Displaying Tactile Sensation Using SMA Actuators and Sensors

Hideyuki Sawada[1]

sawada@waseda.jp
[1] Waseda University, 3-4-1 Okubo, Shinjuku-ku, Tokyo, 169-8555, JAPAN
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ABSTRACT

This paper presents a compact tactile display for the presentation of tactile sensation. By employing shape-memory alloy (SMA) wires, novel tactile devices have been developed for displaying various tactile sensations. The tactile actuator consists of a filiform SMA wire with the diameter of 50 - 100 µm, and generates micro-vibrations with various frequencies and amplitudes in accordance with a driving pulse signal.

1 Introduction

A shape-memory alloy (SMA) is an alloy that remembers its original shape. It is deformable in martensite phase in lower temperature, and returns to its pre-deformed shape when heated to be transited to austenite phase. A filiform SMA wire with the diameter of 50 - 100 µm presents unique characteristics swiftly responding to heat application to the material body, which is related to the phase transition between the martensite and austenite phases. By applying weak current to a SMA wire, heat is instantly generated in the body due to the internal resistance, and the wire shrinks up to 5 % lengthwise. When the current stops and the temperature drops, then it returns to the original length. The SMA wire is thin and flexible enough to be cooled down right after the current stops, and it returns to the pre-deformed length according to the temperature shifts from austenite to martensite. This means that the expansion and contraction of the SMA wire can be precisely controlled by applying the pulse current [1].

In our studies about tactile displays, the SMA wires have been employed for introducing novel tactile actuators that display various tactile sensations to human skin [2]. We have also discovered that the deformation caused by applied stress to a SMA wire generates the change of the electric resistance. With this characteristic, the SMA wire works as a micro-force sensor with high sensitivity, while generating micro-vibration. The developed tactile displays present various tactile sensations in reaction to user's touch actions to the displays.

In this paper, the novel characteristics of a SMA wire are firstly introduced to works as micro-vibration actuators for displaying tactile sensation, while sensing micro-force applied to the wire device. The SMA actuator and sensor have been applied to novel tactile displays that react to hand actions given by a user.

2 Characteristics of Shape-memory Alloy Wires

In this study, we pay attention to the physical properties of a shape-memory alloy consisting of nickel-titanium-copper (NiTiCu), and effectively use the two characteristics related with the phase transition, which are shape memory effect and pseudoelasticity.

Figure 1 shows a schematic diagram of shape memory effects in NiTiCu alloy. SMAs cause the change of the crystal structure between the martensite phase and the austenite phase induced by temperature. An alloy changes from austenite to martensite upon cooling, and inversely from martensite to austenite by heating. In martensite, an alloy can be deformed by applying load, and by heating to transit to austenite. To the contrary, the alloy returns to the memorized shape that has been preliminary given, when the load and the heat are removed.

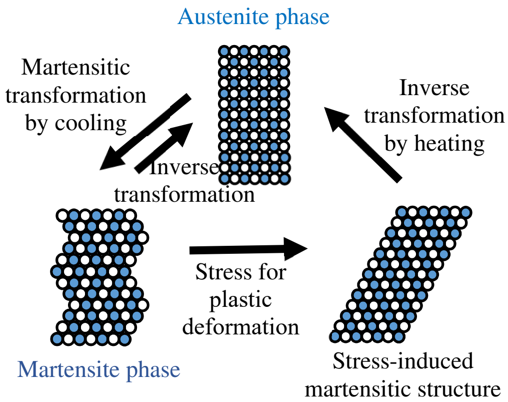


Fig. 1 Shape memory effect of SMA

The NiTiCu wire employed in our study (Toki corporation BioMetal BMF series) is a filiform SMA with the diameter of 50 to 100 µm, and has a memorized crystal structure in the length direction. With the shape memory effect, the wire shrinks in the length direction by heating, and returns to the memorized length by cooling. Figure 2 shows the temperature characteristics of the SMA wire used in this study having the temperatures M_f = 68 and A_f = 72 degrees.

Pseudoelasticity is the other phenomenon found in SMAs [3], [4], and the schematic diagram is shown in Figure 3. With the isothermal application of stress to an alloy in austenite phase, the crystal structure transforms into the stress-induced martensitic state. By removing the stress, the transformed structure inversely returns to the austenite. In accordance to the deformation, the electrical resistance of the alloy changes due to the crystal structural transition. The phase transformation transits from austenite to stress-induced martensite via R phase, which has a rhombohedral crystal structure, and this transition to R phase has high time response. This means that by effectively using the resistance change caused by stress application, an SMA works for sensing micro-force in realtime.

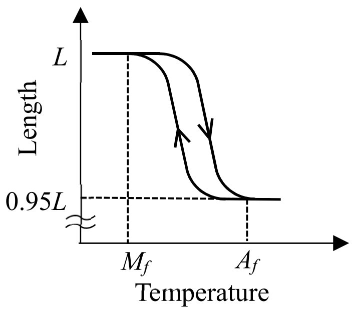


Fig. 2 Temperature characteristics of SMA

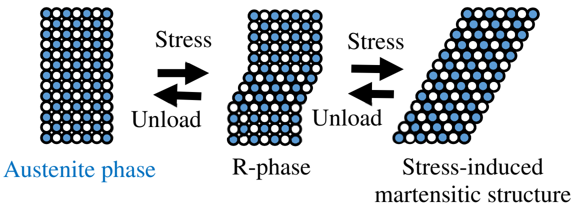


Fig. 3 Pseudoelasticity of SMA

3 SMA actuators and sensors

3.1 Design of micro-vibration actuators

The authors have developed a micro-vibration actuator electrically driven by periodic electric current generated by a control circuit. Figure 4 shows a vibration actuator composed with a 5 mm-long SMA wire with a diameter of 0.05 mm. By applying electric current to the alloy, the temperature rises to A_f due to the generated heat inside the alloy body, and the wire shrinks up to 5% lengthwise of the original length. When the current stops and the temperature drops to M_f, the wire returns to its original length.

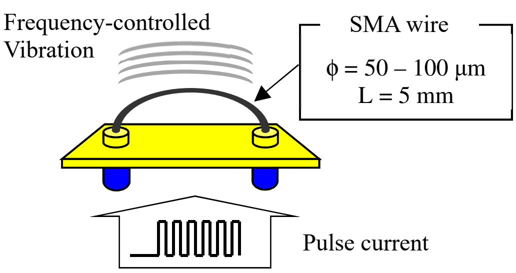


Fig. 4 Micro-vibration actuator using SMA wire

The SMA wire is so thin that it instantly cools after the electric current stops, and returns to its original length when the temperature shifts from A_f to M_f. This means that the shrinkage and the return to initial length of the SMA wire can be controlled by applying pulse current. By driving the SMA wire using periodic pulse current, micro-vibration with the amplitude of micrometers is generated, which is perceived by human skin as tactile sensation. We employ pulse-width modulated (PWM) current generated from a specially designed amplifier to control the vibration mode of the SMA wire. The generated pulse has the amplitude of H [V], the width of W msec and the period of L msec, and the duty ratio W/L determines the heating and cooling time of the SMA. The value W*H, which is equivalent to the calories exchanged, determines the amplitude of vibration, and the vibration frequency is completely controlled by regulating L. When the actuator was driven by pulse current of 50 Hz and 100Hz, for example, we verified that the SMA wire perfectly synchronized with the ON/OFF pulse current, and shrunk about 2 μm toward the length.

We applied the vibration actuator to the display of tactile sensation, since it is able to generate various vibratory stimuli having different frequencies up to 300 Hz. The vibration generated from the SMA wire is able to give physical stimuli to human skin to create various tactile sensations. The greatest deformation of skin given by the wire is, however, approximately 10 μm, which is sometimes difficult for some users to recognize clear tactile sensation.

A pin-type tactile actuator was further developed to amplify the vibration presented to any part of the human body as shown in Fig. 5. By soldering a pin to an SMA wire, micro-vibration generated by the alloy is conducted to the pin to be amplified to become greater vibratory stimuli [5]. We confirm that more than 300 Hz vibration is generated by synchronizing with properly prepared pulse-current, and the mechanical vibrations are preferably perceived by tactile mechano-receptors under the skin, such as Meissner corpuscles and Pacinian corpuscles, which respond to frequencies lower than 100 Hz, and also from 50 to 300 Hz, respectively.

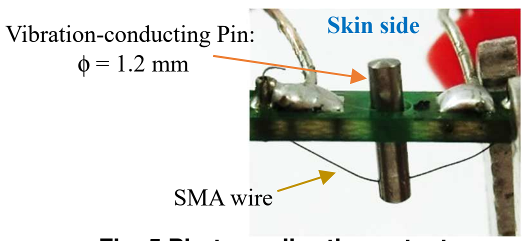


Fig. 5 Pin-type vibration actuator

3.2 Micro-force sensing

The structure of a pin-type vibration actuator shown in Fig. 5 is applicable to construct a micro-force sensor.

When force is applied to the tip of the pin, the force is directly conducted to the SMA wire as a shear stress to the elongating direction of the wire. Austenite state of a SMA wire presents pseudoelasticity against the stress, and the electric resistance changes according to the applied force. By applying weak electric current to the wire, the SMA stays in austenite state, and the change of resistance can be measured electrically using a specially-designed circuit.

We also discovered that while generating micro-vibrations from a SMA wire, applied force could be measured as resistance changes. This can be explained that the vibration is generated in austenite state, which causes pseudoelasticity to induce resistance change against applied stress.

4 Tactile displays and the presentation of texture sensation by the control of pulse-signal density

4.1 Tactile displays in different shapes

Different types of tactile displays have been constructed by arranging plural SMA actuators in arrays. Since SMA wires used in our study are thin enough to be attached to any surface of a conventional interface devices and also stitched in a cloth, various tactile devices can be simply constructed. Figure 6 shows three examples of tactile displays constructed in different shapes, which are a) a tactile mouse with16 pin-type actuators mounted on the surface of a computer mouse [2], b) a tactile pen with 2 actuators installed in a grip of a stylus pen [6], and c) a tactile pad for presenting moving texture sensations [7].

a) Tactile mouse

b) Tactile pen

a) Tactile touch pad

Fig. 6 Examples of Tactile displays

4.2 Displaying texture sensation driven with the use of probability density function

Periodic pulse current is able to present different tactile sensations associated with the vibration frequencies. We further examined the presentation of an object's texture and its rubbing sensation when we stroke our hand on the object. In this section, we introduce a method for driving actuators with the use of randomly generated pulse signals by employing a probability density function.

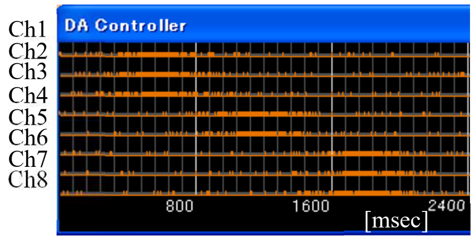
When we touch an object surface with our hand and move it, we feel the object's texture sensation. The recognized sensation is induced by the physical stimuli caused by the contacting situation between the object and our skin. By changing the hand-moving speed or the contacting pressure, the perceived sensation may be changed due to the physical situation. We paid attention to the randomly-generated physical stimuli from the object surface, and tried to display the virtual tactile sensation by changing the pulse density of the driving pulse current. The greater the density of the pulse becomes, the greater the roughness of a surface is expected to be generated. The change of the pulse density among actuators can be related with the hand motion. With these assumptions, we constructed a tactile presentation system to control the driving signals using a pulse-signal probability density function (PPDF) [2].

The probability density of a pulse occurrence is determined by the PPDF using the Gaussian distribution as

$$p(t) = \alpha + \beta \exp\left\{ \frac{-(t-m)^2}{2\sigma^2} \right\} \quad (1)$$

where m : average, σ : variance, α : offset, β : gain, α + β < 1.0,

and the control signals with different probability density for each actuator are generated. An example of control signals for each channel generated by PPDF is shown in Fig.7, where high-density pulses are presented by bold lines. In this presentation, tactile stimuli move from the left to the right in the tactile pad shown in Figure 6 c).



α= 0.1, β=0.6, m=600, σ=200

Fig. 7 Example of signals generated by PPDF

4.3 Tactile glove for displaying tactile sensations in tacto-gestural interaction

An augmented reality (AR) system was also constructed as shown in Fig. 8, in which user's gestural actions were recognized in realtime so that the user was able to interact with a 3D virtual object superimposed in a real environment through the visual and auditory information and the tactile sensation. The system consists of a computer, a head-mounted display (HMD), a pair of webcam, stereo speakers and a pair of tactile gloves. User's gestures are captured by the stereo cameras mounted on the HMD, and the gestural actions are recognized in realtime. The tactile glove presents tactile sensation of a virtual object displayed in the HMD for establishing interaction with the virtual object.

For presenting various tactile sensations from a glove, nineteen SMA wires are stitched inside the glove to directly contact with the skin, where nine wires form a 3 x 3 array to contact to the palm and two wires are placed at the tip of each finger as shown in Fig. 9.

In the AR system called "PhantomTouch", a virtual penguin-like character or a robot character is walking on a user's palm. A user wears the HMD and the Tactile gloves, and interacts with the CG character by the hand gestures and gestural actions, while watching and listening the reactions of the character. In the initial state, the CG character is walking on the palm randomly in the area surrounded by the four color markers, and the user is able to feel the walking and stepping sensations and hears the sounds synchronizing with the character's location and walking behaviors.

The user is able to interact with the CG character by his gestural actions such as tilting the right hand, shaking the right hand and pinching the character with his left hand fingers. For example, if the right hand is tilted, the penguin starts to slip off from the palm, and the slipping sensations are presented from the glove. When the hand moves up and down largely, the penguin bounces up and down on the palm, and at the same time the jumping and hitting sensations are presented. The user is also able to pinch the character up in the air using the left hand fingers. While the character is pinched to move up, the user feels a pressing sensation on the inner surface of the thumb and index fingers. Then, in a couple of seconds, the character starts to slip off from the fingers, and the slipping sensations are displayed on the fingers.

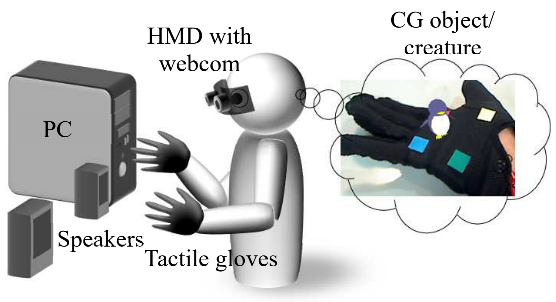


Fig. 8 AR interaction system with tactile gloves

Fig. 9 Tactile glove with 19 SMA actuators inside

5 Conclusions

The paper introduced the physical characteristics of a SMA wire caused by the shape-memory effect and the pseudoelasticity, and the novel applications to the tactile actuators and the micro-force sensors with high sensitivity were presented. With the application of properly prepared pulse-current to a SMA wire, micro-vibration with the controlled frequency up to several hundred hertz is generated. The SMA wires, on the other hand, works for micro-force sensors, and a tactile sensing device has been developed to classify different textures by tracing on objects. We will continue to apply the SMA sensors/actuators to humanoid robots that recognize tactile sensation by effectively employing the properties of SMAs.

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