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研究論文題目

Physical Compensation of Output Non-Linearity in Shape Memory Alloy Actuators

研究論文概要

Shape Memory Alloy (SMA) actuator control, when using temperature as input, is challenging due to the SMA's nonlinear relationship with displacement and force output, often requiring compensation for effective control. In the literature, SMA models have been proposed as a way to provide this compensation, but this method has its drawbacks. The nonlinear output behavior of SMA changes due to various initial and state-dependent variables such as temperature, stress or strain, prestress, martensite fraction, alloy composition, etc., so the compensation may become inaccurate if any of those variables are not measured and taken into account by the model. An approach that could compensate for the nonlinearity of SMA without relying on its initial and state-dependent variables would be desirable. For this reason, the objective of this thesis is to devise a construction concept for SMA actuators that can improve their open-loop output linearity and to assess the effectiveness of the proposed concept by testing prototype actuators.

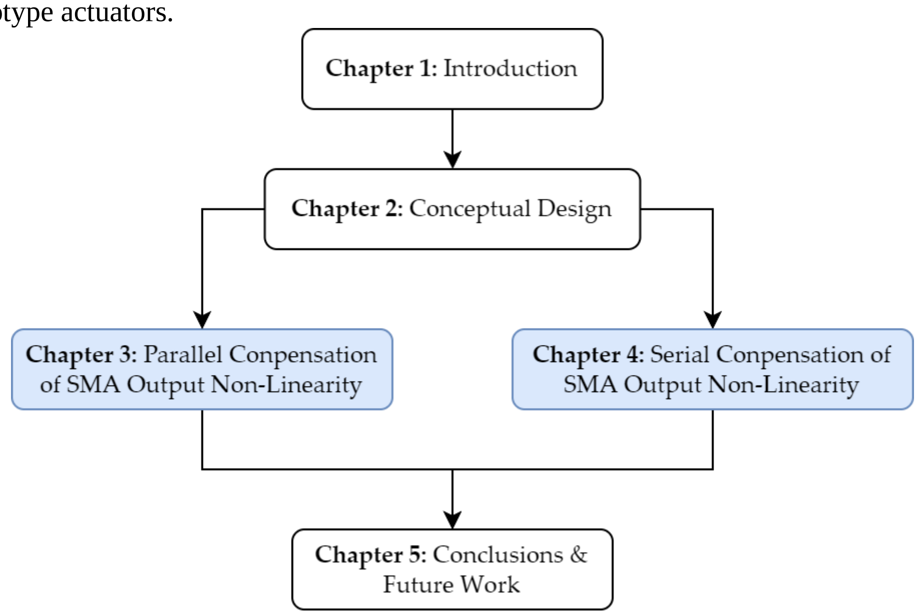

Figure 1. Thesis structure.

This thesis is organized into five chapters, as illustrated in Figure 1. The contents of each chapter are as follows.

- **Chapter 1: Introduction.** This chapter serves as the foundational introduction, presenting the research background, objectives, academic significance, pertinent studies, and general structure of the thesis. It introduces first the general topics of this dissertation, starting from the description of the functionality of NiTi as a Shape Memory Alloy and continuing to its application for actuators. In this subsection, the general characteristics of the SMA for actuators are discussed, including its geometry, activation methods, and an overview of its applications. Then, the concept of scalability for actuators is introduced, describing the overall methods to achieve it. In the second section of this chapter, the fundamentals of the compensation of non-linearity for SMA actuators is discussed, including a description and challenges of such non-linearity, and summarizing the two main methods for compensation: model-based compensation and model-free compensation. Then, an overview of the research is described, including the purpose and problem statement, significance and contributions of the research, and related studies. Finally, an overview of the thesis is included.

- **Chapter 2: Conceptual Design: Output Linearization Through Physical Compensation.** This chapter explores the conceptual design for compensating output non-linearity in SMA actuators. This approach substitutes the non-linear temperature input variable with an 'activation ratio' that is linearly related to displacement or force, reducing the non-linearity of the actuator without requiring initial or state-dependent SMA variables. Two fundamental configurations or construction arrangements are explored for this idea: parallel and serial arrangements. Both configurations use SMA bundles and a fluid that transports the thermal energy to the SMA components, wet activation, as common elements.

- **Chapter 3: Parallel Physical Compensation of Output Non-Linearity.** This chapter focuses on the parallel compensation of SMA Output Nonlinearity. A key feature of the parallel configuration is the use of the number of parallel SMA wires, called the parallel activation ratio, as the input control variable that replaces the temperature. Three prototypes are designed based on this concept: the Zero Flow SMA Linear Actuator (ZFSMALA), the Constant Flow SMA Linear Actuator Version 1 (CFSMALA), and the Constant Flow SMA Linear Actuator Version 2 (CFSMALA-v2). For all prototypes, the activation ratio was manually adjusted. These prototypes were subjected to isometric experiments to assess their ability to enhance the linearity of force output. The experiments also aimed to iteratively improve both the prototypes and the test bench, with a particular focus on response time. The experimental results for all prototypes indicated an improvement in open-loop linearity compared to traditional SMA temperature-controlled actuators. Furthermore, the introduction of forced convection heat transmission, achieved by injecting a thermal liquid into the CFSMALA, significantly reduced the actuator response time relative to the ZFSMALA. In CFSMALA-v2, a reduction in the size of the SMA chamber led to further enhancements in response time. Furthermore, CFSMALA-v2 was tested with a differential wire mechanism, which proved effective in minimizing the impact of variations in the length of SMA wire bundles on the output force, thus improving the force transmission efficiency. Due to its complexity, the parallel configuration in these prototypes was not integrated with a controller.

- **Chapter 4: Serial Physical Compensation of Output Non-Linearity.** In this chapter, the serial configuration for compensating the non-linearity of SMA outputs is explored. In the serial configuration, the ratio of hot to cold water (mix ratio) is used as the primary input control variable, instead of temperature. The mix ratio modifies the position of the inflection point of a temperature gradient that activates specific longitudinal portions of the SMA (the ratio of active to inactive portions is the serial activation ratio). An SMA chamber capable of generating and manipulating this inflection point is presented. The design includes two input ports for hot and cold water, arranged longitudinally and antagonistically, along with uniformly spaced outlets on each side. By varying the flow rate ratio of the hot and cold inputs, the mix ratio, we can control the position of the temperature gradient's inflection point within the SMA chamber, thereby influencing the actuator's serial activation ratio. Two prototypes are introduced: the Gradient-Activated SMA Actuator for Force Output (GASMAA-F) and the Gradient-Activated SMA Actuator for Displacement Output (GASMAA-D), and their performance is assessed through evaluation experiments. In a first performance test, both chambers demonstrated effective control over the actuator's activation ratio. Furthermore, both actuators showed improvements in open-loop linearity and response time compared to those of the temperature-controlled cases and displayed good repeatability. However, GASMAA-F exhibited limitations in covering the full output range of the actuator, which was not the case for GASMAA-D. Finally, both actuators were successfully controlled using a PID controller with output feedback, achieving satisfactory performance in terms of resolution and error.

- **Chapter 5: Conclusions and Future Work.** This chapter synthesizes the research findings and looks ahead to their potential future implications. In general, this thesis addresses output non-linearity in SMA actuators via a model-free approach using physical compensation. Two configurations, parallel and serial, introduce an 'activation ratio' as a linearizing input variable. The prototypes validate the linear relationship between the activation ratio and actuator output. The parallel configuration proves the feasibility and offers design improvements. The serial setup, with an SMA chamber design that produces a temperature gradient, shows automation potential, simplifying SMA actuator control. Future work includes optimizing GASMAA geometry for enhanced performance, exploring arrays of actuators, and demonstrating the application potential over traditional SMA actuators in specific applications.

- **Annex A: Considerations for the identification of the actuation time.** This appendix outlines the identification of time constants for elements affecting the input step impulse for activating the SMA wire, specifically focusing on the BLDC pump and temperature sensors used in the ZFSMALA, CFSMALA, and CFSMALA-V2.