Simplified Shape Memory Alloy (SMA) Material Model for Vibration Isolation

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ABSTRACT

Advances in smart materials and structures technology, especially in applications of Shape Memory Alloys (SMA) as actuators and vibration isolation devices require understanding of the nonlinear hysteretic response found in SMAs. SMA hysteresis can be modeled either through constitutive models based on physical material parameters or through models based on system identification. In this work, a simplified material model for the pseudoelastic response of SMAs is presented, suitable for vibration isolation applications. Response obtained from the simplified model is compared with the response obtained from an existing thermodynamic constitutive SMA model and the results from the two models are found to match well. The computation time required by the simplified model was approximately seven times faster compared with the thermodynamic constitutive model. The simplified model is utilized to simulate a single degree of freedom mass-SMA system where the SMA acts as a passive vibration isolation device, showing a substantial reduction in displacement transmissibility.

Keywords: Shape memory alloy, hysteresis, vibration isolation, damping, constitutive model, smart structures.

1. INTRODUCTION

The goal of vibration isolation is to reduce the force or motion transmitted from one structure to another, which is most commonly accomplished through the use of an isolation system with a relatively small stiffness¹. However, for isolation of heavy loads, a small stiffness will lead to large displacements. This large displacement obstacle has often been overcome through the use of a device with decreasing stiffness, like a softening spring. Such a device would have a very stiff initial response that becomes less stiff as the load is increased, so that the stiff region of the device’s response supports the initial load and the transmissibility is reduced by the lower stiffness in the operating range. One of the problems encountered in vibration isolation is resonant behavior at low excitation frequencies, where the soft nature of the stiffness in the operating range becomes detrimental because it allows for a resonant condition to exist when the frequency of excitation is close to the natural frequency of the system. This condition has lead to the need for the addition of some type of damping to the system, which has the desired effect of decreasing the resonant response but also degrades the response of the isolator at higher frequencies as shown by Harris². Therefore, the task of vibration isolation is often faced with trade-offs. The use of SMA may allow for the elimination of these trade-offs, resulting in better performance with fewer compromises.

Shape Memory Alloys (SMAs) appear to be viable candidates for use in the field of vibration isolation due to the nature of the pseudoelastic behavior³ exhibited when an SMA material is loaded at temperatures greater than the austenitic finish temperature. When a shape memory alloy is loaded while in the austenitic phase, it initially behaves as if it were elastic in nature, however as the stress continues to increase, a point is reached where the material begins to transform into the martensitic phase. This transformation is characterized by a decrease in the tangent stiffness of the material and continues as the load increases until the entirety of the material is transformed into martensite. After this stress induced martensite (SIM) transformation is complete, the material will again begin to deform elastically, with the stiffness of martensite which is usually less than the elastic stiffness of austenite. If the loading is now reversed, the SMA will unload elastically until it reaches a point at with the stress is low enough to permit the transformation back into the parent austenitic phase. As the stress continues to decrease the material transforms completely back to its austenite phase and then continues to unload elastically until the zero stress point is reached. During this unloading process it is possible for the material to recover all of the induced strain, returning to its undeformed, initial, condition at zero stress.

The nature of the pseudoelastic response of SMAs described above makes the application of SMAs to passive vibration isolation an area that has great potential. This is particularly true in applications where the complexity of the isolation device

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should be minimized. Graesser and Cozzarelli introduced a modified model for hysteretic behavior by Ozdemir to model pseudoelastic behavior of SMAs, using ideas from viscoelasticity and applied the results to seismic isolation of structures. A study of the use of SMAs in passive structural damping is also presented in Thompson et al., where three different quasi-static models of hysteresis were introduced and compared with experiments. In work done by Feng and Li, another example of passive vibration damping using SMAs is presented, where a modified plasticity model is used to model the hysteretic response of the shape memory material. Fosdick and Ketema, have considered rate dependency by including "averaged" thermal effects, their work is based on dynamics of single-crystal phase boundaries by Aberayatne, and have studied a single degree of freedom (SDOF) lumped mass oscillator with an SMA wire attached in parallel as a passive vibration damper. Other work on constitutive modeling of SMAs includes phenomenological models (Lagoudas et al., Brinson, Liang, Tanaka, micromechanical models for polycrystalline SMAs (Patoor) and empirical models based on system identification (ID) (Preisach, Mayergoyz, Banks et al., Webb et al.). Although these models are fairly accurate, they are computationally intensive and/or hard to implement under dynamic loading conditions.

In order to realize the goal of designing and simulating a smart structure for vibration isolation using SMAs it is necessary to have structural models that can (a) incorporate a physically based constitutive response of SMAs and, (b) can be used for prediction of dynamic response of smart structures. Most of the models available in the literature do not serve this dual purpose well. In this paper a computationally less intensive simplified material (physically based) model is proposed for pseudoelastic SMA loading. The proposed model is suitable for structures where the hysteresis of the structure is solely due to SMAs, hence there is a need to model SMA hysteretic response and couple it with structural response of nonhysteretic components. The simplified model is presented in section 2, this model can be numerically implemented fast in comparison with an existing phenomenological SMA thermomechanical constitutive model by Lagoudas and Qidwai. A more involved phenomenological constitutive model is presented in Lagoudas et al. but the comparison in this work will be performed with respect to the basic polynomial model. As a first step isothermal conditions are considered for modeling the pseudoelastic response in this work. However, the model is currently being implemented for non-isothermal conditions by incorporating the latent heat and thermomechanical coupling, and will be addressed in a future publication. Finally, in section 3, the simplified model is used to solve a SDOF system using SMAs as a passive vibration isolation device for pseudoelastic response of SMAs.

2. SIMPLIFIED MODEL FOR PSEUDOELASTIC SMA'S

In this section a simplified material model for pseudoelastic SMAs is developed and implemented. This model is capable of accurately predicting the behavior of SMAs at temperatures above the austenite finish (Aₐ) temperature, the temperature at which the reverse transformation from martensite to austenite is complete. Additionally, this model is strain driven and is dependent on the loading history to correctly predict the forward and reverse transformation behavior and the minor loop behavior of SMAs. The basis of the model is the assumption that the relationship between strain and stress in an SMA at temperatures above Aₐ can be accurately represented by a series of linear curves whose form is determined by the extent of transformation experienced. The development of this model will be addressed in the following three subsections. The first subsection will deal with the determination of material response in stress-strain space from the minimum amount of required physical data. The second section will deal with prediction of major loop response and the third section will deal with prediction of minor loop behavior of SMAs. At the end of the major loop and minor loop subsections stress strain response obtained with the simplified model will be compared with the stress strain response obtained from the basic polynomial model (phenomenological SMA thermomechanical constitutive model).

2.1 Determination of material stress-strain response

To begin to adequately determine the response of SMA material, one must be able to predict at what loading conditions transformation between the austenitic and martensitic phases will begin and end. Additionally, this information must be available at all temperatures in which this model is to be valid (T>Aₐ). The model presented in this paper is dependent only upon a few material parameters, which can be gathered from relatively simple thermomechanical tests. From a typical pseudoelastic stress-strain test (Figure 1) performed at a temperature greater than Aₐ the stiffness of austenite (Eₐ) and martensite (Eₘₐ) can be obtained as well as the maximum value of transformation strain (Λ). Through the use of a Differential Scanning Calorimeter (DSC), the temperatures at which transformation occurs under zero stress can be determined (Figure 2 shows a typical DSC plot for an SMA). Finally, through a series of pseudoelastic responses at different temperatures the stress-temperature space can be mapped out. The data, shown in (Figure 2), can be coupled with the above-mentioned pseudoelastic test data, shown in (Figure 1), to provide all the necessary material information for the simplified model.

The stress-temperature phase diagram (Figure 3) can be constructed by one DSC measurement and one pseudoelastic response, assuming that the four lines separating the austenite from martensite phases during loading and unloading are
straight lines with slope $C$. The construction of the simplified model is based upon the utilization of the stress-temperature phase diagram (Figure 3) to recreate the pseudoelastic response of the SMA as shown in Figure 4. From the stress-temperature diagram, and given that the temperature of the SMA is known and constant, it is possible to calculate the stress at which the forward and reverse transformations begin and end from the following equation:

$$\sigma = C(T - T_x)$$  \hspace{1cm} (1)

where $\sigma$ is the stress (either uniaxial stress or the effective stress for a multi-axial stress state), $C$ is the slope of the transformation boundary in the stress-temperature plane, $T$ is the temperature, and $T_x$ is the zero-stress transition temperature for the respective transition. Additionally, using the constitutive relation for SMAs:

$$\varepsilon = E_x(\varepsilon - \varepsilon')$$  \hspace{1cm} (2)

Where, $E_x$ is the respective elastic stiffness of either austenite, martensite or a mixture of the two phases, $\varepsilon$ is the total applied strain and $\varepsilon'$ is the transformation strain in the SMA, one can calculate the strain at which transformation will occur, given that the material state is assumed to be known at the beginning and end of transformation for both forward and reverse transformation. Using this data, one can construct the following stress-strain diagram as shown in (Figure 4) using only the material parameters mentioned above. For pseudoelastic loading, the transitions delineating the beginning and end of forward and reverse transformation are dependent only upon the material parameters and the temperature. For the beginning of the austenite to martensite, or forward transformation (point 1 on Figure 4), the corresponding stress and strain are calculated from the following equations:

$$\sigma = E_x \left( \varepsilon - \varepsilon' \right)$$

Figure 3: SMA stress-temperature diagram with a pseudoelastic loading path for isothermal and adiabatic conditions.

Figure 4: Calculated pseudoelastic stress-strain response for isothermal and adiabatic conditions.
\[ \sigma_{Ms} = C(T - M_{s0}) \]  
\[ \varepsilon_{Ms} = \frac{C(T - M_{f0})}{E_A} \]  

For the end of the Austenite to Martensite (point 2), the corresponding stress and strain are calculated from the following equations:

\[ \sigma_{Mf} = C(T - M_{f0}) \]  
\[ \varepsilon_{Mf} = \Lambda + \frac{C(T - M_{f0})}{E_M} \]  

For the beginning of the martensite to austenite, or reverse transformation (point 3), the corresponding stress and strain are calculated from the following equations:

\[ \sigma_{As} = C(T - A_{s0}) \]  
\[ \varepsilon_{As} = \Lambda + \frac{C(T - A_{s0})}{E_M} \]  

For the end of the martensite to austenite (point 4), the corresponding stress and strain are calculated from the following equations:

\[ \sigma_{Af} = C(T - A_{f0}) \]  
\[ \varepsilon_{Af} = \frac{C(T - A_{f0})}{E_A} \]  

Assuming piece wise linear response and combining all of this information together will result in completely determining the stress-strain response for a complete loading induced transformation of SMA material as shown schematically in Figure 4. The above construction of the pseudoelastic response is for isothermal conditions. However, for a non-isothermal pseudoelastic loading path schematically shown in Figure 3, the presence of latent heat would result in the path indicated by points 1-2′-3′-4 on Figure 3. This change in the loading path on the phase diagram would shift point 2 to point 2′ and point 3 to 3′ on Figure 4.

### 2.2 Major loop loading

To correctly predict the stress-strain response of an SMA, the loading path for full transformation, or the major loop, must be modeled. For the simplified material model, this is accomplished by assuming that both the transformation strain, \( \varepsilon_t \), and the stress, \( \sigma \), vary linearly during transformation and that the stress corresponds to strain in a linear manner when transformation is not occurring. As a result the material can be modeled as a series of straight lines in stress-strain space and transformation strain-strain space, where the intersection of these lines correspond to the transition between elastic loading and transformation for forward and reverse transformation. This can be illustrated schematically, as shown in Figure 4. For elastic loading in the austenite region (4→1), in other words, prior to the beginning of forward transformation, the transformation strain remains zero and the stress is directly related to the strain. This is explicitly stated in the following formulas.

\[ \varepsilon' = 0 \]  
\[ \sigma = E_A(\varepsilon) \]  

For forward transformation, i.e. in the region between points 1 and 2, the transformation strain varies linearly between zero and the maximum value of transformation strain, \( \Lambda \). Additionally, the stress level also varies linearly between the stress levels corresponding to the beginning and end of transformation. Mathematically this is shown below.

\[ \varepsilon' = \Lambda \left( \frac{\varepsilon - \varepsilon_{Ms}}{\varepsilon_{Mf} - \varepsilon_{Ms}} \right) \]
\[ \sigma = \sigma_{Ms} + \frac{\epsilon^t}{\Lambda} (\sigma_{Mf} - \sigma_{Ms}) \]  

At strain levels above the martensite finish level i.e., in region after point 2, the stress again relates linearly to the strain and the transformation strain remains at a constant value equal to \( \Lambda \). This relation remains true even after the onset of unloading until the beginning of reverse transformation begins (point 3),

\[ \epsilon^t = \Lambda \]  

\[ \sigma = \sigma_{Mf} + E_M (\epsilon - \epsilon_{Mf}) \]  

After the beginning of reverse transformation (point 3), and before the transformation to Austenite completes (point 4), the transformation strain again varies linearly, this time between \( \Lambda \) and zero. Likewise the stress varies linearly between the value at the start of reverse transformation and the value at the end of transformation.

\[ \epsilon^t = \Lambda - \Lambda \left( \frac{\epsilon_{As} - \epsilon}{\epsilon_{As} - \epsilon_{Af}} \right) \]  

\[ \sigma = \sigma_{Af} + \frac{\epsilon^t}{\Lambda} (\sigma_{As} - \sigma_{Af}) \]  

At the conclusion of reverse transformation the transformation strain is again zero and the stress again varies linearly with the strain, as shown in equation (12).

![Figure 5: Comparison of basic polynomial model and simplified model for a pseudelastic loading path](image)

Correlation of strain history with resulting stress history for a major loop loading path for the simplified and the polynomial models is shown in Figure 5. The simple model not only matched with the basic polynomial model very well, but also on an average computation time required for the simple model was approximately 7 times less than the time required for the polynomial model. The material data used for the above simulation is tabulated in Table 1 in section 3.

2.3 Minor loop loading

To accurately model SMAs in a particular application, it becomes necessary to model the minor loop loading cycles, those that do not result in complete transformation from austenite to martensite and back to austenite. From inspection of Figure 6 it becomes clear that in order to model this behavior, some modifications must be made to the above equations to account for this incomplete transformation. As a result of the simplicity of this model, the modifications are elementary and easy to implement. The first issue that must be dealt with is the dependence of the current material behavior on the history of loading of the material. This can be accomplished by storing the maximum and minimum values of stress, strain and transformation strain for the previous loading cycle. The second issue to be dealt with is the modification of the points in stress-strain space that initiate the beginning of forward and reverse transformation. The third issue relates to the stiffness of the material. As the material transforms between austenite and martensite, the stiffness of the material changes between the
stiffness of each phase. The stiffness at any given point during transformation is calculated using a rule of mixtures on the compliance (Reuss bound).

$$
\varepsilon_{1} = \frac{A_{f}}{E_{f} + E_{M}^{e}} \varepsilon_{M}^{e} + \frac{A_{s}}{E_{A}^{e} + E_{M}^{e}} \varepsilon_{A}^{e}
$$

Figure 6: Typical strain loading path representing minor loops. Point A and B represent loading reversal points prior to completion of full transformation

Figure 7: Correlation of strain history with resulting stress history for a minor loading path

Figure 7 depicts a minor loop case. When loading from the zero stress in austenite phase, the equations are the same for the initial elastic loading and the forward transformation. However, for a minor loop loading path, the loading is reversed prior to completion of forward transformation (point A). At this point the maximum values of stress, strain and transformation strain are recorded, as they will be used in subsequent calculations. As unloading begins from point A to 3, initially there is no transformation, so that the unloading occurs elastically but at a stiffness that is neither the austenite stiffness nor martensite stiffness. Unloading occurs elastically from the maximum transformation point and the slope is determined by maximum degree of transformation obtained. For this portion of the stress-strain relation, the unloading stiffness, $E_{R}$ and the stress are calculated as follows,

$$
E_{R} = \frac{8}{\max} \left( E_{A}^{e} + E_{M}^{e} \right)
$$

$$
\sigma = \sigma_{\max} + E_{R} (\varepsilon - \varepsilon_{\max})
$$

where $\varepsilon_{\max}^{i}$, $\sigma_{\max}$ and $\varepsilon_{\max}$ are the values recorded when the loading path changed directions. The transformation strain remains the same for this section of the loading path, since the unloading is elastic and no transformation occurs. As the material continues to unload, the path it is following will eventually intersect the line for major loop reverse transformation (point 3). This point is where reverse transformation begins for minor loop loading paths. It is defined by the following equations:

$$
\varepsilon_{q3} = \varepsilon_{A}^{s} + \frac{\varepsilon_{\max}^{i}}{\Lambda} \left( \varepsilon_{A}^{s} - \varepsilon_{A}^{f} \right)
$$

$$
\sigma_{q3} = \sigma_{A}^{s} + \frac{\varepsilon_{\max}^{i}}{\Lambda} \left( \sigma_{A}^{s} - \sigma_{A}^{f} \right)
$$

As this point is reached, reverse transformation begins and the following equations will determine the values of transformation strain and stress, from point 3 onwards:

$$
\varepsilon^{i} = \Lambda - \Lambda \left( \frac{\varepsilon_{q3}^{i} - \varepsilon}{\varepsilon_{q3}^{i} - \varepsilon_{A}^{f}} \right)
$$

$$
\sigma = \sigma_{A}^{f} + \frac{\varepsilon^{i}}{\Lambda} \left( \sigma_{q3}^{i} - \sigma_{A}^{f} \right)
$$

As the material continues to unload, the stress will decrease and the transformation strain will go to zero as the material approaches point 4, where reverse transformation ceases at this point the material will be entirely in austenite again and will unload elastically to zero stress. Now, if the material does not unload entirely into austenite, but instead again changes the loading direction and begins to load again, the stress, strain and transformation strain at this point must again be recorded, this point is shown as point B Figures 6,7. As the material begins to load from point B to 1, it again loads elastically at a stiffness determined by the minimum degree to which transformation had progressed. The stiffness and stress levels are given as follows:
\[ E_p = \frac{E_A E_m}{\left( \frac{\varepsilon_m}{\Lambda} \right) (E_A - E_m) + E_m} \]  
(25)

\[ \sigma = \sigma_{\text{min}} + E_p (\varepsilon - \varepsilon_{\text{min}}) \]  
(26)

where \( \varepsilon_{\text{min}} \), \( \sigma_{\text{min}} \) and \( \varepsilon_{\text{min}} \) are the values of transformation strain, stress, and strain recorded at the point of where loading changes. From this point the material loads elastically until this loading path intersects with the forward transformation path for major loop loading (point 1). This point is calculated in a similar manner to that used in the calculation of the beginning of reverse transformation and is again based on the intersection of the major loop loading path and the minor loop loading path. The formulas defining this point are:

\[ \sigma_{sp1} = \sigma_{Ms} + \frac{\varepsilon_{sp1}^f}{\Lambda} \left( \sigma_{Mf} - \sigma_{Ms} \right) \]  
(27)

\[ \varepsilon_{sp1} = \varepsilon_{Ms} + \frac{\varepsilon_{sp1}^f}{\Lambda} \left( \varepsilon_{Mf} - \varepsilon_{Ms} \right) \]  
(28)

From this point, stress and transformation strain for forward transformation are calculated in a manner similar to that used in the calculation of stress and transformation strain for the reverse transformation. The equations are as follows

\[ \varepsilon^f = \Lambda \left( \frac{\sigma - \sigma_{sp1}}{\varepsilon_{Mf} - \varepsilon_{sp1}} \right) \]  
(29)

\[ \sigma = \sigma_{sp1} + \frac{\varepsilon^f}{\Lambda} \left( \sigma_{Mf} - \sigma_{sp1} \right) \]  
(30)

The continuation of loading along this path will result in complete transformation to martensite as described in the major loop section. A change in loading direction prior to complete transformation will result in additional minor loops and the preceding equations are applicable. Figure 8 shows a typical strain path for minor loops and the resulting stress response is shown in Figure 9. Again the computation time required for the simple model was found to be approximately 7 times less than the time required by the polynomial model.

3. APPLICATION OF SIMPLIFIED MODEL TO VIBRATION ISOLATION

In this section the simplified model is used to solve a coupled structural response using SMAs as passive vibration isolation device. Figure 10 shows a typical SDOF system where the mass displacement is given by \( x(t) \) and the base excitation is given by \( y(t) \). The SMA element in the form of a bar plays the role of a spring as well as a damping device analogous to a typical
spring mass damper system. Reduction in displacement transmissibility takes place because of varying tangent stiffness as the SMA bar undergoes stress induced phase transformations and its hysteretic response.

The force acting on the SMA device is given by:

$$-F^{SMA}_{\text{SMA}} = \sigma A = E\left(\epsilon'\right) A \left(\frac{x - y}{L} - \epsilon'\right)$$

(31)

The equation of motion for the given system can be expressed as

$$M\ddot{x} + E\left(\epsilon'\right) A \left(\frac{x - y}{L} - \epsilon'\right) = 0$$

(32)

Rearranging yields

$$\frac{ML}{A} \ddot{x} + E\left(\epsilon'\right) x = E\left(\epsilon'\right) \left(y + L\epsilon'\right)$$

(33)

The resulting equation of motion is a 2nd order nonlinear differential equation. The nonlinear behavior is due to the nonlinear response of the SMA material introduced through the elastic stiffness, \(E(\epsilon')\), and the transformation strain, \(\epsilon'\).

The above ODE is numerically solved using a constant-average acceleration method (a variant of the Newmark integration scheme). The data utilized for the simulation has been tabulated in Table 1. The values chosen represent generic operating conditions for heavy industrial machinery. All the simulations have been performed in the MATLAB environment.

![Figure 10: SDOF system containing an SMA component](image)

<table>
<thead>
<tr>
<th>Design Parameters</th>
<th>Material Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>500Kg</td>
</tr>
<tr>
<td>Length of SMA bar</td>
<td>1m</td>
</tr>
<tr>
<td>Amplitude of base excitation</td>
<td>0.01m</td>
</tr>
<tr>
<td>Radius of bar</td>
<td>0.01m</td>
</tr>
<tr>
<td>Frequency of base excitation</td>
<td>50Hz</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>315K</td>
</tr>
<tr>
<td>(E_A)</td>
<td>70.0E9 Pa</td>
</tr>
<tr>
<td>(E_M)</td>
<td>30.0E9 Pa</td>
</tr>
<tr>
<td>(E_C)</td>
<td>7.00E6 Pa/°C</td>
</tr>
<tr>
<td>([M_{I0}, M_{d0}, A_{d0}, A_{f0}])</td>
<td>[274 292 296 315]K</td>
</tr>
<tr>
<td>(\Lambda)</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Figure 11 shows the input function \(y(t)\), which corresponds to a harmonic forcing function of frequency 50Hz and amplitude of 0.01m. The corresponding transmitted displacement \(x(t)\) is also shown, indicating a reduction of about an order of magnitude. Figure 12 shows similar results for the basic polynomial model. The corresponding stress-strain response for the SMA element (Figures 13 and 14) confirms the results obtained by using the simplified model. Considerable vibration isolation is observed for the system for the given set of design parameters and material data. Both full and partial transformations and SMA hysteretic response have aided in transmissibility reduction. The computation time required for the simplified model was found to be seven times faster than the basic polynomial model, however on coupling the simplified model with the Newmark integration scheme, the computation time was about four times faster than the basic polynomial model along with the Newmark integration scheme. The total time spent on the whole simulation was found to be about 2 minutes on a Pentium II 400Mhz PC. Further code optimization, to yield faster results, is currently being undertaken.
4. CONCLUDING REMARKS

A physically based SMA simplified material model has been presented, suitable for SMA smart systems and structures where the hysteresis of the structure is solely due to SMAs. The simplified model is shown to predict the material response similar to a basic polynomial model for pseudoelastic loading paths under isothermal conditions. The framework required to incorporate non-isothermal conditions has been introduced. Numerical implementation of the simplified model has been significantly faster as compared to the basic polynomial model. Reductions in displacement transmissibility of approximately an order of magnitude have been shown for a SDOF mass-SMA system. A detailed parametric study to investigate optimal conditions for passive vibration isolation for such a system still needs to be conducted. The simplified model is computationally less intensive so it can be used for design and analysis of complex SMA smart structures. It can also be utilized to determine weighting parameters for system ID based models, where the weighting parameters would be based on the physical parameters of the simplified model. Once the system ID based models are established for SMAs, system ID models can be utilized to model and simulate real-time response smart structures with SMA components.

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REFERENCES