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Axiomatic Design of equipment for analysis of SMA Spring degradation during electronic actuation

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Abstract

The Shape Memory Alloy, Nickel-Titanium i.e. Nitinol is greatly lacking in published research about its properties. Both degradation through electronic actuation and degradation through heat actuation are lacking, as well comparison of them. This means that both inventors and manufacturers are missing important information, limiting their ability to reliably apply the material in the soft robotic field, automotive design, consumer electronics, or aerospace. Accurate and reliable testing equipment is essential to gather needed data about the material for further development. This paper presents a static test bench for SMA springs that is designed according to Axiomatic Design Theory. The tester is designed to actuate and measure six springs at a time to increase the rate at which testing data is gathered. The measurements collected are the force, current, and temperature of each spring along with the ambient temperature. The test bench was successfully designed and built. An initial test run lasted for two days for approximately 6700 cycles; no springs experienced a complete failure.

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Keywords: Axiomatic Design, Shape-Memory Alloy, Nitinol, Springs, SMA life-cycle

1. Introduction

Shape Memory Alloy (SMA) are alloys that can "remember" their shape: if the material is deformed it can reach its original shape by being heated to a certain temperature.

Springs made from Nickel-Titanium Alloy (NiTi i.e. trade name Nitinol) are rarely investigated so information about their abilities under different conditions is minimal. Because of little available performance they are not often used in an actuation capacity, only in a super-elastic mode. Consequently, SMA-specific testing equipment is not commercially available. Actuator performance over its lifetime, especially degradation, is essential for designers and manufacturers to use NiTi as a material of choice. Manufacturers can not produce actuators without known specifications and expect customers to buy them.

SMA's actuation mechanism in its raw state is that of small angular bending or very small strains, 3% or less. One way to increase the strain at a significant drop in generated force is to wind the SMA into a spring shape [1,2]. The objective of this project was to use Axiomatic Design Theory [3] to design a test bench that can quantify the performance of springs made of NiTi focusing on degradation. Electronic heating actuation was explored due to its convenience in engineering applications. A test bench capable of recording force generated to correlate with current and temperature will be valuable for designers of actuators or manufacturers desiring to use Nitinol.

Nomenclature

AD	Axiomatic Design
SMA	Shape Memory Alloy
NiTi	Nickel Titanium alloy or Nitinol
C_n	Constrain *n*
FR_n	Functional Requirement *n*
DP_n	Design Parameter *n*

2. Background

In late 1950's, William Buehler discovered abilities of NiTi, or as often commercially called "Nitinol". This was at the Naval Ordnance Laboratory (NOL) while researching heat resistant alloys for weapon development [4]. SMA has a "one-way" and "two-way" memory effect of its solid-solid transformation from low-temperature martensite to the high-temperature austenite

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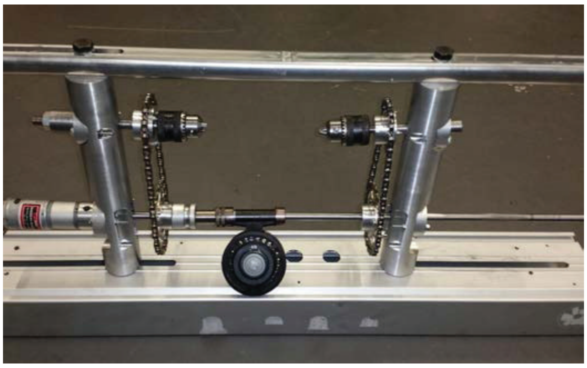

Fig. 1: Spring winder used in project

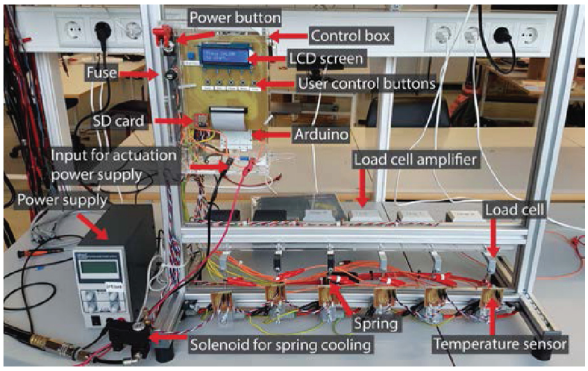

Fig. 2: Completed SMA spring test bench

phase. In this research, we used one-way memory effect Nitinol where an external force is needed to return it to the martensite state. Two-way memory effect is when the alloy changes its phase between austenite and martensite phase without any externally mechanically applied forces, though it can not provide any force to external components in the phase changing [2].

2.1. Existing equipment

When the authors started working on the design, some existing equipment for conducting research on SMA springs was available from the previous work by Einarsson [5]: a single-spring spring tester, a spring winder, and a prototype spring winder frame which was much lighter (Fig. 1). The spring winder was assembled on the new frame for convenience and used to produce springs for use in testing.

The spring-winder consists of a DC brushed motor, fishing reel, axle, and chains for rotating the core. On the lower axle is the motor and fishing reel filled with NiTi wire; the reel provides adjustable tension for consistent winding. A core wire that defines the inner diameter of the spring is attached to the two drill chucks on the upper axle and pulled under tension. The SMA wire is attached to the core and motor engaged for winding the wire on the core. This procedure produces we get one long spring (approximately 10 cm) that is then cut down to appropriate test sizes. By winding one long spring, we can ensure a consistent winding angle for a single set of test samples.

Einarssons's spring tester [5] was made to test one spring at the time using a lever to scale the force on the load cell to be able to test a wider range of springs with a single load cell. The instrument measured tension force from the spring while heated at a fixed current of 5.3 A on a National Instruments (NI) USB-6008 12-Bit, 10kS/s Low-Cost Multifunction DAQ. The graphical user interface and data processing were developed on NI Lab View. The main complaint about this tester was that it took too long to get sufficient data for analysis.

2.2. Considerations for new design

The new test bench that was made in this project (Fig. 2) was designed to test six springs simultaneously to reduce testing time and to get acceptable sample size of data. Choosing the number of simultaneous tests originates from the basics of small sample statistics: Student's t distribution. Normally, it is assumed that small samples $n \leq 30$ adhere to a normal distribution when taken from known normally distributed populations. The Student's t distribution allows us to calculate the required sample size to ensure that the mean of the samples matches the population mean within a certain error limit [6]

$$\delta > t_{\text{crit}} \sqrt{\frac{2\sigma^2}{n}} \tag{1}$$

where

n is the number of samples

σ^2 is the estimated population variance

t_{crit} is the critical value of Student's t read at degrees of freedom $n-1$ and $P = 0.05$

At sample size $n \geq 6$ the determination of significance drops to below half of the estimated population standard deviation. We consider this good enough estimator to provide information on the population of SMA springs created in the same manner to allow aggregate data analysis.

Each spring is directly connected to a load cell and measures tension force; this improves accuracy by removing sine error but means that the load cells must be matched to the expected spring actuation force. Spring temperature, ambient temperature and current through each spring is also measured. The bench also includes a dummy load cell as a base reference for possible environmental changes that might influence measurements.

There are many spring testers available on the market today. United Testing System from Canada offers for example ESM 303 [7]. However, these testers are focused on measuring the spring constant of a compression or extension spring, not on active actuation. It is possible that the tester could be adapted to measure SMA springs, but we could not find any existing systems suitable. An added complication is the large cost usually associated with such industrial instrumentation.

3. Design Attributes

To get the widest data and minimize the time it takes to obtain it we followed Axiomatic Design Theory (AD) [8]. AD