

# Artificial Tendon Driving System Using Skin Effect

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**Abstract—** In this study, "skin effect" a phenomenon often encountered in high-voltage transport systems was investigated on an artificial tendon. Shape memory alloy (SMA) spring was used as an artificial tendon. The SMA is activated by an electric current, which produces heat and initiates a phase transformation. To create a skin effect, direct current was modified as an alternating input signal with different frequencies using an inverter driving circuit. Skin effect based current signals and direct current signals were applied to the artificial tendon respectively. Comparisons of the effect of two signal feeding techniques were accomplished by constant load-cyclic tests. Another focus of the current study was the solution for SMA's late response problem caused by cooling time.

**Index Terms—** Artificial Tendons, shape memory alloy, skin effect

## I. INTRODUCTION

THE development of active materials, such as Electroactive Polymers or Shape Memory Alloys (SMAs), that are operationally similar to the human muscle, have encouraged the development of artificial hands. As an actuator, it is capable of up to 8% strain recovery and 350 MPa restoration stress over multiple cycles. Therefore, such SMAs have been used in engineering applications for shape control, shock absorption, vibration dampening, automatic on-off switching and high force actuation [1,2,3]. Muscle-like actuators present a high power to weight ratio, enabling the development of compact, lightweight prosthetic devices without too much compromising of its power capabilities and eliminating the forced-tradeoff between dexterity and anthropomorphic size, weight and appearance [4,5,6]. Considerable efforts have already been made by different research groups worldwide to develop articulated robotic hands or finger mechanisms using SMAs as power elements for their actuation systems [9,10]. Although SMAs pose many advantages compared to other actuation systems, the main problem of a SMA is its late response time during its return to some previously defined shape or size when subjected to the appropriate thermal procedure. The "skin effect" is the tendency for high frequency alternating currents and magnetic flux that penetrate into the surface of

a conductor only to a limited depth. The "depth of penetration" is a useful dimension, depending on the frequency and also on the properties of the conductive material, its conductivity or resistivity and its permeability. If the thickness of a conductor is much greater than the depth of penetration, its behavior toward high-frequency alternating currents become a surface phenomenon rather than a volumetric phenomenon. "surface resistivity" is the resistance of a conducting surface of equal length and width, and has simply the dimension of resistance. In the case of a straight wire, the width is the circumference of the wire. Due to skin effect, high frequency voltage applied to both ends of a conductor result in temperature increase at the surface of the material. This phenomenon will be studied on functional performance of Shape Memory Alloys (SMAs). This paper focuses on a novel driving method for SMA to get better response.

## II. METHODOLOGY

As previously mentioned, artificial tendons based on shape memory alloy (SMA) wires. Principles of shape memory alloy actuation method and fundamentals of skin effect will be explained in the next section.

### A. Shape Memory Alloys

Shape Memory Alloys (SMAs) are a group of metallic materials that demonstrate the ability to return to some

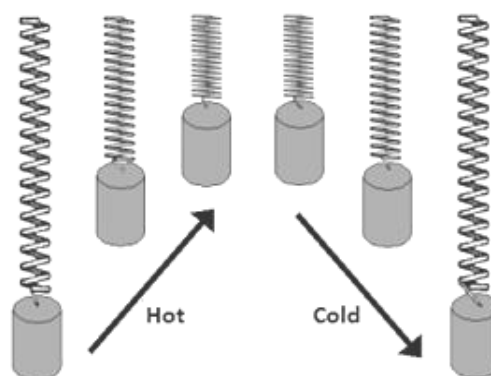


Fig. 1. Relation of SMA with Heat [4].

previously defined shape or size when subjected to the appropriate thermal procedure. The shape memory effect is due to the phase transformation from the austenite (parent) phase to martensite (product) phase and vice versa. These transformations take place because of changes in the temperature, stress, or a combination of both [2,3,4].

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The observable macroscopic mechanical behavior of SMAs can be separated into two categories: the shape memory effect and pseudoelastic (superelastic) effect. In the shape memory effect, an SMA material exhibits a large residual strain after the loading and unloading. This strain can be fully recovered upon heating the material. In the pseudoelastic effect, the SMA material achieves a very large strain upon loading that is fully recovered in a hysteresis loop upon unloading. SMAs show different mechanical behaviors at different temperatures [3,4].

The most common shape memory material is an alloy of nickel and titanium called Nitinol. This particular alloy has very good electrical and mechanical properties, long fatigue life, and high corrosion resistance [9-11]. As an actuator, it

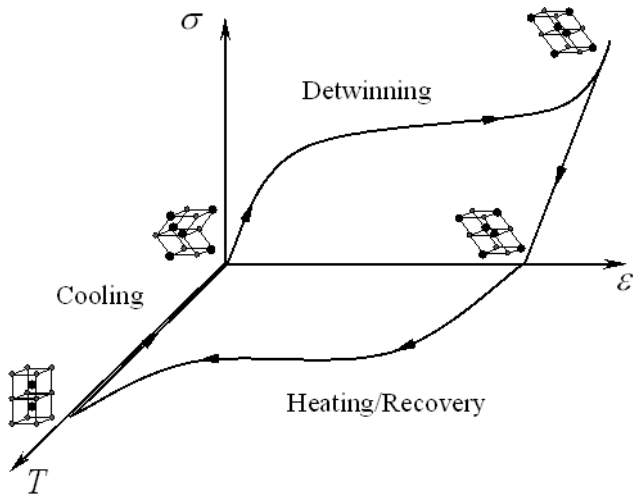


Fig. 2. Phase transformation and mechanical behavior of SMAs.

is capable of up to 8% strain recovery and 350 MPa restoration stress with many cycles. Therefore SMAs have been used in engineering applications for shape control, shock absorption, damping of vibrations, automatic on-off switches, and high force actuators [3,6,7,8]. SMA actuators are the key elements for the development of a lightweight, noiseless and multifunctional prosthesis.

**B. Skin Effect**

Skin effect is the tendency of an alternating electric current (AC) to become distributed within a conductor such that the current density is largest near the surface of the conductor, and decreases with greater depths in the conductor. The electric current flows mainly at the "skin" of the conductor, between the outer surface and a level called the skin depth. The skin effect causes the effective resistance of the conductor to increase at higher frequencies where the skin depth is smaller, thus reducing the effective cross-section of the conductor[12,13,14].

High frequency noise in the range of 1kHz-1.5MHz increases the inductive reactance of the wire. This forces the electrical charge towards the outer surface of the wire. This means that the total available space of the wire is not used to carry the electrical power.

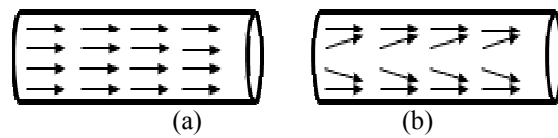


Fig. 3. a-the flow of charge is using all of the available space of the wire.  
 b- the flow of charge in wire when skin effect takes hold

Figure.3, show the cross sectional view of an electrical wire. (a) is the optimal use of wire. The charge flows smoothly through the wire. (b) shows the charge being pushed to the circumference due to high frequency noise.

Overcrowded electrons at the circumference of the wire will not find sufficient room to travel increasing friction among them. This will lead to release of frictional energy also known as heat. Generated heat from the wire will leave the wire through its plastic insulation. Prolonged exposure of plastic to the heat will decrease the life span of the wire. Thermal effect due high frequencies occurs in a shorter time resulting in early actuation of SMA. This property of conductors is investigated in the work described here.

As previously mentioned, the skin effect is where alternating current tends to avoid travel through the center of a solid conductor, limiting itself to conduction near the surface. This effectively limits the cross-sectional conductor area available to carry alternating electron flow, increasing the resistance of that conductor above what it would normally be for direct current. At low frequencies the skin effect is negligible and the distribution of current across the conductor is uniform. As frequency is increased the depth to which the flow can penetrate,  $\delta_s$  / metres, is reduced.

The equation for calculating the skin depth is given here[12]:

$$\delta_s = \sqrt{\frac{2}{\omega * \mu * \sigma}} = \sqrt{\frac{\rho}{\pi * f * \mu}}$$

where;

$\mu$ =permeability

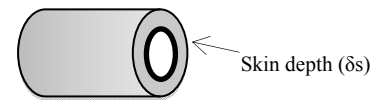
$\pi$ =pi

$\rho$ =resistivity ( $\Omega * m$ )

$\delta_s$ =skin depth (m)

$\omega$ =radian frequency(Hz)

$\sigma$ =conductivity(mho/m)



The degree to which frequency affects the effective resistance of a solid wire conductor is impacted by the gauge of that wire.

**III. EXPERIMENTS AND RESULT**

A experimental setup was developed to facilitate the testing of the SMA–spring (Figure 4). A micro-thermocouple was used to measure the temperature. LVDT was used to measure the rate of contraction and expansion of the SMA under thermal excitation. In our work, the artificial tendon cables were attached to the finger structure, routed through the finger core and connected to their

corresponding SMA actuators. Actuation was controlled by the electrical heating of the Flexinol spring. To show skin effect performance the pulse width modulated (PWM) with high alternating frequencies technique was used. It was compared to DC direct drive technique. We conducted several experiments to show the effectiveness of the Alternating DC driving system. Firstly, we tried to develop the force and moment relations for both signals. For this purpose, we set the input value to 5V Alternating Direct current with 2 kHz and 5V DC in the first application. During the experiments, payload current was 1.06 A for Alternating DC and 2.3A for DC signal. As shown in Figure 5 There are apparent values differences between Alternating DC and DC signals. The experimental results show that the Alternating DC gives better results under various working conditions of the SMA wire. In the second experiment 12V Alternating DC applied to SMA wire with different frequencies (50Hz, 1kHz, 2kHz). In 20 seconds time interval, the displacement of the SMA was easily observed and recorded.

#### IV. CONCLUSION

In this study, skin effect was investigated on an artificial tendon. Shape memory alloy (SMA) spring was used as an artificial tendon. To show skin effect performance of an SMA artificial muscle, strain–power relationship was determined by experimental work. By changing the frequency of alternating DC input, significant improvements were observed as opposed to stationary DC input. This method poses a novel contribution to SMA applications.



Fig. 4. . Experimental Setup

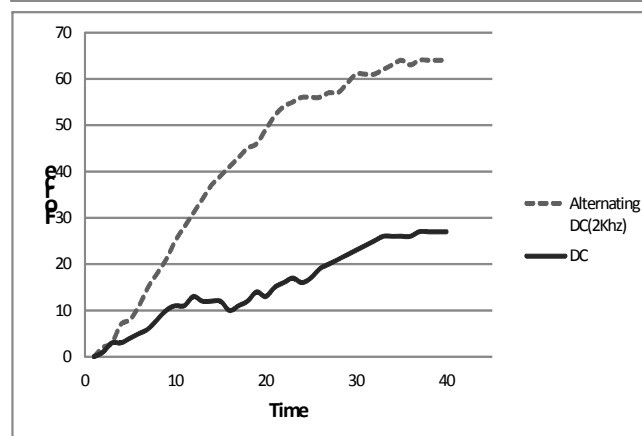
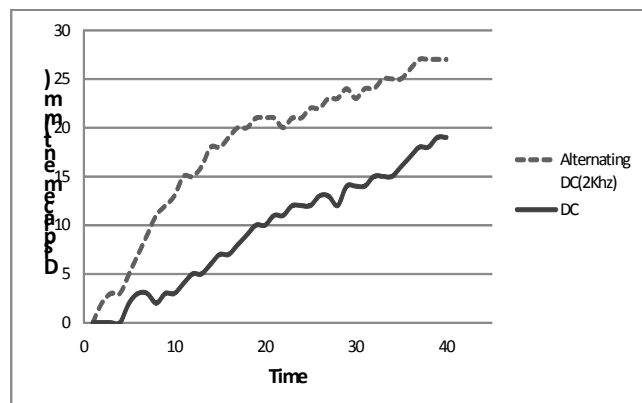


Fig. 5. Comparison of DC and Alternating DC (force & displacement response)

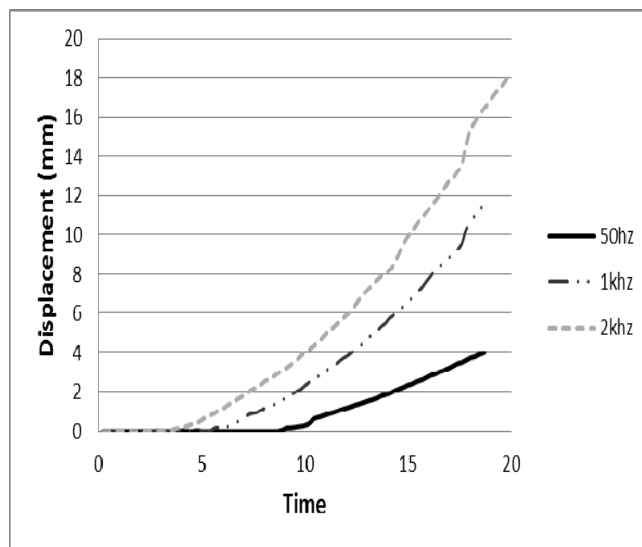


Fig. 6. Comparison of different frequencies

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