SMA(SHAPE MEMORY ALLOY) ACTUATOR USING FORCED CONVECTION

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강제 대류를 이용한 형상기억합금 작동기

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This work discusses the numerical analysis, the design and experimental test of the SMA actuator along with its capabilities and limitations. Convective heating and cooling using water actuate the SMA(Shape memory alloy) 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 experimental test of the SMA actuator system results in 150 MPa stress(force : 1560 N) with 3 % strain and 0.5 Hz actuation frequency. 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

SMAs are metallic alloys that can recover permanent strain by changes either in stress, temperature or combination of both[1]. These change induce a phase transformation from martensite to austenite or from austenite to martensite. The martensite phase is low temperature phase, can be easily deformed and is low symmetric state, while austenite is high temperature phase, is relatively hard and is high symmetric state. During the transformation, SMAs exhibit and recover considerable amounts of strain. Shape Memory Alloy actuators can provide an interesting alternative to conventional actuation methods such as hydraulic actuators and electric motors. SMA actuators can reduce the size, weight and complexity of a system[2].

The main objective of this research is to design, fabricate and test a compact shape memory alloy based actuator that utilizes the high energy density of fuels, such as propane. The fact that the main element of the actuator, the SMA is a heat engine[3,4], is used to convert the thermal energy of a fuel (propane) to mechanical energy. 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 highly compact actuator system. Thus the actuator system can be run wirelessly by low-power digital actuator control signals. The high energy density, high recovery stress and strain of SMA will result in high actuator compactness,

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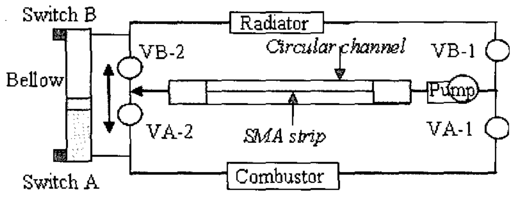

Fig. 1 Schematic of SMA actuator

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 heat transfer(austenite to martensite). This is a rather inefficient heat exchange mechanism[5] 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 Peltier effect, has shown high actuation frequency[6]. But generally this kind of device has very low efficiency. Thus, we propose forced convective 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. Also, the high energy of fuel is transferred easily to the fluid through the combustor and the heat exchanger. Researchers have worked on developing high efficiency, compact combustors and heat exchangers, using micro technology[7,8]. Convective heating and cooling of the SMA, can result in considerable actuation frequencies. In addition, for systems with sufficient parasitic heat, the actuator can utilize the parasitic heat as its energy source, resulting in a relatively high-efficiency actuating system. The actuator design merges the advantages of SMAs and fuels, i.e., the high actuation forces, the large power densities and the silent actuation characteristics of SMAs and the tremendous energy densities of fuels. In this paper we will discuss the design of the SMA actuator system, recovery stress and strain and actuation frequency of

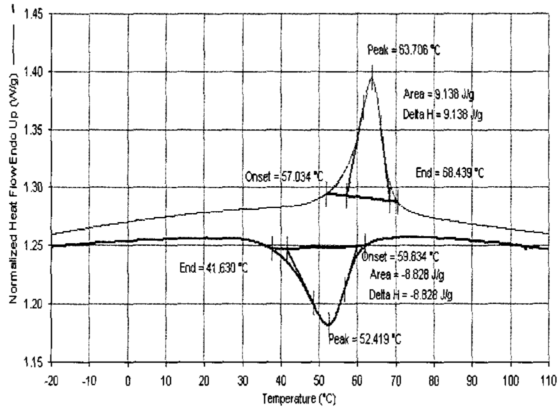

Fig. 2 Transformation temperatures and latent heats for K-alloy SMA strip(DSC test)

the SMA actuator by utilizing the high thermal energy of fuels. Section 2 of this paper presents the principle of the SMA actuator system utilizing fuel as main energy source. Section 3 presents the numerical heat transfer analysis of the SMA actuator. Section 4 is for the design and test results of the SMA actuator system. Section 5 presents conclusions.

2. DESIGN CONCEPT OF SMA ACTUATOR SYSTEM

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 or ethylene glycol) 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 that circulates the two media is equipped with valves that are properly timed through the heating and cooling cycles.

3. NUMERICAL HEAT TRANSFER ANALYSIS

3.1 MATERIAL PROPERTIES OF SMA STRIP

The phase transformation temperatures and latent heat were needed in order to calculate the heat transfer rate and temperature distribution of the SMA strip. The

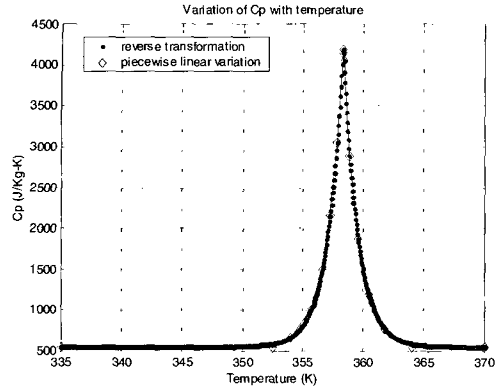

Fig. 3 Variation of Cp with temperature (reverse transformation)

strip is a 10%-Copper 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 temperature and latent heats of the SMA strip. The transformation temperatures, A^f=363.83K(90.68°C) and A^s=353.42K(79.27°C) at 150 MPa obtained from the DSC test and experimental test[9]. Where s and f mean start and finish state of the material.

3.2 Forced Convection Heat Transfer Analysis of SMA

To estimate the period of the heating and cooling cycles(i.e., actuation frequency), a numerical heat transfer analysis of the SMA actuator was carried out with commercial software packages such as FLUENT and GAMBIT. The energy balance equation of the SMA strip (solid) can be expressed as:

$$\rho_s C_{ps}^* \frac{\partial}{\partial t}[T_s] = \nabla \cdot (k_s \nabla T_s) + q_{gen} \quad (1)$$

Where T is the temperature, k is the thermal conductivity, ρ is the density, Cp* is the specific heat of the SMA strip and t is the time. The subscript s indicates the SMA strip. In Eq.(1), qgen represents the energy generation rate per unit volume and can be ignored for forced convection heat transfer case. In the phase transformation of an SMA, heat is absorbed during the reverse transformation (martensite to austenite) and is released during the forward transformation

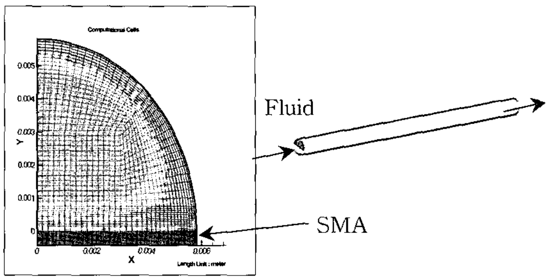

Fig. 4 Computational domain of circular channel with SMA actuator

(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. When performing a transient heat transfer analysis it is therefore important to account for this effect. An empirical relation describing the dependence of the specific heat on temperature is given in [6]. Certain transformation temperatures (such as A^f=363.83K=90.68°C and A^s=352.42K=79.27°C), latent heat and specific heat capacity at a stress level of 150 MPa were utilized in the followings equations.

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

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

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

$$C_{ps}^* = C_{ps}^o + \Delta H \frac{\ln(100)}{\left|A^s - A^f\right|} e^{-\frac{2\ln(100)}{\left|A^s - A^f\right|}\left|T - \frac{A^s + A^f}{2}\right|} \quad (3)$$

The heat value of the SMA (C_{ps}^o) under M^f and above A^f is 550 J/Kg/K[10].

The curves obtained for the variation of the specific heat of the SMA with temperature, during the forward and reverse transformations at 150 MPa stress, are shown in Fig. 3. Eqs. (2)-(3) were modeled as a series of piece-wise linear segments, as shown Fig. 3, for implementation in FLUENT. For the numerical calculation, the initial temperature of the SMA strip

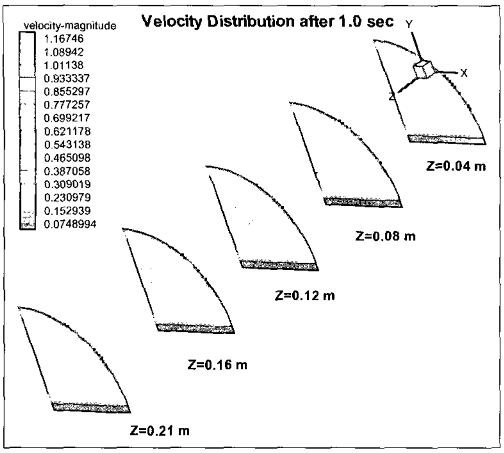

Fig. 5 Velocity distribution of SMA strip

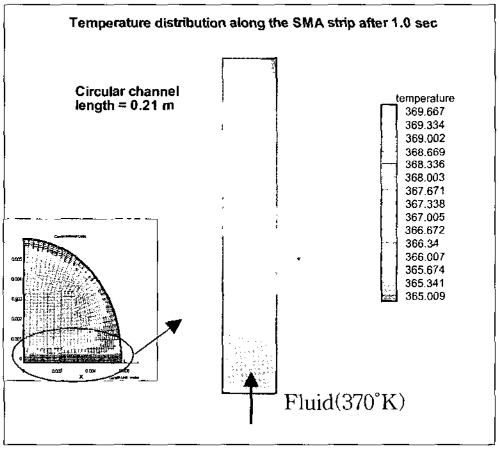

Fig. 6 Temperature distribution of SMA strip

was 335K(61.85°C) and the inlet velocity and temperature of the heating medium were 1 m/sec and 370K(96.85°C), respectively.

The working fluid was hot water. Energy losses through both ends of the channel and channel walls were ignored. A channel and an SMA strip embedded in it were the computational domain. The temperature distribution along the SMA strip in a circular channel (R=5.84 mm, L=210 mm) was obtained from the numerical analysis. The actuator utilized an SMA strip in a circular silicon channel to allow passing of hot and cold fluids alternatively according to the heating and cooling cycles.

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. Figs. 4 and 5 show cross sections of the computational domain and velocity distribution. The grid was generated by GAMBIT and was denser near the SMA strip and the wall in order to capture the turbulent boundary layer.

Fig. 6 shows the temperature distribution of the half 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 MPa stress after 1.0 sec, thus the strip was fully transformed.

4. DESIGN OF SMA ACTUATOR SYSTEM

To measure available force, displacement and actuation frequency, an SMA actuator system was designed. The SMA actuator system is composed of a pump, valves, a combustor(burner), an SMA element, a hot fluid tank, bellows and heat exchangers. The bellows used to prevent mixing between hot and cold fluid.

Fig. 7 shows the first design of the SMA actuator system and the corresponding, its experimental setup. The load is applied constantly by dead weight for entire heating and cooling cycles. The strip was put through multiple thermal cycles by cycling its temperatures from below the martensite finish temperature($T<M^f$) to above the austenite finish temperature($T>A^f$) under a constant applied stress of 71 MPa and 150 MPa. The displacement was measured with a LVDT(DCT2000C, RDP Group). National Instrument AT-MIO-16XE-50 board and PCI-6704 D/A board with Lab-Windows program were utilized to acquire displacement and control the pump and valves.

Water was selected as heating and cooling medium from the numerical results because it was easy to handle and the boiling temperature of water is high enough to heat and cool the SMA strip around 0.5 Hz under high stress(150 MPa). 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 by adjusting the power of the pump, thus the flow velocity inside the channel was around 1 m/sec. The actuator system was tested under 735 N(constant load).

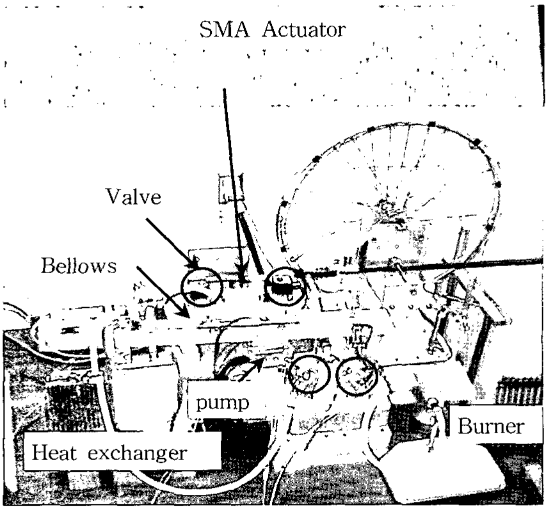

Fig. 7 SMA Actuator System: its experimental setup and SMA actuator

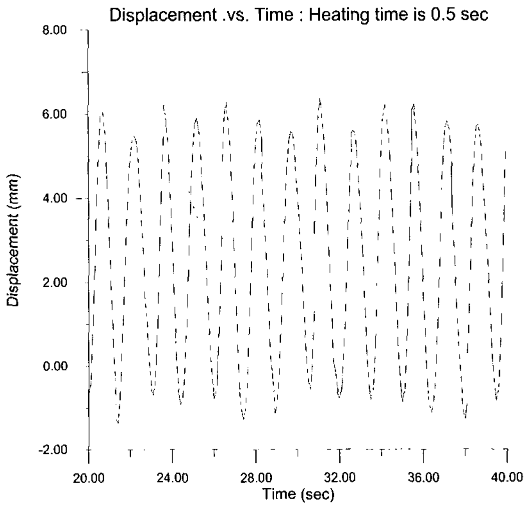

Fig. 9 Displacement vs. time under 735 N, for open-loop test

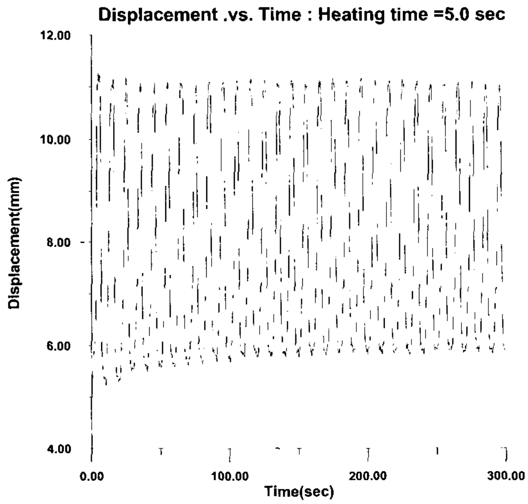

Fig. 8 Displacement vs. time under 735 N, for closed-loop test.

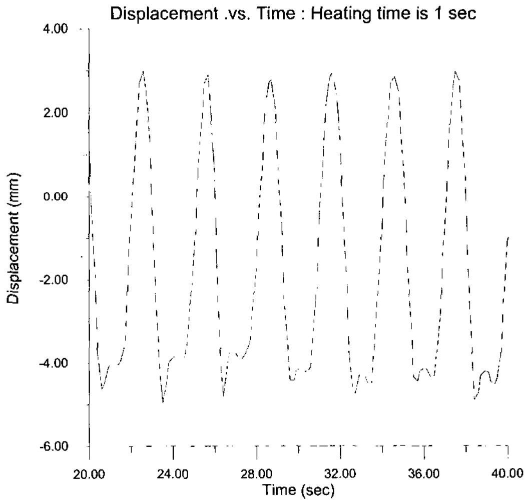

Fig. 10 Displacement vs. time under 1560 N, for open-loop test

Fig. 8 shows the displacement of the strip under 735 N load for the closed-loop system. The hot water, after heating the SMA strip, returned back to the heater(burner), which added enough energy to the hot water to compensate for its energy loss due to heating of SMA strip and other energy dissipations. The cold water, after cooling the SMA strip, returned back to the radiator where the thermal energy removed from SMA strip was dissipated to the surroundings by air forced convection.

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. Figs. 9 and 10 show the results of the open-loop system.

The SMA actuator system can generate enough recovery stress and strain at 0.5 Hz actuation frequency for the open-loop test. Fig. 9 shows higher frequency under 735 N than that of Fig. 10 under 1560 N. The maximum operating pressure of the closed-loop system is about 69 KPa in the heating (hot fluid) circuit. Pressure losses of the system and water vapor caused this pressure.

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 MPa load(735 N), and up to 0.5 Hz under 150 MPa load(1560 N). At least 3 % strain can be obtained by utilizing hot water(370K) and cold water(295K).

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. As the number of cycles increases, the energy loss caused by the mixing increases. The cylinder(bellows) and the pump are also heat loss devices because they contain heating and cooling medium alternatively. Hence the hot fluid temperature goes down and the cold fluid temperature goes up. This degrades the performance of the heating and cooling circuits. More powerful heater and heat exchanger can overcome this mixing, but in that case the system might lose compactness and high energy density. One of the methods to prevent mixing is to adjust stroke length of the cylinder(bellows), thus making the channel volume and volume of other sharing passages equal to the volume of bellows. If the mixing and energy loss were prevented properly, at least 0.5 Hz actuation frequency and 3 % recovery strain could be obtained.

The heating period of experimental results under high stress condition(150 MPa) and 3 % recovery strain was around 1.0 sec in the open-loop test. This shows same value of the numerical results, which show the heating period around 1.0 sec at 150 MPa stress considering latent heat of the transformation. Thus the numerical analysis is reasonable and shows good agreement with the experimental test.

5. CONCLUSIONS

The results of the numerical heat transfer analysis are useful and reasonable compared to the results of the experimental test. Thus, in designing of the thermal induced SMA actuator, the transient heat transfer analysis with latent heat must be carried out and confirmed numerically to determine the design parameters and operating conditions. 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 MPa stress with 3 % strain. Considering the size of strip, the forced convective heating and cooling gènerated relatively high actuation frequency compared to resistive heating(martensite to austenite) and air forced convective cooling(austenite to martensite).

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