Forced Convection heated and cooled SMA(Shape Memory Alloy) Actuator

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강제대류 열전달을 이용한 형상기억합금 작동기

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This work discusses the numerical analysis, the design and experimental test of the SMA (Shape Memory Alloy) actuator along with its capabilities and limitations. Convection heating and cooling using water actuate the SMA element of the actuator. The fuel such as propane, having a high energy density, is used as the energy source for the SMA actuator in order to increase power and energy density of the system, and thus in order to obviate the need for electrical power supplies such as batteries. The system is composed of a pump, valves, bellows, a heater (burner), control unit and a displacement amplification device. The actuation frequency is compared with the prediction obtained from numerical analysis. For the designed SMA actuator system, the results of numerical analysis were utilized in determining design parameters and operating conditions.

Key Words: Shape Memory Alloy, actuator, forced convection, heat transfer, energy density

1. Introduction

This research is to design, fabricate and test a compact SMA based actuator that utilizes the high energy density of fuels, such as propane. The high energy density of fuels compared to typical electrical batteries, or even fuel cells, allows for the energy source, i.e. the fuel, to be incorporated inside the actuator system. The energy density (J/Kg) of these fuels is much greater than that of most advanced batteries. This, along with the incorporation of the actuation control hardware and software inside the unit, can result in a compact SMA actuator system. The high-energy density, high recovery stress and strain of SMA will result in high actuator compactness, force and stroke, respectively.

The phase change in a NiTi SMA is achieved by heat exchange with a heat source and a heat sink. The actuation frequency of the SMA actuator is only dependent on the rate of heat transfer with its surroundings. Until recently, the heat transfer mechanism for most SMA actuators has been based on resistive heating (martensite to austenite) and cooling with forced convection or natural convection (austenite to martensite). This is a rather inefficient heat exchange mechanism [1] and requires the use of electrical power and thus heavy, low energy density (at least as compared to fuels) power supplies or batteries. The thermoelectric heat transfer mechanism by utilizing semiconductors, which employing the

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Peltier effect, has shown high actuation frequency [2]. But generally this kind of device has very low efficiency. Thus, we propose forced convection heating and cooling to actuate the SMA actuator. This can overcome the low energy density of resistive heating systems and the low efficiency of the thermoelectric heat transfer mechanism, even though it should need additional devices such as a pump and valves. The actuator design merges the advantages of SMAs and fuels, i.e., the high actuation forces, the large power densities, the silent actuation characteristics of SMAs and the tremendous energy densities of fuels.

2. Design Concept

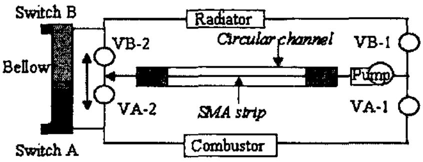

Fig. 1 Schematic of SMA actuator.

The SMA actuator system, as shown in Fig. 1, is composed of a pump, a combustor, valves, the SMA element, the heat exchanger and utilizes fuel as the main energy source. An SMA strip is embedded in a channel. Heating and cooling fluid medium alternatively circulates through the channel to achieve the M-to-A and A-to-M transformations, respectively. The heating medium (hot water) is heated through the burning of the fuel in the combustor. The cooling medium, after it removes the heat from the SMA strip, goes through a heat exchanger where it disposes of the energy obtained from the SMA strip. The pump circulating the two media is equipped with valves that are properly timed through the heating and cooling cycles.

3. Numerical Analysis

3.1 Material properties of SMA strip

The strip is a 10%-Cu NiTi alloy (K-alloy) and it was annealed at 450°C for 20 minutes. A Perkin-Elmer Pyris 1 Differential Scanning Calorimeter (DSC) was used to determine the phase transformation temperatures and latent heat. Fig. 2 shows the transformation temperatures and latent heats of the SMA strip. The transformation temperatures, A^f=363.83°K (90.68°C, f:finish) and A^s=353.42°K (79.27°C, s:start) at 150 M Pa obtained from the DSC test and experimental test.

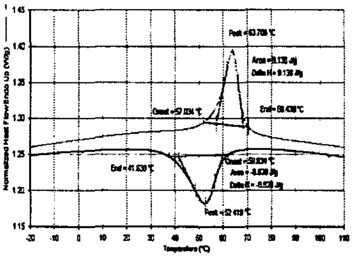

Fig. 2 Transformation temperatures and latent heats for K-alloy SMA strip.

3.2 heat transfer analysis

The heat transfer analysis of the SMA actuator was carried out with commercial software packages such as FLUENT and GAMBIT. In the phase transformation of an SMA, heat is absorbed during the reverse transformation (martensite to austenite) and is released during the forward transformation (austenite to martensite). This heat is called the latent heat of transformation (ΔH). The area under the curve described by the specific heat is the latent heat of transformation. During phase transformation, the heating and the cooling of the SMA are slowed down due to the latent heat of the transformation. An empirical relation describing the dependence of the specific heat on temperature is given in [2]. Certain transformation temperatures (such as A^f=363.83° K=90.68°C and A^s= 352.42°K=79.27°C), latent heat and specific heat capacity at a stress level of 150 M Pa were utilized in the followings equations.

For the forward transformation: $M^f < T < M^s$

$$C_{ps}^{*} = C_{ps}^{o} + \Delta H \frac{\ln(100)}{|M^s - M^f|} e^{-\frac{2\ln(100)}{|M^s - M^f|}\left|T - \frac{M^s + M^f}{2}\right|} \tag{1}$$

For the reverse transformation: $A^f < T < A^s$

$$C_{ps}^{*} = C_{ps}^{o} + \Delta H \frac{\ln(100)}{|A^s - A^f|} e^{-\frac{2\ln(100)}{|A^s - A^f|}\left|T - \frac{A^s + A^f}{2}\right|} \tag{2}$$

The heat value of the SMA (C_{ps}^{o}) under M^f and above A^f is 550 J/Kg°K [3]. Eqs. (1)-(2) were modeled as a series of piece-wise linear segments, as shown Fig. 3, for implementation in FLUENT. The initial temperature of the SMA strip was 335° K (61.85°C) and the inlet velocity and temperature of the heating medium were 1 m/sec and 370°K (96.85°C), respectively. The working fluid was hot water. Energy losses through both ends and walls of the channel were ignored. A channel and an SMA strip embedded in it were the computational domain. The first-generation actuator utilized a SMA strip in a circular silicon channel (R=5.84 mm, L=210 mm) to allow passing of hot and cold fluids alternatively according to the heating and cooling cycles.

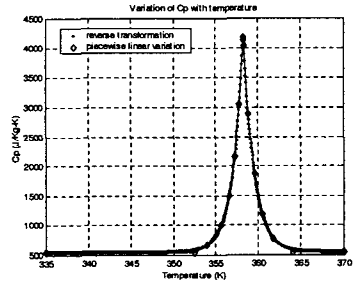

Fig. 3 Variation of C_p with temperature (reverse transformation).

The flow was in a turbulent state (circular channel: Red=22400), thus the standard k-e model, in combination with an enhanced wall treatment method for the near-wall region, was used. A quarter of the channel and the SMA strip were considered by using symmetry conditions. Fig. 4 shows cross sections of the computational domain.

Fig. 5 shows the temperature distribution of the middle cross-section of the SMA strip (where temperature is the lowest in the SMA strip). The strip temperature was above the austenite finish transformation temperature under 150 M Pa stress after 1.0 sec, thus the strip was fully transformed.

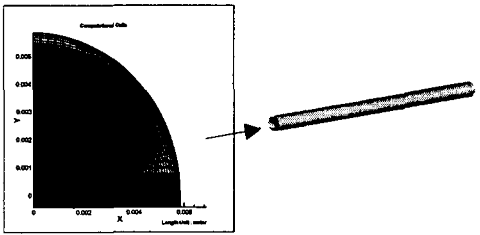

Fig. 4 Computational domain.

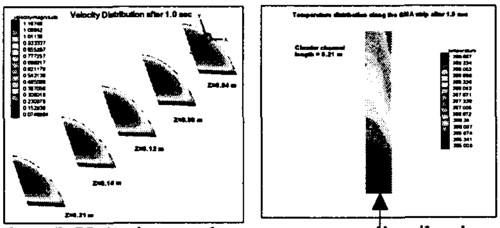

Fig. 5 Velocity and temperature distributions.

4. SMA Actuator System

The SMA actuator system is composed of a pump, valves, a combustor(burner), an SMA element, a hot fluid tank, bellows and heat exchangers as shown in Fig.6.

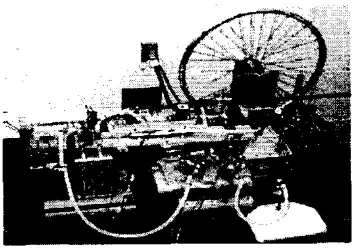

Fig. 6 SMA Actuator system.

The bellows used to prevent mixing between hot and cold water. The load is applied constantly by dead weight for entire heating and cooling cycle. The inlet velocity and inlet temperature were also determined based on numerical analysis. The volume flow rate of hot water and cold water was set as 0.11 l/sec, thus the flow velocity inside the channel was around 1 m/sec. The actuator system was tested under 735 N constant load. Fig. 7 shows the displacement of the strip under 735 N load for the closed-loop system.

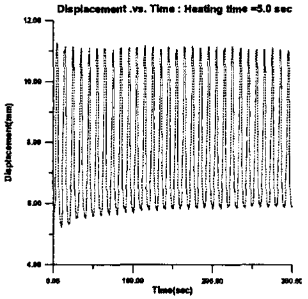

Fig. 7 Displacement vs. time under 735 N, for closed-loop test.

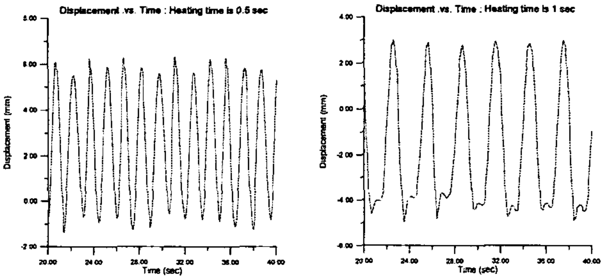

Fig. 8 Displacement vs. time under 735 N(left) and 1560 N(right) for open-loop test.

The 2.4% strain (5 mm stroke) and 0.1 Hz (heating time: 5 sec & cooling time: 5 sec) actuation frequency was obtained from the closed-loop system test. This result shows lower strain and slower frequency compared to the open-loop system, in which the hot and cold water was not re-circulated. In the open-loop test, actuation frequency of the SMA actuator (K-alloy, 12 mm x 0.9 mm) can be raised to 1 Hz (heating and cooling cycle) under 71 M Pa load (735 N), and up to 0.5 Hz under 150 M Pa load (1560 N) as shown in Fig.8. 3 % strain can be obtained by utilizing hot water (370°K) and cold water (295°K).

The lower strain and slower actuation frequency in the closed-loop system was mainly due to the mixing between hot and cold fluid in the system. If the mixing and energy loss were prevented properly, at least 0.5 Hz actuation frequency and 3 % recovery strain could be obtained. This (open-loop test) shows same value of the numerical results, which show the heating period around 1.0 sec at 150 M Pa stress considering latent heat of the transformation.

5. Conclusions

The SMA actuator system is simple and compact potentially compared to other actuator systems. The forced convection heating and cooling generated relatively high actuation frequency compared to resistive heating and air forced convection cooling. The results of the numerical heat transfer analysis are useful and reasonable compared to the results of the experimental test. The first designed SMA actuator system could actuate the SMA strip (12 mm x 0.9 mm x 254 mm) at 0.5 Hz under 150 M pa stress with 3 % strain. This frequency is fairly high considering the size of strip. This research also shows the energy savings that SMAs present us with, in systems where parasitic heat is already present. Heating of the SMA by utilizing existing parasitic heat in the vehicle/plant, this will yield a high energy density actuator.

References

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