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Finite State Machine-Based Modeling of Shape Memory Alloy Actuators: A Multi-Physics Approach for Controlling Thermo-Mechanical Behavior and Hysteresis

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Objectives

This work proposes an innovative one-dimensional multi-physics model for shape memory alloy (SMA) wire actuators, focused on efficiently modeling the electro-thermo-mechanical coupling and hysteretic behavior. The main objective is to integrate a constitutive model based on Brinson's formulation with a Finite State Machine (FSM) methodology to capture the path-dependent phase transformations inherent to SMAs, and develop a model suitable for real-time simulations and control strategies.

Methodology

An FSM approach was implemented to represent and manage the complex phase transitions in SMAs, simplifying system representation and enhancing scalability. The model was developed through subdivision into subsystems: input signal block, thermo-electrical block, phase diagram with external input priority block, constitutive model, and mechanical system. Brinson's original equations for transformation kinetics were modified to better capture the hysteretic behavior, using a dual-phase approach that combines Brinson's formulation for pre-strain modeling with Tanaka's phase diagram for thermal cycling. Experimental validation was conducted using NiTi wires under various thermo-mechanical loading conditions, with special attention to cyclic and partial transformation.

Results

Experimental tests confirmed the accuracy of the proposed model under different loading conditions, including spring-assisted recovery and constant load recovery. The model demonstrated good capability in predicting both stress-temperature and strain-temperature responses, with maximum deviations of approximately 6% during the cooling phase. Validation of the model as a control tool was performed by implementing a PID controller in the Simulink environment, demonstrating the system's ability to accurately follow both trapezoidal and sinusoidal target displacement signals. Additional simulations demonstrated the model's versatility in handling different types of mechanical configurations, including linear and non-linear mass-spring systems, and in simulating multiple actuation cycles with partial transformations.

Conclusions

The proposed FSM framework has successfully demonstrated the ability to capture the complex thermo-mechanical behavior of SMAs, including path-dependent hysteresis and phase transformations under various loading conditions. The modification of Brinson's original equations and the implementation of the dual-phase approach significantly improved model accuracy, particularly evident in the smooth transition curves and accurate reproduction of material state evolution. The FSM architecture provides an efficient computational framework that maintains accuracy while enabling real-time simulations, making it particularly suitable for integration into dynamic control systems for applications in robotics, aerospace, and biomedical devices.

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