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Design optimization study of a shape memory alloy active needle for biomedical applications

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ABSTRACT

Majority of cancer interventions today are performed percutaneously using needle-based procedures, i.e. through the skin and soft tissue. The difficulty in most of these procedures is to attain a precise navigation through tissue reaching target locations. To overcome this challenge, active needles have been proposed recently where actuation forces from shape memory alloys (SMAs) are utilized to assist the maneuverability and accuracy of surgical needles. In the first part of this study, actuation capability of SMA wires was studied. The complex response of SMAs was investigated via a MATLAB implementation of the Brinson model and verified via experimental tests. The isothermal stress–strain curves of SMAs were simulated and defined as a material model in finite element analysis (FEA). The FEA was validated experimentally with developed prototypes. In the second part of this study, the active needle design was optimized using genetic algorithm aiming its maximum flexibility. Design parameters influencing the steerability include the needle's diameter, wire diameter, pre-strain and its offset from the needle. A simplified model was presented to decrease the computation time in iterative analyses. Integration of the SMA characteristics with the automated optimization schemes described in this study led to an improved design of the active needle.

1. Introduction

To date, many biomedical devices have utilized the pseudoelastic properties of advanced, active and adaptive materials such as coronary stents, eyeglasses and orthodontic wires [1]. The actuation properties of the active materials have also attracted a lot of attention, especially in medical devices such as active cardiac catheters [2], artificial muscles [3] and cochlea implants [4]. Shape memory alloys (SMAs), well known smart materials, have become increasingly popular in various applications due to their ability to remember their initial shape. Their unique thermomechanical characteristics of pseudoelasticity, shape memory effect and biocompatibility have made them a suitable option to revolutionize many diagnostic and therapeutic biomedical tools [5]. The primary concept of active surgical needle (Fig. 1) was suggested by Konh et al. [6] where the feasibility of using SMA wires to actuate the surgical needles was shown. The SMA wires, i.e., Nitinol wires in our design, supply bending forces to the needle body to guide the needle through desired trajectories inside the tissue. The active needle [7] provides several advantages such as improvements in accuracy to reach the target locations, avoiding critical organs during insertion and minimizing trauma to patients.

The success of many needle-based interventions such as brachytherapy, thermal ablation and biopsy highly depends on the accuracy of the needle placements at target locations. For improvement of the accuracy of needle placement, many groups have tried variety of options to activate the needle. For example, Tang et al. [8] used magnetic forces in order to help the navigation of the needle inside the body. Ayvali et al. [9] utilized pre-curved SMA wires on the needle body to provide external actuations. The electrical resistance and the fatigue behavior of SMA wires used as actuators have been studied by Meier et al. [10]. They developed a control loop based on the electrical resistance feedback.

Material characteristics of SMAs (the actuators) are complicated due to the history dependent hysteresis relationships between the materials' stress, strain and temperature. A large recoverable strain of SMAs is due to the transformation between two major internal phases known as martensite and austenite. The transformation temperatures are known as M_s, M_f, A_s, A_f, where M represent martensite, A austenite, while subscripts s and f shows the starting and finishing point of the transformation process, respectively. Several researchers [11–13] have developed mathematical models to predict the SMA's response. Brinson [14] developed a model that includes the transformation between twinned and detwinned martensite. This model was able to predict the SMAs' pseudoelasticity and shape memory effects, simultaneously. Also privileging from non-constant coefficients this model provided an enhanced accuracy with respect to the previously

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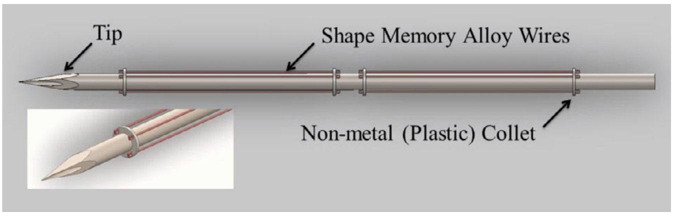

Fig. 1. Schematic of the proposed active needle design.

developed models [11,12]. Brinson model was used in this study for its accuracy and consistency with our SMA wires.

In this study, optimized design of the active needle has also been presented. The past design and developments of systems consisting SMAs had been based on graphical design trial and error [15]. Automated tools of the commercial software (ANSYS) were used here to develop a predictive algorithm to assess the active needle response. The novelty of our design optimization study lies on the incorporation of smart materials in our system. Prior to constructing an optimization algorithm, implementation of a constitutive model capable of predicting the inelastic strain response of SMAs is necessary. The inelastic response of SMA wires with different diameters was first studied via both experimental and numerical approaches. Since the material properties of SMA wires could be different due to different manufacturing processes, details of the constitutive model have been described in this work so that it can be used in assessments of any other systems with active components.

In previous optimization studies with SMAs [16–19], the desired dynamic properties were found by optimizing the placement of a single wire component to eliminate the high stress regions. The active material optimization was done by Main et al., and Seeley and Chattopadhyay [20,21] using analytical and gradient based studies. In other work, design optimization of a system with a SMA spring was investigated by Dumont and Kühl [22] using genetic algorithm. To overcome some limitations of previous studies, such as expensive computational time and incorporation of SMAs' constitutive models, we present an automated optimization approach based on a simplified model that benefits from extensive experimental and numerical studies on SMA actuators.

This work is organized as follows: Section 2 introduces the overall analysis tools and methodologies utilized for modeling and optimization. Section 3 describes the constitutive model of SMAs in detail including the numerical and experimental studies. Section 4 describes the FE model and the prototype developed for verification purposes. Section 5 validates the 3D FE analysis of the active needle via the experimental tests and suggests a simplified model as an alternative for optimization studies followed by evaluation of its accuracy. In Section 6, the optimization methods are described along with the proposition of the best possible design of the active needle. Finally, the conclusions are briefly summarized in Section 7.

2. Analysis tools to optimize the active needle

The methodology used for the first part of this study is shown in Fig. 2. The thermomechanical behavior of SMAs needs to be included in the analysis since they are the most important components of the structure. Three experimental setups developed to study the complex behavior of SMAs are discussed in detail in Section 3. Numerical and experimental studies on SMA wires prior to the finite element analysis ensured a coherent material model to be used in the FE model. The isothermal stress–strain curves obtained from a MATLAB implementation of Brinson model and provided as the material model for the FE analysis. The detail of this constitutive model is explained in the next section.

The process of design optimization is shown schematically in Fig. 3. Our design objective targets the highest deflection of the active needle while considering the restrictions such as maximum stress, strain and elastic deformation of different components. Using this approach different design configurations were evaluated seeking the best design. The iterative structural analysis was performed over the defined domain of design parameters to reach the design objectives. The ANSYS design optimization module was used for this objective that is capable of being linked to the ANSYS parametric design language (APDL) module of the software where the FE model was generated and run the analysis automatically. The optimization process consists of an APDL input file with all design parameters and the required output parameters defined which was iteratively solved through the whole domain.

3. Constitutive model: formulation and numerical integration

3.1. Description of the material model

SMAs show two different behaviors known as (i) shape memory and (ii) pseudoelastic effects. The shape memory is its ability to recover a large residual strain by rising up the temperature whereas pseudoelasticity is its ability to resume a high amount of strain upon unloading in a hysteresis loop. Two major phases exist in these alloys which are known as austenite and martensite. Austenite is known as the parent phase, which only exists at high temperatures. Only decreasing the temperature will result in a phase change into martensite. The martensite phase exists in two different orientations which are known as twined and detwined, with respect to its multiple variants and twins. The phase transformation between martensite and

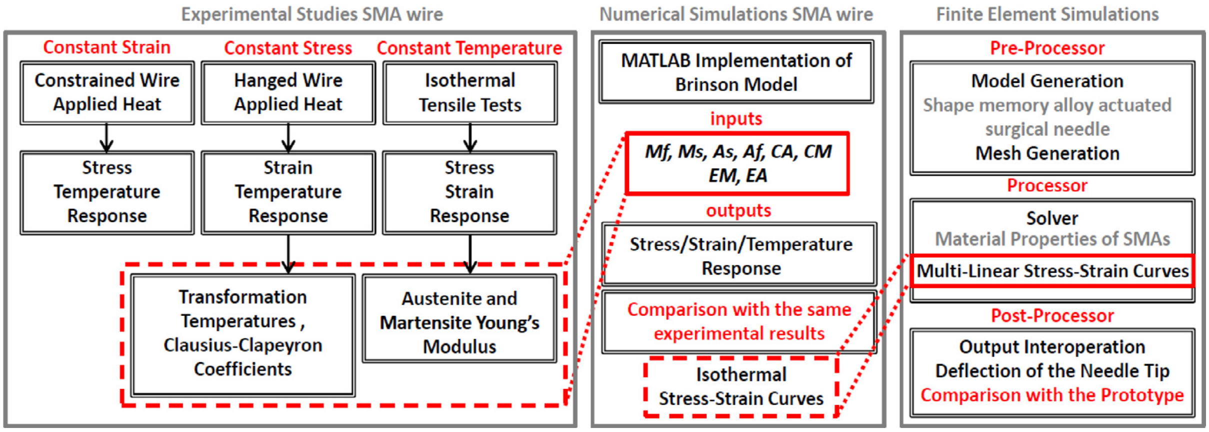

Fig. 2. Engineering tools used to show the actuation capability of SMA wires in the active needle design.