Principles of Active Vibration Control: Shape Memory Alloy

Introduction:

Metals are characterized by physical qualities as tensile strength, malleability and conductivity. In the case of shape memory alloys, we can add the anthropomorphic qualities of memory and trainability. Shape memory alloys exhibit what is called the shape memory effect. If such alloys are plastically deformed at one temperature, they will completely recover their original shape on being raised to a higher temperature. In recovering their shape the alloys can produce a displacement or a force as a function of temperature. In many alloys combination of both is possible.

The metals change shape, change position, pull, compress, expand, bend or turn, with heat as the only activator. Key features of products that possess this shape memory property include: high force during shape change; large movement with small temperature change; a high permanent strength; simple application, because no special tools are required; many possible shapes and configurations; and easy to use - just heat. Because of these properties shape memory alloys are helping to solve a wide variety of problems. In one well–developed application shape memory alloys provide simple and virtually leakproof couplings for pneumatic or hydraulic lines. The alloys have also been exploited in mechanical and electromechanical control systems to provide, for example, a precise mechanical response to small and repeated temperature changes. Shape memory alloys are also used in a wide range of medical and dental applications (healing broken bones, misaligned teeth etc.).

First observations of shape memory behaviour were in 1932 by ¨ Olander in his study of “rubber like effect” in samples of gold–cadmium and in 1938 by Greninger and Mooradian in their study of brass alloys (copper–zinc). Many years later (1951) Chang and Read first reported the term “shape recovery”. They were also working on gold–cadmium alloys. In 1962 William J. Buehler and his co–workers at the Naval Ordnance Laboratory discovered shape memory effect in an alloy of nickel and titanium. He named it NiTiNOL (for nickel–titanium Naval Ordnance Laboratory). Buehler’s original task was finding a metal with a high melting point and high impact resistant properties for the nose cone of the Navy’s missile SUBROC. From among sixty compounds, Buehler selected twelve candidates to measure their impact resistance by hitting them with hammer and noted that a nickel–titanium alloy seemed to exhibit the greatest resistance to impact in addition to satisfactory properties of elasticity, malleability and fatigue. One day he took some NiTiNOL bars from melting furnace and laid them out on a table to cool. He intentionally dropped one on the floor out of curiosity. The bar produced a bell–like quality sound. Than he ran to the fountain with cold water and chilled the warm bar. The bar was once again dropped on the floor. On his amazement it exhibited the leaden–like acoustic response. Buehler knew that acoustic damping signalled a change in atomic structure that can be turned off and on by simple heating and cooling near room temperature, but he did not yet know that this rearrangement in the atomic structure would lead to shape memory effect.

It was in 1960 when Raymond Wiley joined Buehler's research group. He worked on failure analysis of various metals. He demonstrated to his management the fatigue resistance of a NiTiNOL wire by flexing it. The directors who were present at this meeting passed the strip around the table, repeatedly flexing and unflexing it and were impressed with how well it held up. One of them, David Muzzey, decided to see how it would behave under heat. He was a pipe smoker, so he held the compressed NiTiNOL strip in the flame of his lighter. To the great amazement of all, it has stretched out completely. When Buehler heard about that, he realized that it had to be related to the acoustic behaviour he had noted earlier. After this moment, NiTi alloys increased interest of developing applications based on a shape memory alloys.

Definition of a Shape Memory Alloy

Shape memory alloys are a unique class of metal alloys that can recover apparent permanent strains when they are heated above a certain temperature. The shape memory alloys have two stable phases - the high–temperature phase, called austenite (named after English metallurgist William Chandler Austen) and the low–temperature phase, called martensite (named after German metallographer Adolf Martens).

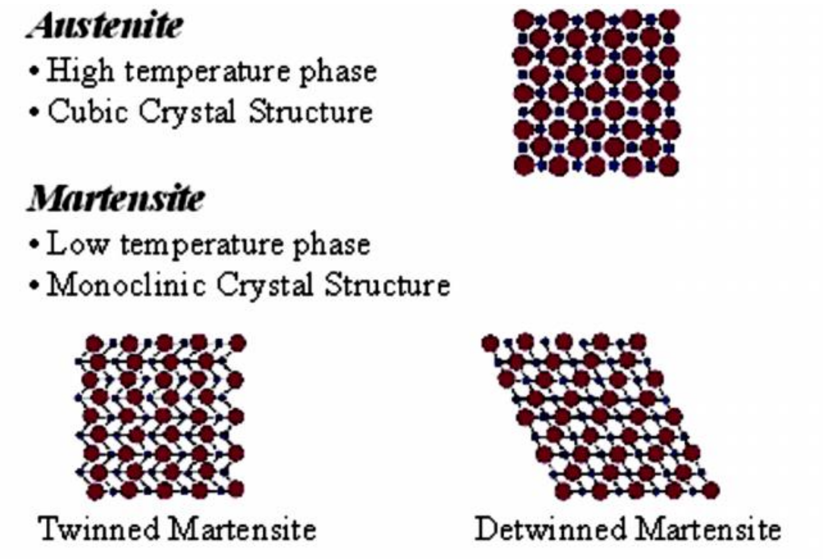


Fig 8.42 Different phases of a shape memory alloy.

The key characteristic of all shape memory alloys is the occurrence of a martensitic phase transformation which is a phase change between two solid phases and involves rearrangement of atoms within the crystal lattice. The martensitic transformation is associated with an inelastic deformation of the crystal lattice with no diffusive process involved. The phase transformation results from a cooperative and collective motion of atoms on distances smaller than the lattice parameters. Martensite plates can grow at speeds which approach that of sound in the metal (up to 1100m/s). Together with fact, that martensitic transformation can occur at low temperatures where atomic mobility may be very small, results in the absence of diffusion in the martensitic transformation within the time scale of transformation.

The absence of diffusion makes the martensitic phase transformation almost instantaneous (a first-order transition). When a shape memory alloy undergoes a martensitic phase transformation, it transforms from its high–symmetry (usually cubic) austenitic phase to a low symmetry martensitic phase (highly twinned monoclinic structure). NiTiNOL's high temperature phase has B2 crystal structure and its low temperature phase has B19' crystal structure. If one ignores the difference between Ni and Ti atoms, B2 crystal structure is simply body–centred cubic and B19 has the same symmetry as hexagonal–close packed, except that the two species of atoms break hexagonal symmetry making the structure to tetragonal. B19' is a small distortion from B19. See Figure 8.43.

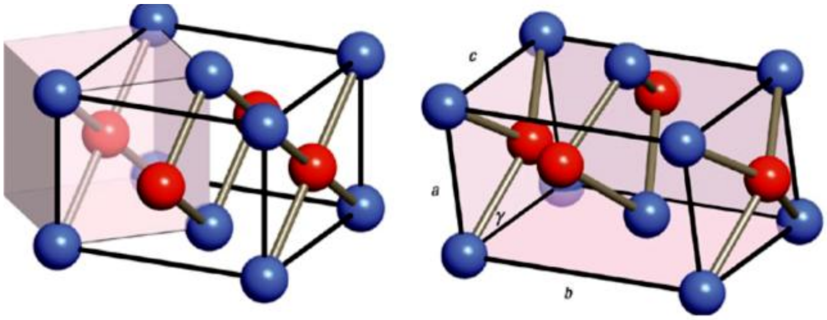


Figure 8.43: The cubic B2 cell (shaded box) of NiTi (left). The distortion to the stress–stabilized B19’ structure (right). Structural parameters for B2 structure are a = 2.949 °A, b = 4.171 °A, c = 4.171 °A and = 90_; structural parameters for B19’ structure are a = 2.861 °A, b = 4.600 °A, c = 3.970 °A and = 97.8 [9].

A feature of all martensitic transformations is that there are number of equivalent shear directions through which the martensite can form within a region of parent–phase. This results in the formation of martensite variants within the microstructure of a transformed alloy. In Figure 1 at twinned martensite phase, we can see two crystallographically equivalent martensite variants created by different atomic shears from the parent phase. Two opposite shears maintain the macroscopic shape of the crystal block. Such a microstructure, where the shear of one variant is accommodated or “cancelled” by that of the other is known as a self–accommodated structure. Three–dimensional self–accommodation requires a large number of variants (typically up to 48 in many alloys).

Upon cooling without of applied load the material transforms from austenite into twinned martensite. With heating twinned martensite, a reverse martensitic transformation takes place and as a result the material transforms to austenite. This process is shown in Figure 8.44. There are four critical temperatures defined. Martensitic start temperature (Ms) which is the temperature at which the material starts transforming from austenite to martensite. Second is martensitic finish temperature (Mf), at which the transformation is complete and material becomes fully in the martensitic phase. Similar temperatures are defined for reversible transformation. Austenite start temperature (As) is the temperature at which the reverse transformation starts and austenite finish temperature (Af) at which the reverse transformation is finished and the material is in the austenitic phase.

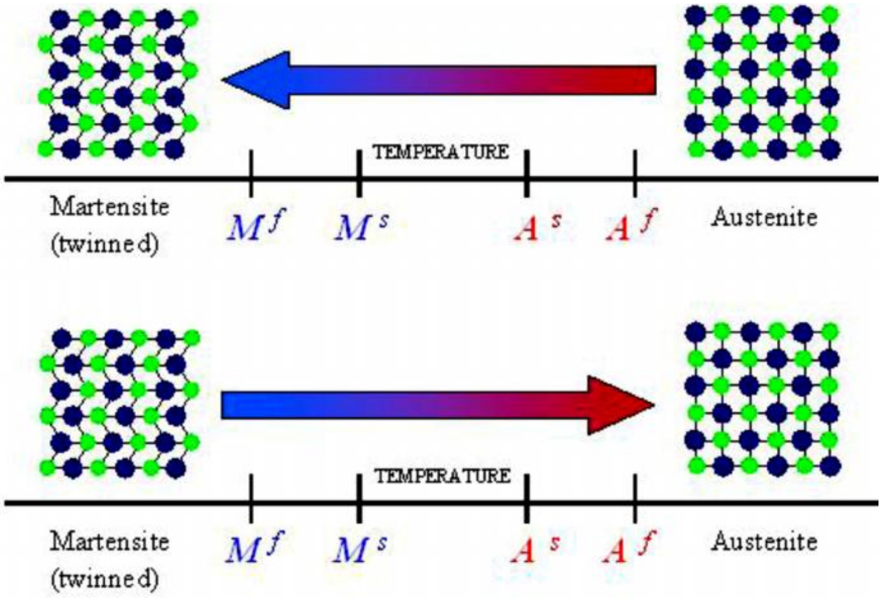


Figure 8.44: Temperature–induced phase transformation of a shape memory alloy without mechanical loading [8].

We get hysteresis curve for a thermoelastic martensitic transformation as seen on Figure 8.44. The overall hysteresis between forward and reverse transformation pathways in shape memory alloys is small, typically between 10 and 50 _C. Thermoelastic martensitic transformations form the basis of shape memory alloys behaviour and can be repeated indefinitely as long as high temperature excursions are avoided.

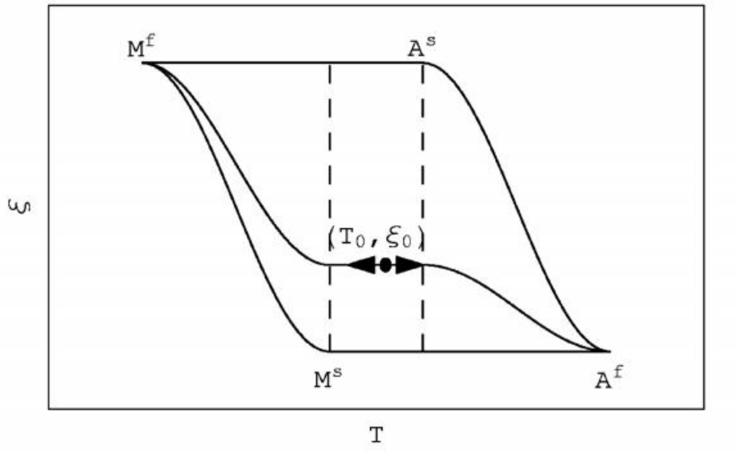


Figure 8.45: Hysteresis curve for a thermoelastic martensitic transformation. _ denotes the fraction of martensite in the material, ξ0 and T0 are prescribed initial conditions. They represent a condition that the material contains some martensite (ξ0) and some austenite (1 − ξ0) at a temperature T0.

Applications for Shape Memory alloys

Bioengineering:

Bones: Broken bones can be mended with shape memory alloys. The alloy plate has a memory transfer temperature that is close to body temperature, and is attached to both ends of the broken bone. From body heat, the plate wants to contract and retain its original shape, therefore exerting a compression force on the broken bone at the place of fracture. After the bone has healed, the plate continues exerting the compressive force, and aids in strengthening during rehabilitation. Memory metals also apply to hip replacements, considering the high level of super-elasticity. The photo above shows a hip replacement.

Reinforcement for Arteries and Veins: For clogged blood vessels, an alloy tube is crushed and inserted into the clogged veins. The memory metal has a memory transfer temperature close to body heat, so the memory metal expands to open the clogged arteries.

Dental wires: used for braces and dental arch wires, memory alloys maintain their shape since they are at a constant temperature, and because of the super elasticity of the memory metal, the wires retain their original shape after stress has been applied and removed.

Anti-scalding protection:

Temperature selection and control system for baths and showers. Memory metals can be designed to restrict water flow by reacting at different temperatures, which is important to prevent scalding. Memory metals will also let the water flow resume when it has cooled down to a certain temperature.

Fire security and Protection systems:

Lines that carry highly flammable and toxic fluids and gases must have a great amount of control to prevent catastrophic events. Systems can be programmed with memory metals to immediately shut down in the presence of increased heat. This can greatly decrease devastating problems in industries that involve petrochemicals, semiconductors, pharmaceuticals, and large oil and gas boilers.

Golf Clubs:

A new line of golf putters and wedges has been developed using_____. Shape memory alloys are inserted into the golf clubs. These inserts are super elastic, which keep the ball on the clubface longer. As the ball comes into contact with the clubface, the insert experiences a change in metallurgical structure. The elasticity increases the spin on the ball, and gives the ball more "bite" as it hits the green.

Helicopter blades:

Performance for helicopter blades depend on vibrations; with memory metals in micro processing control tabs for the trailing ends of the blades, pilots can fly with increased precision.

Eyeglass Frames:

In certain commercials, eyeglass companies demonstrate eyeglass frames that can be bent back and forth, and retain their shape. These frames are made from memory metals as well, and demonstrate super-elasticity.

Tubes, Wires, and Ribbons:

For many applications that deal with a heated fluid flowing through tubes, or wire and ribbon applications where it is crucial for the alloys to maintain their shape in the midst of a heated environment, memory metals are ideal.

Shape Memory Alloys

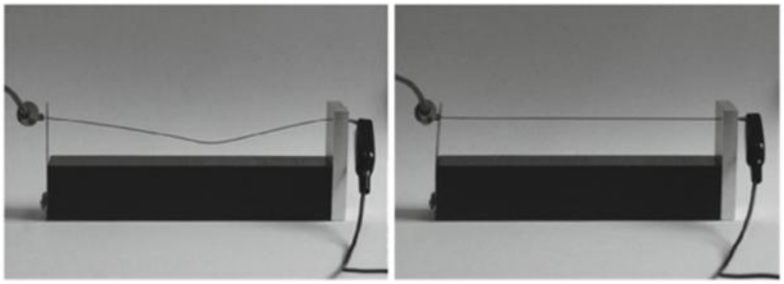
Shape memory alloys (SMA) demonstrate apparent plastic deformation and recovery to the original shape after heating. SMA can recover as much as 5% strain, which compared to materials like piezoceramics is a considerable shape change. The main advantage of this type of smart material is the ability to perform complex movements with few elements. The shape change and the resulting movement can be achieved by a small temperature change, and causes the SMA to undergo a type of solid state phase transformation. This change is the so-called martensitic deformation in metals. Shape memory alloys may be used to supply energy to systems with very slow dynamics and thus induce vibrations, effectively creating an active vibration control system. It is also common to utilize the SMA as a type of slowly changing adaptive part to form a semi-active vibration suppression system. Figure 8.46 illustrates the use of shape memory alloy materials to create slow-speed morphing wing surfaces on aircraft and SMA-wire based linear motors.

SMA Materials and Properties

The most common SMA material is an alloy of nickel and titanium, which is often referred to as nitinol. In the nickel and titanium (NiTi)-based alloys, the two elements are present in approximately equal atomic percentages. Several other alloys exist of which we list FeMnSi, copper-based alloys such as CuZnAl or CuAlNi and some. This nickel and titanium alloy was discovered and developed by Buechler et al. In 1963 at the U.S. Naval Ordnance Laboratory, thus the name is NiTiNOL. The advantage of NiTi-based SMA is its high electric resistivity, thus allowing the material to be rapidly heated upon the application of electric current.

Shape memory alloys present two interesting macroscopic properties, these are:

- superelasticity
- shape memory effect



(a) A wing-like SMA demonstration device **(b)** SMA based actuators

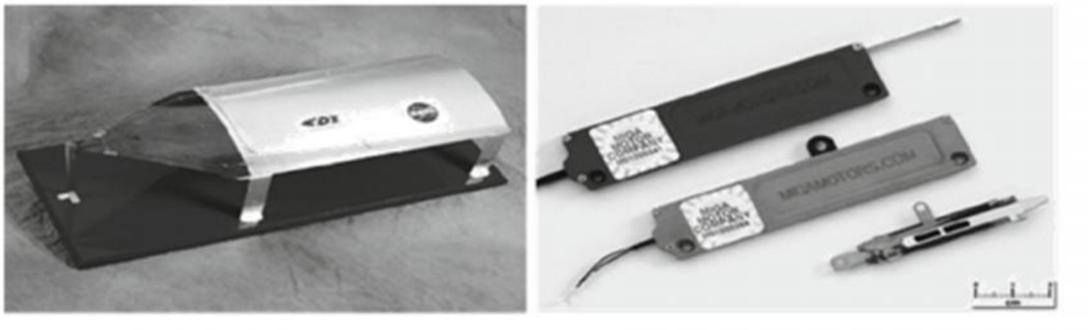
Fig. 8.46 A SMA-based demonstration device resembling an aircraft surface is featured in (**a**) [78], while (**b**) shows small actuators in a linear motor mode based on SMA wires [6]

The former, super-elasticity is the ability of this type of material to return to its original shape after a considerable amount of mechanical stress and deformation. This process needs no temperature change to be completed, and it is called the mechanical memory effect. Elasticity is approximately 20 times higher than other elastic metallic materials [6]. Objects manufactured from the superelastic version of nitinol find their application mainly as medical instruments, there are several laboratory experiments investigating the use of superelastic (austenitic) nitinol as means for passive vibration damping.

The latter property is more interesting for the control community, as nitinol can be effectively used as an actuator. Because of the shape memory effect or the thermal memory effect, the plastically deformed SMA material returns to its original memo-rized shape after applying a small amount of heat as illustrated in Fig. 8.47. The defor-mation is not limited to pure bending as in bi-metallic structures, but may include tensional and torsional deformations or their mixtures [6]. A 4 mm diameter nitinol wire may lift even a 1000 kg load; however, it will lose its memory effect because of this large loading. To prevent this, a load limit is usually enforced, for example, in this case a 150 kg load would not induce a loss of the memory effect while still being a very high force output [6]. Enforcing such load limits to prevent the loss of the memory effect call for control systems encompassing constraint handling for which model predictive control (MPC) is an ideal candidate.

Stress, Strain and Temperature

Both the superelastic and shape memory effects are due to a phase change from *austenite*, which is the higher temperature and stronger phase, to *martensite* which is the lower temperature and softer phase. Unlike the phase changes that come to mind like the change from solid to liquid and gas, this is a solid phase change. The austenitic solid phase is stable at elevated temperatures and has a strong body centered cubic crystal structure. The martensitic phase has a weaker asymmetric parallelogram structure, having up to 24 crystal structure variations.



(a) SMA wire prior to activation **(b)** SMA wire after activation

Fig. 8.47 An SMA wire is placed in between a spring steel blade and a rigid aluminum clamp. The wire is loose prior to activation as shown in (**a**). Due to the applied current (9 V battery) the wire temperature is raised above the activation temperature. The wire regains its original straight shape in (**b**) and exerts a force, which is enough to deform the spring steel

When martensitic nitinol is subject to external stress it goes through different variations of the possible crystal structures and eventually settles at the one allowing for maximal deformation. This mechanism is called *detwinning*. There are four temperatures characterizing the shape memory effect of SMA:

- M_f : martensite finish—this is the lowest temperature, below all of the material has the soft martensitic structure

- M_s : martensite start—an intermediate temperature, when the martensite phase starts to appear in the prevalently austenitic phase

- A_s : austenite start—an intermediate temperature, when the austenite phase starts to appear in the prevalently martensitic phase

A_f : austenite finish—this is the highest temperature, above which all of the material has the hard martensitic structure. Superelastic SMA are designed to work over this temperature, while the thermal-induced memory effect finishes at this temperature.

These temperature characteristics and limits may be set upon manufacturing the alloy. For example, it is possible to create an alloy with a reshaping temperature close to the normal temperature of the human body. For the case of uniaxial loading, the stress–strain curve for SMA is denoted in Fig. 8.48 [7]. The curve shows a pseudoelastic behavior, where the applied load takes the material from the austenite phase to the martensite phase along the upper curve. This is the stress-induced super-elastic behavior of austenitic nitinol, therefore we may state that the temperature here is a constant $T > A_f$. The reverse transformation occurs in unloading the SMA material, when the material transforms from martensite into austenite along the lower curve, thus forming a hysteresis loop [7]. In Fig. 8.48, ε denotes strain, σ denotes stress. Martensite starts to form at M_s and finishes at M_f, while the austenite starts to form at A_s and finishes at A_f.

The dashed line in Fig. 8.48 denotes a scenario, where the SMA is subject to a temperature change in constant stress. Note, however that the phase change start and finishing temperatures are linearly dependent on the loading stress. Temperature is marked by T while stress is σ.

Finally, Fig. 8.48 illustrates the percentual composition of martensite and austenite phases in a temperature-induced martensitic deformation. The curve starts from below the low temperature M_f and takes the right side of the hysteresis path. At a certain A_s temperature the phase change to austenite begins, while the martensite composition decreases. Eventually the material gets to the A_f temperature where 100% of it is converted into the austenite phase. Shape setting of an SMA actuator can be done in a high temperature oven. The heat treatment is performed in two steps: first the material is constrained into the desired.

SMA in Vibration Control

The free and/or forced vibration behavior of plates and other structures with embedded SMA materials is studied using analytic or FEM methods in. The cited works focus on modeling issues for the need of optimal design for classical vibration response manipulation, without actively controlled components. The inclusion of SMA elements in plates, beams and other mechanisms can be understood as a form of semi-active control. SMA has been already considered as passive or semi-active vibration damping devices in civil engineering structures.

Although several models have been proposed for SMA, the constitutive description of the complex pseudoelastic and shape memory effect phenomena cannot be developed by classical plasticity theory. Models based on the nonlinear generalized plasticity have been successfully applied for SMA [7]. SMA as an actuator is suitable for low frequency and low precision applications; therefore, their usage in active vibration attenuation applications is questionable.

It is interesting enough to note that SMA can also be used as a type of sensor. The work of Fuller et al. pointed out that embedded SMA wires in a Wheatstone configuration may give accurate estimation of strain levels due to oscillations in a beam [6]. The use of SMA as sensors is, however, atypical as piezoelectric or resistance-wire based sensors are also cheap and readily available. Active vibration control is proposed utilizing an SMA actuator in [5]. Here, the temperature of the SMA is manipulated to change mechanical properties. The wire and the plates on the *left* are set to a straight shape, while the darker plate is memorized to a curved shape. Vibration damping is achieved combining active and passive methods. In a review article Bars et al. lists shape memory alloys as a particularly interesting tool for smart structures and states the need for advanced control algorithms such as MPC to tackle issues such as multi-point inputs and outputs, delays and possibly actuator nonlinearity [8].

Shape memory alloy materials are utilized in [7] for vibration damping purposes. According to the step response of the material, upon the application of a constant current jump the SMA wire exerts force, which can be approximated according to a first order response [7]:

$$T_c \frac{df(t)}{dt} + f(t) = i(t) \qquad (8.17)$$

where the force exerted by the SMA wire is denoted by f (t), the actuating current by i (t) while Tc is the time constant of the first order transfer. The temperature in an SMA wire actuator is approximately linearly dependent on the applied current [7]. Unfortunately, the time constant is different in the heating and cooling cycles [8]. The time constant is also highly dependent on the prestrain applied to the wire. Because of these parameter variations it is likely that an MPC control-based SMA system would require the explicit handling of model uncertainties. The above cited work of Choi et al. utilized sliding mode controlled nitinol wires to damp the first modal frequency of a building-like structure in the vicinity of 5 Hz, providing certain basis to use SMA for lightly damped structures with a low first resonant frequency. Here, the time constant was approximated to be 125 ms that would indicate an approximately 8 Hz bandwidth.

A very interesting possibility is utilizing an adaptive passive approach instead of actively controlling the vibration amplitudes, velocities or accelerations. Using a structure or mechanism with integrated SMA parts, one could tune its vibration frequency in real-time according to the outside excitation [6]. By this method, the resonant frequency of the structure could actively adapt to the quality and character of the measured outside excitation. Using the idea an actively controlled steel structure has been presented in [6]. The resonant frequency of the structure could be shifted about 32% of its nominal value through the application of heat into the SMA.

An overview of the civil engineering applications of SMA materials is given in [7]. John and Hariri investigate the effect of shape memory alloy actuation on the dynamic response of a composite polymer plate in [7]. The work examines the stiffness change and thus the shift of natural frequencies in a composite plate both in simulation and in experiment, founding a basis for the future application of SMA-enhanced active materials for vibration attenuation. Spools of SMA wire with different diameters are illustrated in Fig. 8.48a, while an SMA actuated F-15 aircraft inlet is shown[5] in Fig. 8.48b.

(a) SMA wire (b) SMA actuated F-15 inlet

Fig. 8.48 Spools of shape memory alloy wires with different diameters are shown in (**a**), while (**b**) shows a full-scale F-15 inlet (modified flight hardware) with integrated shape memory alloy actuators installed in the NASA Langley Research Center 16-foot Transonic Tunnel [81]

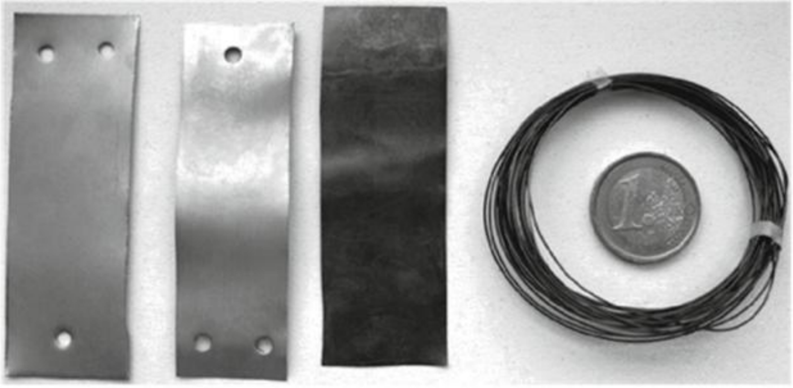


Fig. 8.49 SMA materials can be memorized to different shapes. The wire and the plates on the left are set to a straight shape, while the darker plate is memorized to a curved shape

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