SHAPE MEMORY ALLOY VS SMART MATERIAL ACTUATORS

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1. Introduction

The category of traditional actuators includes three main technologies, namely, electromagnetic motors, pneumatic actuators and hydraulic actuators. There are new emerging technologies based on components of smart materials. Piezoelectric materials and Shape memory alloys (SMA) are among the best known smart structure. They are multi-functional structure, suitable not only for actuators.

Shape memory alloys belong to a class of shape memory materials, which have the ability to 'memorise' or retain their previous form when subjected to certain stimulus such as thermomechanical or magnetic variations. SMAs have drawn significant attention and interest in recent years in a broad range of commercial applications, due to their unique and superior properties. New study on SMAs, which was published [1], finds almost quadruple increase articles and U.S. patents per decade.

2. Smart materials

Smart materials are multi-functional, transitional materials that can undergo changes in properties in response to an external stimulus. Seven main energy domains are considered, namely: chemical, electrical, magnetic, mechanical, optical, fluid and thermal. Transduction can be found between any two of these energy domains. In addition, different transduction phenomena are possible for a given pair of energy domains [2].

Tab. 1. *Variables in transducer ports for various energy domains.*

Energy domain	Variables in transducer ports			
	Flow	f	Effort	E
Electric	Current	i	Voltage	V
Magnetic	Magnet. flux	Φ_m	Magnet. force	F_m
Thermal	Heat flow	h	Temperature	T
Fluid	Flow rate	q	Pressure	P
Mechanical translation	Velocity	v	Force	F
Mechanical rotation	Angul. velocity	ω	Torque	T

A transducer is a two-port device. Unless it is intended to transduce between different types of energy within the same domain, it has four terminals. Two conjugate variables (effort, E and flow, f) at each port define the power entering and leaving the transducer. A general scheme of this two-port device is shown in Fig. 1.

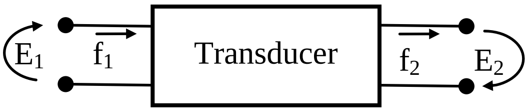

Fig.1: *Two-port transducer. E - Effort, f - flow.*

An actuator converts some form of input energy (typically electrical energy) into mechanical energy. An actuator can be seen as a system that establishes a flow of energy between an input (electrical) port and an output (mechanical) port. The actuator is transducing some sort of input power into mechanical power. Some actuators, for example rheological fluids, are semi active, it can only dissipate the energy of the plant.

Transduser phenomena is described in [2] for emerging actuator technologies. The transducer from the traditional concept of the actuator and sensor can be extended to energy harvesters. Smart materials have function of actuator, sensor or energy harvester. In many cases, the combination of these functions is possible in one device.

In the literature [2-4] are smart materials usually grouped into several categories.

Electroactive ceramics (EAC): Piezoelectic materials and electrostrictive materials; Feroelectric Shape Memory (SM) ceramics; Viscoelastic and martensitic SM ceramics

Smart alloys (SMA): Shape memory alloys, SMA; Magnetic SMA and Feromagnetic SMA; Magnetostrictive materials.

Electroactive polymers (EAP): Shape Memory Polymers, SMP; Ferroelectric Polymers and Conductive Polymers; Electrostrictive Graft Elastomers; Dielectric Elastomers; Liquid Crystal Elastomers, LCE*;* Ionic Electroactive Polymers, and Ionic Gels.

There are many other smart systems, for example: Active fiber composites, electroactive and electrochemical fluids, intelligent optical materials (color change), intelligent plasticine (plastic-elastic-brittle), etc.

In order to move closer properties of the smart materials, will be presented to selected materials [5]. Comparison groups by technology of smart materials: shape memory alloys (SMA), electroactive polymers (EAP) and electroactive ceramics (EAC) are in Tab. 2.

Tab. 2. *Comparison groups of smart materials.*

Parameter	SMA	EAP	EAC
Strain [%]	3-5	30- 90	0,1 -0,3
Stress [MPa]	200-350	1 - 50	30-40
Delay [s]	0,1–10	10^{-6}–10	10^{-6}–1
Activation [V]	1 – 20	1-7	50- 800
Density [g/cm^3]	6-8	1-2,5	6-8
Energy density [J/m^3]	10^6-10^7	10^2-10^4	10^2-10^5

The *SMA actuators* cover slow actuators delivering high force. Electrical Joule heating is commonly used to activate SMAs. Shape memory alloys enable development of simple, very compact, reliable actuators that can be integrated into components and structures.

Magnetostriction and piezoelectricity are characterized by high-force, relatively low stroke actuators with attainable frequency bandwidths up to several kilohertz. *Magnetostrictive actuators* are mostly suited to active vibration control applications. There are many successful types of *piezoelectric actuators*, which have wide practical application.

The maximum relative stroke exhibited by *electroactive polymers (EAP) actuators* is larger than that of any other actuator technology. It may be as large as 300–400% in the case of *dielectric elastomer actuators* (both silicone and acrylic based) or as low as 5% in the case of *conductive polymers (CP) actuators*. The stress attainable by EAP actuator technology is high in the case of *CP actuators* (of the order of 50 MPa) and low in all the other technologies (up to 1 MPa).

Four aspects for creation of a smart material actuator:

1. Existence of a suitable transducer of smart material which efficiently converts energy (especially electrical) into mechanical domain.
2. Suitable (electro-thermal-mechanical) construction.
3. Electronics for controlling power input to the smart material. Electronics for feedback (sensors).
4. Control system with sufficient a priori information (model).

3. SMA Actuator

The considered SMA actuator is heated by electrical resistance heating and cooled by natural air cooling. The complex model is based on the physical and empirical behavior of the Ni-Ti alloy straight wire actuator with preloaded steel spring. Generally, the designed SMA actuator model consists of non-linear static and dynamic parametric differential equations with several internal feedback loops. Significant feature of SMA materials is a complex hysteresis with a memory.

3.1. Mathematical model of the SMA Actuator

Basic state variables of model are temperature T, mechanical stress σ, strain ε and rate of phase transformation, called fraction of martensite X. The input variables of model are thermal power P or electric current i, the ambient temperature T_0, mechanical stress σ_L in the form of force F_L acting in the longitudinal axis of the actuator. The thermo mechanical behavior of SMA is described using the Tanaka's equation [6]

$$d\sigma = D_X d\varepsilon + \Theta dT + \Omega dX \qquad (1)$$

where D_X, Θ, and Ω are elastic modulus, thermo-coefficient, and phase-transformation coefficient of SMA, respectively; in general, the elastic modulus of the SMA is nonlinear, and different for austenite (D_A) and martensite (D_M). To derive the modified model, the SMA elastic modulus has been approximated as follows

$$D_X(X) = D_A - (D_A - D_M)X \qquad (2)$$

The curve in Fig. 2 demonstrates total change from the Martensite M (X=1) to the Austenite A (X=0) and the same total reverse change back to martensite. Transformation temperatures A_F, A_S, M_S, M_F are decisive for the shape of hysteresis curve. Smaller (internal) hysteresis loop in Fig. 3 is formed under the condition of unfinished change from M to A (MA), and from A to M (AM), respectively. The thermal hysteresis can be approximated by the following two equations [7]: from M to A Eq.(3) and back from A to M Eq.(4).

$$X_{MA} = 0.5X_{0AM}(\cos(K_A(T - A_S - \sigma/C_A)) + 1) \qquad (3)$$

$$X_{AM} = 0.5(1 - X_{0MA})\cos(K_M(T - M_F - \sigma/C_M)) + (1 + X_{0MA})/2 \qquad (4)$$

where $K_A = \pi/(A_F - A_S)$ and $K_M = \pi/(M_S - M_F)$ are material coefficients.

X_{0MA} and X_{0AM} are initial martensitic fractions of the internal loop representing *the alloy memory* localized in points of motion reversal, Fig. 3.

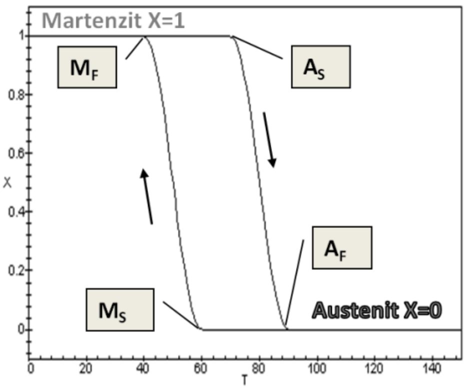

Fig.2: *Thermal hysteresis under stress-free condition.*

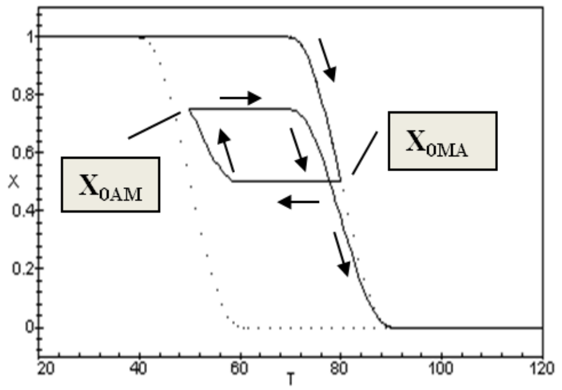

Fig.3: *Internal hysteresis loop with a memory which represent X_{0MA} and X_{0AM} in the points of motion reversal.*

The SMA material coefficients C_A and C_M are related to the *stress-induced phase transformation* called “stress rate”. Induced martensite arises under mechanical load and acts in opposite direction to the temperature. Induced martensite shifts the transformation temperatures A_F, A_S, M_S, M_F to higher values: $A_S=A_{S0}+\sigma/C_A$, $A_F=A_{F0}+\sigma/C_A$, $M_S=M_{S0}+\sigma/C_M$, $M_F=M_{F0}+\sigma/C_M$ and causes displacement of the whole hysteresis curve; A_{F0}, A_{S0}, M_{S0}, M_{F0} are transformation temperatures under stress-free conditions.

According to [5], [8] *electrical heating and natural air cooling* are described as follows

$$C_T\, dT/dt + \Delta L_H\, dX/dt = i^2 R_E - (T - T_0)/R_T \qquad (5)$$

where ΔL_H, R_E, C_T and R_T are latent heat of phase transformation, electric resistance, thermal capacity and thermal resistance of the NiTi wire, respectively. The “thermal” time constant $\tau'=C_T\,R_T$ of the actuator usually dominates the dynamics of the model. It is also assumed that the temperature field along the NiTi wire actuator is free of malformations. Note that due to thermal conduction to the clamp, the NiTi wire near the clamp is often more cooled than the rest of the wire, and the actuator can lose power and other characteristics in this part [9].

Dynamics of motion with a return spring load is described by the equation

$$F_L - \sigma S_0 = m l_0\,(d^2\varepsilon/dt^2) + C_v\, l_0\, d\varepsilon/dt + C_{sp} l_0\, \varepsilon \qquad (6)$$

where C_{sp} and C_v are coefficients of spring stiffness and viscous friction, respectively, l_0, S_0 are length and cross-section of NiTi wire, m is mass, F_L is load force which includes preload (bias) of the spring [5].

3.2. Main features of SMA actuators

SMA has excellent force-to-weight ratio and excellent power-to-weight ratios. It generates movement without the use of gears. It is quiet, without lubrication. SMA works only in one direction, so it needs the return mechanism. The weakness of the SMA actuators is their slow response to cooling. At the same time, cooling is the most significant disturbance in the SMA actuator regulation. On the contrary, when heated, the SMA is able to achieve a short delay (0.1 s). Most SMA applications are of on-off control type.

The disturbance and the dependence on the history (especially on reversing points) of the SMA actuator inputs are the reasons why position control of SMA actuators without sensors in feedback cannot be achieved. In general, the SMA actuator is necessary to control with a hybrid control system that combines logic control (to switch according the direction and according phase transformation) and continuous control by using the nonliner model and feedback. For the SMA actuator with thermal hysteresis the basic control objective is to achieve overshoot-free robust regulation of position. If overshoot occurs, the settling time has to be extended significantly because it has to cross the temperature hysteresis loop, Fig. 3; crossing the hysteresis loop shows as a time delay.

4. Conclusion

Piezoelectric materials and shape memory alloys are among the best known smart structure. The original SMA actuator model is derived from the laws of physics. The model comprises dominant thermal hysteresis with memory, and variable elastic modulus. Hysteresis is approximated by trigonometric functions and depends on the martensite fraction. Benefit of the presented model is in understanding of SMA drives behavior through the physical and mathematical relationships. The developed model is also starting-point for design of the actuator control. Given the complexity of the model and the effect of various physical quantities and disturbances cannot be achieved position control of SMA actuators without sensors in feedback. These sensors and the necessary additional technical measures may yet to hamper wide practical application of SMA actuators.

Emerging smart material actuators have a wide application potential and complement the traditional ones. Emerging and traditional actuators should be seen as complementary rather than competing device.

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