

APPLICATIONS OF NI-TI WIRES SHAPE MEMORY TRAINING ON ACTUATORS

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Resumo. Este estudo busca investigar as propriedades de ligas de níquel-titânio (Ni-Ti) e desenvolver um atuador de alto desempenho baseado em ligas de memória de forma (shape memory alloys - SMAs), aproveitando o efeito de memória térmica. Os objetivos incluem compreender o comportamento termomecânico de fios Ni-Ti, implementar programação de forma unidirecional e fabricar um atuador compacto para aplicações dinâmicas. A metodologia envolve uma revisão bibliográfica abrangente, modelagem por elementos finitos para simular respostas termomecânicas e modelagem matemática para prever o desempenho do atuador. Protocolos de programação treinarão fios Ni-Ti sob condições controladas de pré-deformação e temperatura, seguidos pela fabricação do atuador com mecanismos de retorno elástico. Testes experimentais avaliarão velocidade de atuação, comprimento de curso e capacidade de carga, com análise de dados comparando resultados a atuadores convencionais e validando modelos preditivos. Espera-se demonstrar controle preciso de deslocamento e força por efeitos de memória de forma repetíveis. Destaca-se a viabilidade dos atuadores Ni-Ti como alternativas compactas de alta densidade de trabalho, enfrentando desafios como taxas de arrefecimento e abrindo caminhos para aplicações em sistemas biomédicos, aeroespaciais e robóticos.

Palavras chave: Atuador. Fios de Ni-Ti. Liga de Memória de Forma. Treinamento de Memória de Forma.

Abstract. This study aims to investigate the shape memory properties of nickel-titanium (Ni-Ti) shape memory alloys (SMAs) and develop a high-performance SMA-based actuator leveraging the thermally driven shape memory effect. The objectives include understanding the thermomechanical behavior of Ni-Ti wires, implementing unidirectional shape programming, and fabricating a compact actuator for dynamic applications. The methodology encompasses a comprehensive literature review to establish foundational knowledge, finite element modeling to simulate thermomechanical responses, and mathematical modeling to predict actuator performance. Shape programming protocols will train Ni-Ti wires under controlled pre-strain and temperature conditions, followed by actuator fabrication integrating trained wires with elastic return mechanisms. Experimental testing will evaluate actuation speed, stroke length, and load capacity, with data analysis comparing results to conventional actuators and validating predictive models. The study is expected to demonstrate precise control over displacement and force through repeatable shape memory effects. Key conclusions highlight the viability of Ni-Ti SMA actuators as compact, high-work-density alternatives to traditional systems, addressing challenges like cooling rates and paving the way for applications in biomedical, aerospace, and robotic systems requiring adaptive mechanical control.

Keywords: Actuator, Ni-Ti Wires, Shape Memory Alloy, Shape Memory Training

1. INTRODUCTION

Shape memory alloys (SMAs) are emerging as intelligent materials capable of meeting demands in many areas of engineering, due to their unique ability to recover specific shapes through unidirectional shape programming when heated above the austenitic transformation temperature (A_f) (Lagoudas, 2008). This remarkable capability stems from the reversible phase transition between martensite, a low-temperature, highly deformable crystalline structure, and austenite, a high-temperature more rigid stable phase. The transition enables SMAs to combine the shape memory effect (SME) with high-energy dissipation capacity, making them ideal for applications requiring compact, high-performance actuators (Hu *et al.*, 2021). Exceptionally, SMAs exhibit two key behaviors: the shape memory effect, which allows recovery of large, seemingly permanent strains via thermal stimulus, and pseudoelasticity, enabling large, hysteretic stress-strain excursions without permanent deformation at sufficiently high temperatures (Lester *et al.*, 2015). These properties, coupled with high energy density, reasonable operational strain, biocompatibility, and long life cycle (up to 10^4 cycles under 1% strain), position SMAs as advanced and cost-effective solutions for reducing mechanical complexity and size in structures. This dual functionality sets the stage for understanding the specific mechanisms driving SMAs, particularly the thermally

activated shape memory effect that underpins many of their practical applications.

The thermally driven shape memory effect (SME) in shape memory alloys (SMAs), such as nickel-titanium (Ni-Ti or Nitinol), is a remarkable property that enables these materials to recover a predefined shape after deformation upon heating above a critical temperature (Otsuka and Wayman, 1998). This phenomenon relies on a reversible solid-state phase transformation between a low-temperature martensite phase, which is deformable due to its twinned or detwinned crystalline structure, and a high-temperature austenite phase, characterized by a rigid cubic lattice (Lagoudas, 2008). When cooled below the martensite start temperature (M_s), an SMA can be deformed into a temporary shape; subsequent heating above the austenite start temperature (A_s) triggers the reverse transformation, restoring the original shape with high precision and significant force, often accommodating strains up to 8.5% (Duerig *et al.*, 1990). Governed by transformation temperatures (M_s , M_f , A_s , A_f), this repeatable process underpins applications like biomedical stents, which expand at body temperature, and aerospace actuators, though challenges like fatigue and temperature control persist (Jani *et al.*, 2014). While the shape memory effect highlights the thermally responsive nature of SMAs, it is complemented by another critical property, pseudoelasticity, which expands their versatility by enabling deformation recovery without the need for thermal input.

Building on these capabilities, pseudoelasticity serves as a complementary and equally vital property, enabling Ni-Ti wires to undergo significant elastic deformations—often reaching 8–10% elongation—and revert to their original shape without thermal activation (Lagoudas, 2008). Unlike the thermally driven shape memory effect, pseudoelasticity operates above A_f , where stress induces a reversible transformation from austenite to martensite, followed by spontaneous recovery upon stress removal. This behavior, characterized by a hysteresis loop that dissipates energy, makes SMAs highly effective for adaptively tuned vibration absorbers (ATVAs), providing a dynamic real-time response to vibrational excitations (Tabrizikahou *et al.*, 2022). Thus, while the shape memory effect excels in controlled actuation for shape-changing systems, pseudoelasticity enhances SMAs' utility as passive dampers, broadening their applicability in scenarios where thermal control is impractical. Together, these properties make SMAs exceptionally adaptable, bridging the gap between active and passive engineering solutions.

Taking into consideration all those properties, one interesting aspect of SMAs is their ability to be considered a viable alternative, almost on their own, to conventional actuators. While the conventional methods involve a bigger volume to work with, considering motors, transmission, pneumatic or hydraulic lines, a SMA actuator can be built with as little as the alloy itself and an elastic return (Kim *et al.*, 2023). The main source of power, in these cases, would be the simple Joule effect heating caused by the actuator SMA body acting as the resistance in a closed electrical circuit. With this information, a direct relationship between electrical current, heat generation, and activation speed can be traced, as well as acknowledging the efficiency and simplicity of a low-diameter Ni-Ti wire (Hu *et al.*, 2021).

Albeit all benefits seem excellent, the main issues with SMAs as actuators are in regards to the low cooling rate, which impacts the return of the actuator and, consequently, the frequency of use. The relatively high heat capacity and density of these alloys result in a lower heat transfer rate in general, with natural air convection being, in the literature, the most commonly used method to cool the SMAs. This brings about another great advantage of the Ni-Ti wire, it being the higher surface-to-volume ratio, caused by the wire's small diameter, resulting in a faster cooling rate (Jani *et al.*, 2014). Although improvements to cooling can be made by changing the convective condition (forced air currents or the use of other fluids), this could counterpoint the simplicity and hinder the high-work density proposed initially for this unconventional actuator.

Examples concerning the applicability of the SMAs actuators can be seen throughout the literature, as well as their commercial viability being extended to vastly different fields. They can be used in automobiles to substitute actuators such as DC motors and solenoids present on mirrors, making an effective lightweight and compact replacement (Williams and Elahinia, 2008). They can be used, likewise, in the medical robotics field as surgical robots, wearable exoskeleton robots, and rehabilitation robots, especially considering it being one of the few types of actuators that are MRI (magnetic resonance imaging) friendly (Ding *et al.*, 2022). Furthermore, they can be used in biomimetic or bio-inspired engineering such as a flying robot simulating a bat (Colorado *et al.*, 2012), a water-based robot imitating a seal (Hwang and Wang, 2022), or anthropomorphic fingers that include multiple junctions that are actuated simultaneously (Uleru *et al.*, 2022).

With that in mind, this recently started project aims primarily to study and comprehend the shape memory properties of SMAs, such as Ni-Ti alloys. This ongoing study will be driven by implementing shape memory training onto Ni-Ti wires and, in alignment with that, the development and testing of an SMA actuator.

2. METHODOLOGY

In order to achieve the established objectives, this methodology is proposed, with each section designed to outline the steps to be followed.

2.1 Literature Reviewing

A comprehensive review will be conducted using databases such as Scopus, Web of Science, and CAPES, with descriptors related to shape memory alloy programming and actuator development. This review will establish a foundation

for methodologies to train SMAs and design SMA-based actuators for dynamic applications.

2.2 Finite Element Modeling

A finite element model (FEM) will be developed in ANSYS to simulate the thermomechanical behavior of Ni-Ti SMA wires during shape programming and their dynamic response post-programming. The model will predict the performance of programmed SMA wires integrated into actuators.

2.3 Shape Programming Protocols

Unidirectional shape programming protocols will be applied to Ni-Ti wires, varying pre-strain and temperature in a controlled furnace and testing machine. These protocols aim to train SMAs to exhibit repeatable shape memory effects, characterized by the austenitic transformation temperature (A_f), enabling precise control of actuator displacement and force output.

2.4 Mathematical Modeling

In order to effectively evaluate the conceptualized actuator prior to building a prototype, a mathematical model will be developed, generating qualitative results of the idealized actuator. The SMA actuator will be modeled by incorporating the heat transfer and the phase transformation kinetics of the wires.

2.5 Actuator Fabrication and Integration

SMA-based actuators will be fabricated by embedding trained Ni-Ti wires into adaptive actuators, guided by FEM simulations. The fabrication process will ensure alignment between the SMAs' trained shape memory behavior and the actuator's mechanical requirements. Actuators will be designed to leverage the SMAs' phase transformation, where heating above (A_f) induces shape recovery to actuate the system, and cooling below (M_s) allows deformation under external loads. The return system will need to be developed in tandem; however, taking into consideration the commitment to simplicity, it will be done using elastic means. The actuators will utilize the SMAs' shape memory effect to enable precise control of mechanical motion and force in standalone configurations.

2.6 Experimental Testing

With the prototype in hand, some testing will be carried out to acquire parameters regarding the functionality of the actuator. A few examples of the desirable measurements would be the time needed for activation and return (directly affected by the heating and cooling of the Ni-Ti wires), the amplitude of movement or stroke length of the actuator, and lastly the maximum load it can carry.

2.7 Data Analysis

To conclude, an analysis will be made of everything gathered in testing, making a comparison between the results of the developed actuator to the conventional ones available in the market, verifying the viability of the SMA actuator. Concurrently, the analysis will validate prior finite element and mathematical models or identify previously unknown variables affecting outcomes, enabling refinements for future modeling and prototyping.

3. RESULTS

The development of Ni-Ti shape memory alloy (SMA) actuators is anticipated to yield several key outcomes. The finite element model (FEM) and mathematical model are expected to accurately predict the thermomechanical behavior of SMA wires during shape programming, demonstrating repeatable shape memory effects characterized by the austenitic transformation temperature (A_f). The shape programming protocols are projected to successfully train Ni-Ti wires to exhibit precise control over displacement and force output, with transformation temperatures aligning with design specifications. Fabricated SMA-based actuators are expected to showcase reliable phase transformation-driven actuation, achieving consistent shape recovery upon heating above (A_f) and deformation under external loads upon cooling below (M_s). Experimental testing is anticipated to validate actuator performance. Overall, the results are projected to confirm the actuators' suitability for precise mechanical control, paving the way for applications in dynamic systems.

4. CONCLUSION

This work, focused on developing Ni-Ti shape memory alloy (SMA) actuators through advanced shape programming and fabrication techniques, presents a highly viable approach for innovative actuation solutions. By combining

a comprehensive literature review, finite element and mathematical modeling, precise training protocols, and thorough experimental validation, it addresses critical challenges in achieving reliable SMA actuator performance. This work is poised to advance the field of smart materials, offering versatile applications in dynamic systems requiring precise mechanical control. The project's interdisciplinary methodology and rigorous validation framework underpin its potential for successful implementation and impactful contributions to actuators' technologies.

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7. RESPONSIBILITY FOR THE INFORMATION

The authors are solely responsible for the information included in this work.