is increasing the strength of spring so with higher loads diameter should be decreased.
- Spring 1 with bigger diameter is extending faster and reaches bigger and needed displacement faster but is also harder to control. Its time of stabilizing is almost two times bigger than for other spring so can be used in systems with not so high level of precision.

This study will guide engineers in design of linear actuators using shape memory springs.

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