SPECIAL ISSUE: INABIO 2006

CONTENTS

Guest Editorial 161

S. Sudo, K. Tsuyuki and T. Honda
Swimming mechanics of dragonfly nymph and the application to robotics 163

F. Kojima
Flaw detection of underground pipeline using electrical potential method 177

S.-B. Choi, Y.-M. Han and K.-G. Sung
Vibration control of vehicle suspension system featuring ER shock absorber 189

J.C. Lee, J. Chung, et al. and B.G. Min
Clinical applications and recent progress of therapeutic artificial organ using moving-actuator mechanisms 205

T. Kanomata, S. Murakami, D. Kikuchi, O. Nashima and H. Nishihara
Magnetic properties of Ni-Mn-Fe-Ga ferromagnetic shape memory alloys 215

J.-H. Roh, I. Lee and J.-H. Han
Damping characteristics of SMA films and their application for passive vibration isolation 225
Damping characteristics of SMA films and their application for passive vibration isolation

Jin-Ho Roh, In Lee and Jae-Hung Han*

Department of Aerospace Engineering, Korea Advanced Institute of Science and Technology, 373-1 Guseong-dong, Yuseong-gu, Daejeon, 305-701, Korea

Abstract. In applications of shape memory alloys (SMAs) as actuators and vibration isolation devices, understanding of the nonlinear hysteretic response of SMAs is important. The thermomechanical response, especially the pseudoelastic behavior of Ni-Ti SMAs at various annealing temperatures is investigated. The 2-D numerical model of the SMAs is proposed to predict the thermomechanical behaviors of SMA thin film. The methodology to attenuate vibrations of a host structure by using an SMA film is numerically demonstrated. For the damping enhancement, the structure with SMA films bonded onto it is numerically modeled and the effectiveness of SMA on passive vibration isolation is investigated.

Keywords: Pseudoelasticity, SMA film, damping, passive vibration isolation

1. Introduction

Increased demands for improving the structural performance with smart materials have produced adaptive structures which include the ability to sense, diagnose, and actuate. Smart materials have the ability to change stiffness, shape, natural frequency, damping, and other mechanical characteristics in response to change in temperature, electric field, or magnetic field. One of the most common smart materials, shape memory alloys (SMAs) have shown significant advantages in the area of structural response control [1], structural shape control [2], and damping enhancement [3]. Especially, pseudoelastic behaviors of SMAs are very attractive for passive vibration isolation due to their ability to sustain and retrieve large amount for strain, dissipate high levels of energy and provide a restoring force to the system. So, SMAs have been increasingly applied in the passive vibration isolation of the host structure.

In this research, the thermomechanical behavior of SMAs especially pseudoelasticity is experimentally and numerically investigated for the application of SMA as vibration isolation devices. A numerical algorithm of the 2-D SMA model is proposed to predict the thermomechanical behaviors of SMAs. The effect of annealing temperature on pseudoelastic behavior of Ni-Ti SMAs is observed. A differential scanning calorimeter (DSC) is applied to characterize the temperature-induced transformation. To understand damping characteristics of SMA film, the nonlinear hysteresis of load-displacement curve when it is subjected to bending load in the austenite finish temperature is characterized. For the damping enhancement, the structure with SMA films bonded onto it is numerically modeled and the effectiveness of SMA films on passive vibration isolation is investigated.

*Corresponding author. Fax: +82 42 869 3710; E-mail: jaehunhan@kaist.ac.kr.
2. Numerical model of SMA films

For the numerical analysis, the 2-D incremental formulation of the SMA constitutive model is proposed to predict the thermomechanical responses of SMA films. For 2-D problems, the general expressions derived in Lagoudas model [4] have to be modified. The model consists of three sets of equations: i) the constitutive equation, ii) the transformation equation, and iii) the transformation surface equation. The constitutive equation can be expressed by describing the increment of strain, \( \dot{\varepsilon}_{ij} \), in terms of the increments of stress, \( \dot{\sigma}_{ij} \), temperature, \( \dot{T} \), and martensite fraction, \( \dot{\xi} \), i.e.,

\[
\dot{\varepsilon}_{ij} = S_{ijkl} \dot{\sigma}_{kl} + \alpha_{ij} \dot{T} + Q_{ij} \dot{\xi}
\]

where, \( S_{ijkl} = C_{ijkl}^{-1} \) is the elastic compliance matrix, \( \alpha_{ij} \) is the thermal expansion coefficient vector. The stress, strain, thermal expansion, and compliance matrix can be expressed in the condition of plane stress.

\[
\begin{align*}
\sigma_{ij} &= [\sigma_{xx}, \sigma_{yy}, \sigma_{xy}]^T, \\
\varepsilon_{ij} &= [\varepsilon_{xx}, \varepsilon_{yy}, \varepsilon_{xy}]^T, \\
\alpha_{ij} &= [\alpha_{xx}, \alpha_{yy}, 0]^T, \\
S_{ijkl} &= \begin{bmatrix}
1/E & -v/E & 0 \\
-v/E & 1/E & 0 \\
0 & 0 & 2(1 + v)/E
\end{bmatrix}
\end{align*}
\]

The other term in Eq. (1) is defined by,

\[
Q_{ij} = \Delta S_{ijkl} \dot{\sigma}_{kl} + \Delta \alpha_{ij} (T - T_o) + \Lambda_{ij}
\]

Here, the prefix \( \Delta \) in Eq. (3) indicates the difference of a quantity between the martensite and austenite phases as follows:

\[
\Delta S_{ijkl} = S_{ijkl}^M - S_{ijkl}^A, \quad \Delta \alpha_{ij} = \alpha_{ij}^M - \alpha_{ij}^A
\]

The superscript \( A \) stands for austenite phase, and superscript \( M \) stands for the martensite phase. \( \Lambda_{ij} \) is the transformation strain direction and is assumed to have the following form:

\[
\Lambda_{ij} = \begin{cases}
\frac{H}{2\varepsilon_{t-r}^f} [(2\sigma_{xx} - \sigma_{yy}), (-\sigma_{xx} + 2\sigma_{yy}), 3\sigma_{xy}]^T, \\
\frac{H}{\varepsilon_{t-r}^f} [\varepsilon_{t-r}^f, \varepsilon_{t-r}^f, \varepsilon_{t-r}^f]^T,
\end{cases}
\]

where \( H \) is the maximum uniaxial transformation strain, \( \varepsilon_{t-r} \) is the transformation strain at the reversal of phase transformation, and

\[
\varepsilon_{t-r}^f = \sqrt{\sigma_{xx}^2 + \sigma_{yy}^2 - \sigma_{xx}\sigma_{yy} + 3\sigma_{xy}^2}, \quad \varepsilon_{t-r} = \sqrt{\frac{2}{3} \varepsilon_{t-r} \cdot \varepsilon_{t-r}}
\]

The transformation equation relates the increment of martensite fraction to transformation strain, \( \dot{\varepsilon}_{ij}^t \), as

\[
\dot{\varepsilon}_{ij}^t = \Lambda_{ij} \dot{\xi}
\]
and the transformation surface equation, which controls the start of the forward and reverse phase transformation is given as

\[ \pi = \sigma_{ij} \Lambda_{jk} + \frac{1}{2} \sigma_{ij} \Delta S_{ijkl} \sigma_{kl} + \Delta \alpha_{ij} \sigma_{jk} (T - T_o) \]

\[ + \rho \Delta c \left[ (T - T_o) - T \ln \left( \frac{T}{T_o} \right) \right] + \rho \Delta s_o T - \rho \Delta u_o = \pm Y^* \]

where \( \pi \) is the thermodynamic force conjugated to \( \xi \). Also, \( \rho, c, s_o, \) and \( u_o \) are the mass density, specific heat, specific entropy, specific internal energy at the reference state, respectively. The plus sign on the right hand side in Eq. (8) should be used for the forward phase transformation (austenite to martensite), while the minus sign should be used for the reverse transformation (martensite to austenite). Note that the material constant \( Y^* \) is the measure of internal dissipation due to phase transformation and can be interpreted as the threshold value of the transformation surface \( \pi \) for the start of the phase transformation.

The transformation function can be defined in terms of the transformation surface equation as follows:

\[ \Phi = \begin{cases} 
\pi - Y^*, & \dot{\xi} > 0 \\
-\pi - Y^*, & \dot{\xi} < 0 
\end{cases} \]

The transformation function \( \Phi \) takes a similar role to the yield function in plasticity theory, but in this case, an additional constraint for martensite fraction \( \xi \) must also be satisfied. Constraints on the evolution of the martensite fraction are expressed as,

\[ \dot{\xi} \geq 0, \quad \Phi (\sigma, T, \xi) \leq 0, \quad \Phi \dot{\xi} = 0 \]

\[ \dot{\xi} \leq 0, \quad \Phi (\sigma, T, \xi) \leq 0, \quad \Phi \dot{\xi} = 0 \]

The inequality constraints on \( \Phi (\sigma, T, \xi) \) is called as the transformation condition and regarded as a constraint on the state variables’ admissibility. For \( \Phi < 0 \), Eq. (10) requires \( \dot{\xi} = 0 \) and elastic response is obtained. On the other hand, the forward-phase transformation (austenite to martensite) is characterized by \( \Phi = 0 \) and \( \dot{\xi} > 0 \), while the reverse-phase transformation (martensite to austenite) is characterized by \( \Phi = 0 \) and \( \dot{\xi} < 0 \).

In the numerical implementing of the SMA constitutive model, the tangent stiffness and the stress at each integration point of all elements should be updated in each iteration for given increments of strain and temperature. The relationship between stress increments and strain and temperature increments can be expressed by,

\[ \sigma_{ij} = L_{ijkl} \dot{\xi}_{kl} + l_{ij} \dot{T} \]

where the tangent stiffness \( L_{ijkl} \) and tangent thermal moduli \( l_{ij} \) are defined by,

\[ L_{ijkl} = \left( S_{ijkl} - Q_{ij} \frac{\partial \Phi}{\partial \sigma_{kl}} \right)^{-1}, \quad l_{ij} = S_{ijkl}^{-1} \frac{\partial \Phi}{\partial \sigma_{kl}} \times \left( Q_{kl} \frac{\partial \Phi}{\partial T} - \frac{\partial \Phi}{\partial \sigma_{ij}} \times S_{ijkl}^{-1} \times \alpha_{kl} \right) \]

To calculate the increment of stress for given strain and temperature increments, Newton-Raphson iteration method has been used. For the numerical results of the SMAs, the ABAQUS finite element program has been utilized with user material (UMAT) subroutine. A numerical algorithm of SMA constitutive equation for the UMAT subroutine is illustrated in Fig. 1.
For verification of the numerical algorithm of SMA film, the numerical results of thermomechanical behaviors of SMA thin film are compared with experimental results of Lexcellent et al. [5]. The dimension of the SMA thin film specimen is 1 mm (width) × 5 mm (length) × 0.006 mm (thickness). For the numerical model of SMA, 10 × 4 membrane elements (M3D4) supported by ABAQUS are used.
Thermomechanical properties of SMA thin film measured by experiment are shown in Table 1 [5].

The critical stresses and the stress influence coefficients \((d\sigma/dT)^M\) and \((d\sigma/dT)^A\) of the SMA thin film are different for forward and reverse phase transformation. However, Lagoudas [4] just derived the equation and simulate in case of \((d\sigma/dT)^M = (d\sigma/dT)^A\). So, new strain hardening parameters are proposed in this research. The effective specific entropy difference is suggested differently in case of forward and reverse phase transformation as follows:

\[
\Delta s^A_o = -\frac{H}{\rho} \left( \frac{d\sigma}{dT} \right)^A, \quad \Delta s^M_o = -\frac{H}{\rho} \left( \frac{d\sigma}{dT} \right)^M
\]

Based on the Eq. (13), transformation strain hardening material constants can be derived such as follows:

\[
\gamma = \frac{1}{2} \rho \left( \Delta s^M_o M^{os} + \Delta s^A_o A^{of} \right), \quad \rho b^A = -\rho \Delta s^A_o (A^{of} - A^{os}), \\
\rho b^M = -\rho \Delta s^M_o (M^{os} - M^{of})
\]

Also, the measure of internal dissipation due to phase transformation, \(Y^*\), can be induced.

\[
Y^* = -\frac{1}{2} \rho \Delta s^A_o A^{of} + \frac{1}{2} \rho \Delta s^M_o M^{os} + \frac{1}{4} \rho \Delta s^M_o (M^{os} - M^{of}) - \frac{1}{4} \rho \Delta s^A_o (A^{of} - A^{os})
\]

The simple uniaxial stress-strain curves with various temperatures are investigated and the results are compared with experimental results. In Fig. 2, there are very good agreements between numerical and experimental results. However, some discrepancy is shown in Fig. 2(b). The thickness of the SMA thin film is very thin (0.006 mm) and the stress-strain curves of SMA thin film show the high nonlinearity with respect to the difference of environmental temperature from Fig. 2. Therefore, it is expected that the discrepancy between experiment and simulation in Fig. 2(b) should be due to the error in calculation of the strain based on the experimental measurement of uniaxial displacement and the high nonlinearity of stress-strain curve with respect to environmental temperature.

### 3. Pseudoelastic behaviors of Ni-Ti SMAs

#### 3.1. Experimental details

In order to characterize the pseudoelasticity of Ni-Ti SMAs, experimental measurements are carried out on Ni-55.32 at.% Ti SMA ribbon, manufactured by Special Metals Corporation, USA [6]. The dimension of the Ni-Ti SMA specimen is 7 mm (width) \(\times\) 150 mm (length) \(\times\) 0.25 mm (thickness).

<table>
<thead>
<tr>
<th>Material properties of SMA thin film</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moduli, Poisson’s ratio, Transformation temperatures Transformation constants Maximum transformation strain</td>
</tr>
<tr>
<td>(E^A = 40.0 \times 10^9 ) Pa (\nu^A = 0.34)</td>
</tr>
<tr>
<td>(E^M = 30.0 \times 10^9 ) Pa (\nu^M = 0.34)</td>
</tr>
<tr>
<td>(\nu^A = 22 \times 10^{-6}/K)</td>
</tr>
<tr>
<td>(\nu^M = 10 \times 10^{-6}/K)</td>
</tr>
</tbody>
</table>
Annealing temperature is an important factor affecting the thermomechanical behavior of Ni-Ti SMAs. The effect of annealing on shape memory and pseudoelastic behaviors of Ni-Ti SMAs has been reported [7]. So, with various temperatures of 673 K, 773 K, and 873 K, the specimens of Ni-Ti SMA ribbon are annealed in an electric muffle furnace for 30min, and air cooled to room temperature. To characterize the temperature-induced transformation, Differential Scanning Calorimeter (DSC, 204 F1 Phoenix®) is used (Fig. 3). The evolution of phase transformation temperatures with respect to various annealing temperatures is observed. Figure 4 shows the heat flow curves of the Ni-Ti SMA ribbon using DSC. Figure 4(a) shows the DSC curve of the specimen annealed at 673 K, where a two-step transformation occurred during cooling. The transformation product of the first exothermic peak at higher tempera-
Fig. 3. Differential Scanning Calorimeter (DSC), 204 F1 Phoenix®.

Table 2  
Transformation temperatures with respect to various heat treatments

<table>
<thead>
<tr>
<th>Heat treat</th>
<th>$M_{f}^\text{co}$</th>
<th>$M_{f}^\text{on}$</th>
<th>$R_{f}^\text{co}$</th>
<th>$R_{f}^\text{on}$</th>
<th>$A_{f}^\text{on}$</th>
<th>$A_{f}^\text{co}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>673 K 30 min</td>
<td>238 K</td>
<td>299 K</td>
<td>313 K</td>
<td>337 K</td>
<td>315 K</td>
<td>348 K</td>
</tr>
<tr>
<td>773 K 30 min</td>
<td>292 K</td>
<td>306 K</td>
<td>315 K</td>
<td>323 K</td>
<td>333 K</td>
<td>350 K</td>
</tr>
<tr>
<td>873 K 30 min</td>
<td>315 K</td>
<td>329 K</td>
<td>×</td>
<td>×</td>
<td>345 K</td>
<td>366 K</td>
</tr>
</tbody>
</table>

Isothermal tensile tests of Ni-Ti SMA ribbon are performed by using the INSTRON® universal testing machine 5583 and INSTRON® SFL thermal chamber for loading and unloading test at various temperatures (Fig. 5). To measure the strain, 45 mm gauge length of the extensometer is used. The strain rate during the loading and unloading process is 0.1% strain/min. Figure 6 shows the effect of annealing temperature on pseudoelastic behaviors. In shape memory alloys, pseudoelasticity transformation should generally appear above the austenite finish temperature range. However, when annealing temperature is 773 K, the Ni-Ti SMA ribbon shows that pseudoelasticity is incomplete and permanent elongation is remained. In case of 873 K, stress and strain curve shows more similar pattern with that of general plasticity.

The shape memory alloys of Ni contents exceeding 50.5% are sensitive to heat treatment at temperature between 573 K and 773 K due to the resulting precipitation of Ni-Ti those of the alloys. So, when fully annealed, SMA behaves pseudoelastically only partially [8]. In this SMA specimen of which Ni content is 55.32%, it is found that pseudoelastic behavior takes place only partially when this Ni-Ti SMA ribbon is annealed at 773 K which is considered as a nearly fully annealed temperature. Also, it is expected that recrystallization process take place when annealed at 873 K, because the behaviors of SMA show a different mechanism with general SMA's.

3.2. Simulation

As mentioned in Section 3.1, for the specimens annealed at 873 K, which is the critical recrystallization temperature, stress-strain curve shows different mechanism with the unique behavior of SMAs. In case
Fig. 4. Evolution of DSC heating/cooling curves.
of annealing temperature of 773 K, pseudoelastic behavior of SMA only occurs partially. So, the results of specimens annealed at 673 K are considered as the simulation model. The parameters needed to simulate the thermomechanical behaviors of Ni-Ti SMA ribbon are determined based on the experimental results. These constants are involved in the transformation functions and thus are directly linked to the thermodynamic energy equation. All these constants are calculated by experimental data fitting. They are chosen on the basis of minimizing the area between experimental and simulated results.

The stress-strain curve of Ni-Ti SMA ribbon shows R-phase transformation and permanent elongation due to slip deformation. To simulate such extraordinary behavior of SMAs, new parameters are introduced, $H^P$ and $H^R$ which are permanent elongation strain and R-phase intermediate transformation strain, respectively. The parameters of $H^P$ and $H^R$ as well as $H$, maximum residual strain, can be measured from Fig. 7(a). Also, Young’s modulus of austenite and martensite can be obtained from Fig. 7(b). The critical stresses, which induce phase transformation, are increased as the temperature increases. The stress influence coefficients are defined as the slopes of the lines representing the dependence of the critical stresses on the temperature of the specimen. The critical stresses and the stress influence coefficients $(d\sigma/dT)^M$, $(d\sigma/dT)^A$, and $(d\sigma/dT)^R$ of the Ni-Ti SMA ribbon are presented in Fig. 8.
The effect of R-phase transformation and permanent elongation can be considered as the thermodynamic energy to determine the unique characteristic of the Ni-Ti SMA ribbon. The effective specific entropy difference is introduced such as follows:

\[
\rho \Delta s_A^o = -(H + H^P) \left( \frac{d\sigma}{dT} \right)^A, \\
\rho \Delta s_M^o = -H \left( \frac{d\sigma}{dT} \right)^M, \\
\rho \Delta s_R^o = -H^R \left( \frac{d\sigma}{dT} \right)^R.
\]

(16)

Based on the Eq. (16), transformation strain hardening material constants can be derived such as follows:

\[
\gamma = \frac{1}{2} \left( \rho \Delta s_o^M M^{os} + \rho \Delta s_o^A A^{of} + \rho \Delta s_o^R R^{os} \right), \\
\rho b_A^o = -\rho \Delta s_o^A \left( A^{of} - A^{os} \right), \\
\rho b_M^o = -\rho \Delta s_o^M \left( M^{os} - M^{of} \right) - H \left( \frac{d\sigma}{dT} \right)^R \left( R^{os} - R^{of} \right) - \frac{1}{2} H \sigma_c^R.
\]

(17)
where, $\sigma_c^R$ is the critical stress of R-phase transformation and can be measured from Fig. 8. Also, the measure of internal dissipation due to phase transformation, $Y^*$, can be derived.

$$Y^* = -\frac{1}{2} \rho \Delta s^A_0 (A^\text{of}) + \frac{1}{2} \rho \Delta s^M_0 (M^\text{os}) + \frac{1}{4} \rho \Delta s^M_0 (M^\text{os} - M^\text{of})$$

$$- \frac{1}{4} \rho \Delta s^A_0 (A^\text{os} - A^\text{of}) - \frac{1}{2} \rho \Delta s^R_0 (R^\text{os}) + \frac{1}{4} \rho \Delta s^R_0 (R^\text{os} - R^\text{of})$$

(18)

One pseudoelastic curve at one temperature gives the critical stress for forward and reverse phase transformations as well as R-phase transformation. Transformation strains $H$, $H^P$, and $H^R$ are also measured on the stress-strain curves. These values and the transformation temperatures, $M^\text{os}$ and $A^\text{os}$, as
well as $R^{\text{os}}$ are enough to obtain the thermodynamical parameters in Eqs (16–18); i) the effective specific entropy difference, ii) transformation strain hardening material constants, iii) internal dissipation due to phase transformation. Therefore, stress-strain curves in various temperatures and phase transformation temperatures are enough to obtain the phenomenological material constants, and the result is shown in Table 3.

Stress-strain curves at various temperatures are calculated by the modeling. As can be seen from Fig. 9, the fitting between the calculated and experimental results is fairly good.

4. Damping characteristics of SMA film

The damping characteristic of SMA film is investigated. Figure 10 shows the hysteresis of load-displacement curve when SMA is subjected to bending load in the temperature of austenite finish, $A_{\text{of}}$. The dimension of the SMA film specimen is 20 mm (width) $\times$ 100 mm (length) $\times$ 1 mm (thickness). Thermomechanical properties of SMA film are shown in Table 1. The large hysteretic loop shown in Fig. 10 pass through closer zero. Since its area is equivalent to the amount of energy dissipation due to the internal friction between the austenite and martensite phases, SMAs should be applied effectively as passive damping devices. The variation of martensite fraction is illustrated in Fig. 11. The value of martensite fraction is increased due to stress-induced martensitic phase transformation and returns to the initial complete austenite state during loading and unloading cycles.

5. Passive vibration isolation using SMA film

For the passive damping enhancement, the structure with SMA films bonded onto it is investigated (Fig. 12). The Young’s modulus, Poisson’s ratio and density of the aluminum are given as $E = 69$ GPa, $\nu = 0.33$, and $\rho = 2700$ kg/m$^3$, respectively. The material properties of SMA film are used from Table 1.
The dynamic response of the structure is investigated when external pressure $F(t) = -800000 \cdot \sin (2 \pi \cdot 800t)$ is applied and all edges of the structure are clamped.

The vibration response of the structure with SMA film is compared with that of the reference structure where only the damping effect of SMAs is ignored. It is assumed that the temporal temperature change of an SMA film due to dynamic loading isn’t considered in this research. The nondimensional amplitude of vibration, where the center deflection (D) is divided by the length of x-direction (Lx), is attenuated comparing to the structure without SMA damping effect from Fig. 13. Moreover, the Von Misses stress at center is effectively reduced by using SMA thin film (Fig. 14). Figure 15 shows the distribution of martensite fraction when maximum deflection is reached due to external loading. The variation of martensite fraction provides the energy dissipation due to the internal friction between the austenite and...
martensite phase to attenuate vibrations of the structure.

6. Conclusion

The thermomechanical behavior of SMAs especially pseudoelasticity is experimentally and numerically investigated for the application of SMA as vibration isolation devices. The effect of annealing temperature on pseudoelastic behavior of Ni-Ti SMAs is investigated. The numerical model of the 2-D SMAs is proposed to predict the thermomechanical behaviors of SMA thin film. To understand damping
characteristics of SMA film, the nonlinear hysteresis of deformation is characterized. For the damping enhancement, the structure with SMA films bonded onto it is numerically modeled and the effectiveness of SMA on passive vibration isolation is investigated.

Based on the experimental results, it can be concluded that the annealing temperature has affected the pseudoelastic behavior of Ni-Ti SMA. The rhombohedral phase (R-phase) transformation occurs in the specimen of Ni-Ti SMA ribbon. Also, the permanent elongation and partial pseudoelastic behaviors are observed depending on annealing temperatures. New parameters of transformation function, which
considers the R-phase transformation as well as permanent elongation, are introduced to describe unique behaviors of this SMA ribbon and the good prediction of the thermomechanical behaviors of Ni-Ti SMA ribbon is presented. The numerical model of the structure with SMA films bonded onto it is considered for the passive vibration isolation. The vibration damping device using SMA film can be effectively applied to attenuate vibrations of a host structure by providing additional energy dissipation due to the pseudoelastic hysteresis. But the energy dissipation (damping) characteristics of SMAs are very complicated phenomena and should be function of several factors, such as loading/unloading rates, amplitude and frequency of the loading and temperature. Therefore, more improved numerical model of SMAs is necessary to effectively evaluate the damping characteristics of SMAs.

Acknowledgments

This work was supported by the Brain Korea 21 Project in 2006. The authors also appreciate the support by the Korea Research Foundation Grant funded by the Korean Government (MOEHRD) (KRF-2005-041-D00168).
References


