Parameter estimation of an SMA actuator model using an extended Kalman filter

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**Abstract**

Brinson model is one of the most-widely used models for shape memory alloy (SMA) wires. The parameters of this model must be determined experimentally. This paper has focused on identifying these parameters for a one-dimensional model of SMA wire. This model is identified in order to predict the outputs of a one-DOF SMA actuator. The parameters of Brinson model are estimated experimentally using an extended Kalman filter (EKF). The main contribution of this paper is designing a procedure to identify the model parameters based on experimental tests performed on the SMA actuator, without needing separate laboratory tests. In the designed procedure, the effects of unmodeled factors and sensor biases are taken into account. The estimation is performed in a pre-designed sequence to avoid the divergence of EKF and validated by comparing the outputs of the identified model with the actual output of the actuator. The results of the identified model match precisely with the experimental data in both phase transformation and linear regions. However, some mismatches are observed in transition regions that may be related to the Brinson model structure, where the governing equation suddenly changes in the transition region. The results show the capability of the EKF to estimate Brinson model parameters. This estimation can be performed directly on SMA actuators.

1. Introduction

Shape memory alloy (SMA) wires possess a large recoverable strain, great power to weight ratio and high forces [1,2]. These advantages make them a great choice to be used as an actuator, particularly when reducing the size of the actuator matters. Their operation induces fewer electrical noises, as compared to electric motors and actuators. However, for controlling these actuators, precise models are needed to predict their behavior.

The physical behavior of SMA actuators is a function of strain, stress, and temperature and SMA constitutive models try to simulate SMA actuator's behavior as a function of these variables [2]. Tanaka, Liang-Rogers and Brinson Models are three examples of such one-dimensional models [3–6]. Most of these constitutive models use some parameters that must be determined experimentally [7].

Several methods have been reported for determining the parameters of SMA constitutive models. In some researches, the parameters of three-dimensional models are identified. Meraghni et al. [8] have used a gradient base method that utilizes an analytical computation of the sensitivity matrix to identify the parameters of a thermodynamic constitutive model for SMA materials. This research is focused on model identification in the super elastic region. In another research, strain fields that are measured by digital image correlation technique are compared to the strain fields computed by the finite element method to identify the parameters of a thermodynamic constitutive model [9]. The identification process is done using a mixed genetic/gradient-based optimization algorithm. In this work, we have focused on one-dimensional models that are widely used for SMA wires as a special case of SMA materials [1,2,10–14].

There are many researches that are worked on the parameter identification of one-dimensional models of SMA materials. Since the SMA constitutive models are derived based on the thermodynamic concepts, in most of the reported methods, the model parameters are identified based on the thermodynamics of the phase transformation [15]. The most common identification method is a combination of DSC, mechanical loading and isothermal test methods. This method is a manual procedure where the transformation temperatures are obtained by finding the intersections of some tangential lines. In this method, several experiments should be performed to identify the full model parameters [15–17]. The described methods can estimate and verify the
parameters only in laboratory conditions using some samples of the wire \[15\]. Moreover, no objective criteria are utilized to assess the efficiency of these methods \[8\].

The electrical resistance (ER) of SMA wires varies with change of the martensite volume fraction \(\xi\). Increase and decrease of ER can be used to determine the transformation temperatures \[15,18\]. The accuracy and coherence of three identification methods (DSC, ER and Applied Loading method) are compared in \[18\]. This comparison shows that the ER method can be used to determine \(M_s\) and \(M_f\). However, \(A_\text{s}\) and \(A_\text{f}\) are not accurately identifiable by this method.

In most of the above mentioned methods, the model parameters are estimated in a laboratory condition using special facilities. In these methods, the parameter estimation is performed on some special specimens of SMA wire. However, the SMA actuator behavior may differ from the model predictions due to unmodeled factors such as friction and temperature gradient \[15\]. Moreover, the noise or the bias of sensors may result in error in identification of the model parameters. The alternative method for estimating the parameters is to use estimators that compare the outputs of the model and the real measurements obtained from sensors. Extended Kalman filter (EKF) is an estimator that can be used for estimation of model parameters \[19,20\]. This filter is a data fusion method that works based on both model predictions and sensor measurements. It is a powerful tool for estimating the parameters of nonlinear models, especially for the cases with imprecise models or noisy sensors \[10\]. Although several researchers have used EKF and other nonlinear extensions of Kalman filter for parameter estimation of nonlinear systems \[21–25\], a few researchers have estimated the state variables of SMA using Kalman filter or EKF. Eslahinia and Ahmadian used an EKF to estimate the state variables (not the parameters) of a rotary mechanism actuated by an SMA wire \[11\]. They investigated the performance of the EKF estimator and used it as an observer in a feedback control system \[16,13\]. Tai and Ahn used an EKF to filter the measurement noises in an SMA actuator. They showed that the EKF estimations can be used to control the actuator \[26\]. Hassanzadeh et al. used EKF to estimate state variables and some parameters of an SMA actuated mechanism such as spring stiffness and friction coefficient \[12\]. However, they did not estimate the parameters of the SMA model. All of the mentioned studies have used a Liang-Rogers model to simulate the behavior of the SMA wire, while this model cannot precisely simulate the SMA behavior at low temperatures \[2\]. Gurung and Banerjee used an EKF for self-sensing of an SMA wire based on the Brinson model. They estimated the wire strain just by measuring the wire electrical resistance \[1\].

In this work, the goal is to identify a model that is appropriate for controlling the SMA actuator. So, the model must be able to predict the output of the SMA actuator. An important part of the actuator model is the model of the SMA wire. The Brinson model is used for simulating the SMA behavior that is more precise than the Liang-Rogers model \[2\]. The parameter estimation is performed using an EKF. To the best of authors’ knowledge, this filter has not been used for identifying the parameters of the Brinson model. The parameter estimation is conducted in a predesigned sequence, such that in each estimation procedure, only 2 or 3 parameters are estimated by EKF. Furthermore, the governing equation of the Brinson model does not change during each estimation procedure. By this way the EKF does not diverge. However, the main contribution of this paper is identifying the model parameters of the SMA wire on the final working actuator. The parameters are estimated based on data sets that are gathered from designed experimental tests carried out on the SMA actuator. These experimental tests are performed using the sensors that are mounted on the setup. Therefore, the effects of temperature gradient, inertial effects of mechanical parts, friction and sensor biases are taken into account in the estimation process. Moreover, in this approach all the model parameters are identified directly on the SMA actuator, without needing extra experiments on the SMA wire in laboratory conditions; thence reducing the cost of the parameter identification. The organization of this paper is as follows: In Section 2, SMA constitutive models are presented. In Section 3, a brief introduction to EKF and parameter estimation procedure is presented. In Section 4, the one-DOF SMA actuator used in this research is explained. In Section 5, a set of experimental tests are designed to estimate the parameters of the Brinson model. In Section 6, the parameters of the Brinson model are estimated and in each estimation procedure, an EKF is developed. In Section 7, the results of the identified model are compared to the data obtained from the actual SMA actuator. Finally, major findings of the paper are summarized in Section 8.

2. SMA constitutive model

In SMA materials, the strain changes due to phase transformation as a function of stress and temperature. Several one-dimensional constitutive models have been presented to express the relation between these three parameters. Tanaka \[4\] and Liang-Rogers \[3\] are two most popular models used to represent the behavior of SMA materials. The major drawback of both Tanaka and Liang-Rogers models is that they only can describe the phase transformation from martensite to austenite and vice-versa. They are not able to model the detwinning martensite phenomenon that is the cause of the shape memory effect at lower temperatures \[2\]. This problem is solved by the Brinson model \[5,6\]. In this model, the martensite fraction is decomposed into stress-induced fraction \((\xi_s)\) and temperature-induced fraction \((\xi_t)\):

\[
\xi = \xi_s + \xi_t
\]  

(1)

If the martensite transformation is carried out in the absence of stress or in a low stress condition, the material is fully transformed to thermal induced (twinned) martensite and there is no considerable residual strain. However, if the transformation is done in a high stress condition, some of the material is transformed to stress-induced martensite and it causes some residual strain.

The main equation of the Brinson model is \[6\]:

\[
\sigma = E(\xi)(\varepsilon - \varepsilon_0) + \theta(T - T_0)
\]  

(2)

where \(\theta\) is the thermal expansion coefficient of the material and \(T_0\) is the wire temperature at the beginning of the current thermal cycle when the sign of the temperature derivative changes. \(\varepsilon_0\) is the maximum residual strain of the material and \(E(\xi)\) denotes the elasticity module of the material and is assumed to be a linear function of the martensite volume fraction:

\[
E(\xi) = E_A + \xi(E_M - E_A)
\]  

(3)

where \(E_A\) and \(E_M\) are the modules of elasticity in the austenite and martensite phases, respectively. In (2), the thermal expansion strain (the second term) can be neglected with respect to the transformation strain (the first term) \[6\] and hence, the strain is obtained as:

\[
\varepsilon = \frac{\sigma}{E(\xi)} + \varepsilon_0\xi_s
\]  

(4)

In the original form of this model, multiple relations are presented for calculating the martensite volume fraction as a function of stress and temperature. However, Chung et al. \[14\] showed that these relations may result in an inadmissible volume fraction \((\xi > 1)\) in some cases. They corrected this model with some modifications. In this paper, the Brinson model with the corrected evolution kinetics is used \[14\]:

- **Conversion to martensite:**

For \(T > M_s\) and \(\sigma < \sigma - C_M(T - M_s) < \sigma_f\)

M. Soltani et al.

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