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Shape Memory Actuators for Automotive Applications

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Shape Memory Actuators for Automotive Applications

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Abstract

With the better understanding of the metallurgy and more open discussion within the scientific community, shape memory actuators are becoming increasingly popular for automotive applications. This paper surveys current and potential uses.

Actuators are devices which perform a task, like moving an object, either on demand or in response to certain changes in their environment (temperature, pressure, etc). In a modern car more than 100 actuators are used to control engine, transmission and suspension performance, to improve safety and reliability and enhance driver comfort. Most of these actuators today are electric motors, solenoids, thermobimetals, wax motors, vacuum or pressure actuators.

Shape memory actuators have not yet penetrated this growing market significantly. This is due in part to low market awareness about shape memory technology, as well as little engineering data for the alloys. However, as the scientific community comes to understand the metallurgy and discuss it more openly, shape memory actuators are becoming increasingly popular for automotive applications. Japan, which leads in this area, has an impressive number of patent applications. About 100 patents for automotive applications are filed annually in Japan, outnumbering American and European applications by an order of magnitude. Japan not only leads in the development of new applications, but also in their commercialization (Refs 1-8). Shape memory actuators are also produced commercially in Europe, but no base businesses are known in the United States. This is even more astonishing, as Ni-Ti alloys have been developed in the United States and used for over 20 years (mainly in the aerospace industry).

Design principles

There are only two commercially available groups of shape memory alloys for actuator applications today, the Cu-Zn-Al alloys and the Ni-Ti alloys. For automotive applications, Ni-Ti is preferred because of a number of advantages like high strength, high electrical resistivity, large recovery strains, easy workability, and excellent corrosion resistance. Therefore, in the following, we will focus on Ni-Ti alloys only.

The design of shape memory actuators is generally based on the different stress-strain curves of the material in its austenitic and martensitic condition. Although two-way shape memory actuators are available, most applications use the one-way effect with an external reset force. Figure 1 shows the schematic load / deflection diagrams for shape memory springs working against a constant force (load) and against a bias spring. Work against a biasing or reset spring is the most common case in automotive actuator applications.

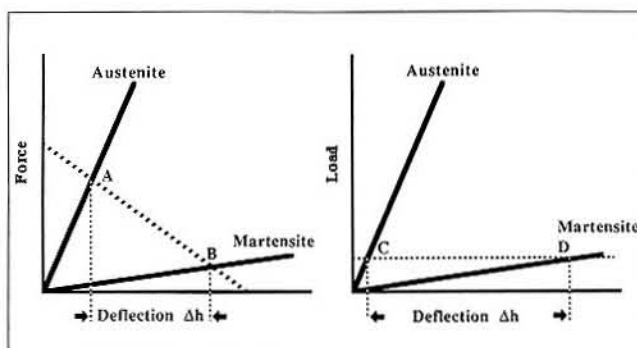


Fig 1 Design principle for shape memory actuators (left: work against bias spring; right: work against constant force)

Shape memory actuators can be used in two basically different ways: as thermal or as electrical actuators. *Thermal actuators* combine the sensing and the actuating functions, responding to a temperature change by changing shape and/or generating a force. The function of *electrical actuators*, on the other hand, is simply to move an object or perform a task on demand. Usually, a current is passed through the shape memory actuator, internally heating it above A_f to recover its shape.

Thermal actuators

As mentioned earlier, thermal actuators respond to changes in temperature by changing their shape and/or generating a force. Shape memory actuators, in this area, generally compete with thermobimetals and wax motors, and sometimes with electric/electronic devices or vacuum/pneumatic systems. Thermal actuators have a variety of applications in cars. Figure 2 schematically shows areas of both potential and realized applications for shape memory thermal actuators.

There are three different temperature ranges, in which thermal actuators either are already used or could provide significant benefits:

- <0°C:
 - low temperature performance (engine, transmission, suspension, brakes)
- 0-60°C:
 - cold start performance
 - cold start performance
 - climate control

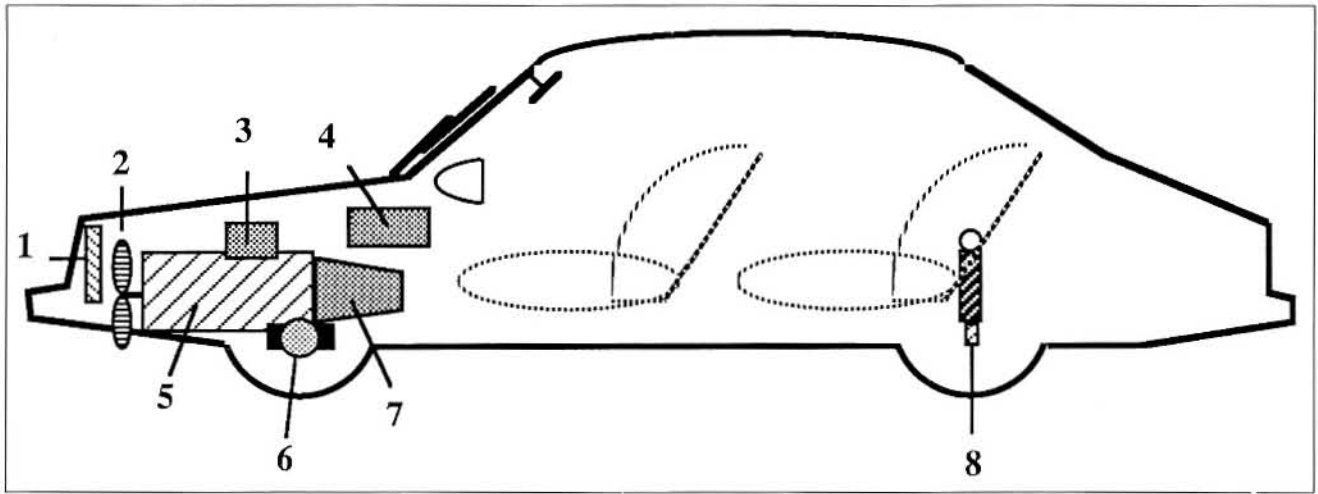


Fig 2 Potential applications of shape memory thermal actuators in automobiles: (1) radiator shutter; (2) fan clutch; (3) fuel management; (4) climate control; (5) engine control; (6) brake ventilation; (7) transmission control/rattling noise reduction; (8) suspension adjustment

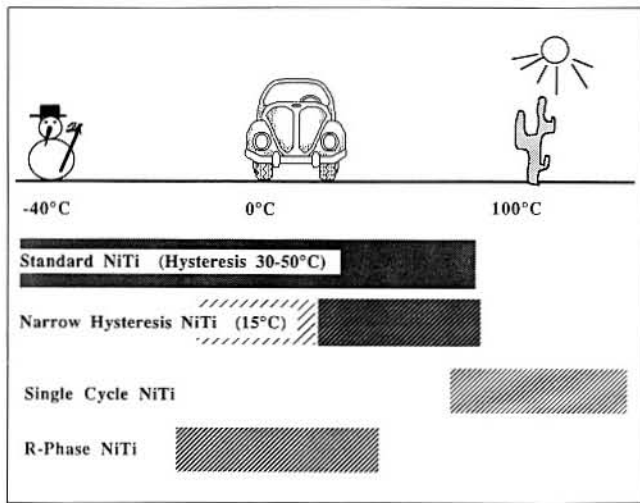


Fig 3 Range of transformation temperatures of commercially available Ni-Ti alloys

- 60–120°C:
- cooling systems (engine, brakes)
 - restart ability
 - climate control
 - rattling (engine, transmission)

Most of these temperature ranges can be covered by Ni-Ti shape memory alloys available today. However certain limitations, like transformation temperature ranges *versus* required number of cycles, hysteresis width, and stability, have to be considered. Figure 3 shows the transformation temperature ranges of the most common Ni-Ti alloys. For multiple cycle applications, standard binary Ni-Ti alloys with transformation temperatures from -50°C to approximately $+70^{\circ}\text{C}$ perform well. These alloys exhibit a hysteresis width of about 30 to 50 degrees and are reasonably stable during cycling. Binary alloys with higher transformation temperatures (up to $+120^{\circ}\text{C}$) tend to 'walk' and, therefore, can only be used for single or low cycle applications. Walking is usually defined as accumulated amnesia. It causes drifting of the zero-point during repeated actuation.

Most actuator applications require Ni-Ti alloys with both a narrow hysteresis and high stability of the shape memory effect. The hysteresis width of ternary and quaternary Ni-Ti-Cu alloys, with transformation temperatures from -30°C to $+70^{\circ}\text{C}$, is only about 15°C . They show excellent stability even after 100 000 thermal cycles. Another important advantage of Ni-Ti-Cu alloys is the low martensitic strength, which allows low reset forces and thus improved work output.

Unfortunately, presently available Ni-Ti alloys having transformation temperatures above 80°C are not sufficiently stable for multiple cycle applications. However for single cycle applications (eg over-temperature protectors) binary and ternary Ni-Ti alloys with transformation temperatures up to 150°C are available. Besides having the highest transformation temperatures, ternary alloys can provide high austenitic and martensitic strength.

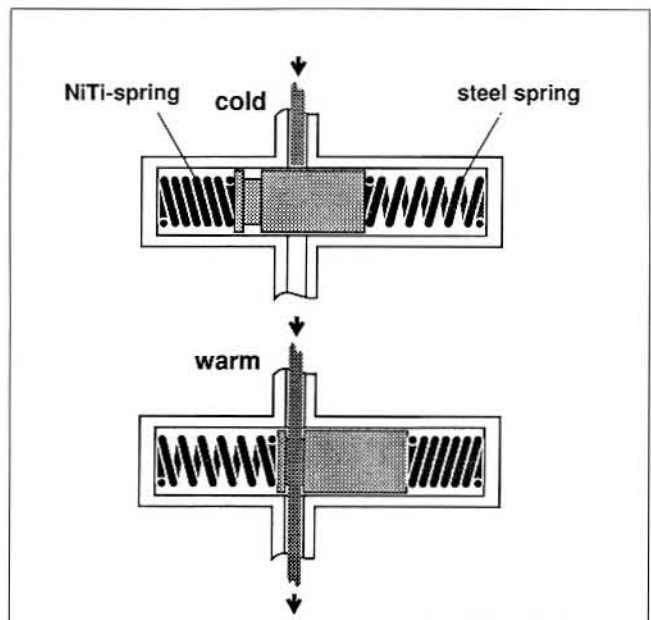


Fig 4 Function of a thermal valve

Patent literature proposes many applications for shape memory thermal actuators. One successful application is a temperature-sensitive governor valve, which controls the shifting pressure in automatic transmissions. This valve's function is shown schematically in Figure 4. At low temperatures, the spring force of a steel bias spring is higher than that of the Ni-Ti shape memory spring in the martensitic state. Consequently, the steel spring can compress the Ni-Ti spring, pushing the moveable piston of the valve into the 'closed' position for this particular application. When the temperature of the transmission and the transmission fluid increases to operating temperature, the Ni-Ti shape memory spring in the martensitic state expands, overcoming the steel spring force, and eventually, pushing the piston into the 'open' position. This pressure regulating valve improves the cold start performance of the transmission, allowing smoother shifting at low temperatures (Figure 5). Other shape memory governor valves control the warm-up phase of automatic transmissions, reducing smog emission and fuel consumption.

Figures 6 and 7 show two different versions of temperature-sensitive boost compensators, and Figure 8 a temperature-compensated valve lifter. Pressure actuators can acquire thermal response by incorporating shape memory springs into diaphragm-type pressure or vacuum actuators. The low temperature characteristics would therefore be different from the high temperature characteristics.

Another automotive application of shape memory thermal actuators, which has been described frequently in the patent literature, is using shape memory washers to reduce gearbox noise. The thermally reactive washers, either Belleville or wave-washers, are intended to compensate for the slackness in sprocket assemblies caused by the differential in thermal expansion of dissimilar materials, like aluminium and steel, when

temperature increases. Washers are useful because they provide very high forces for little motion during recovery. Figures 9 and 10 show examples.

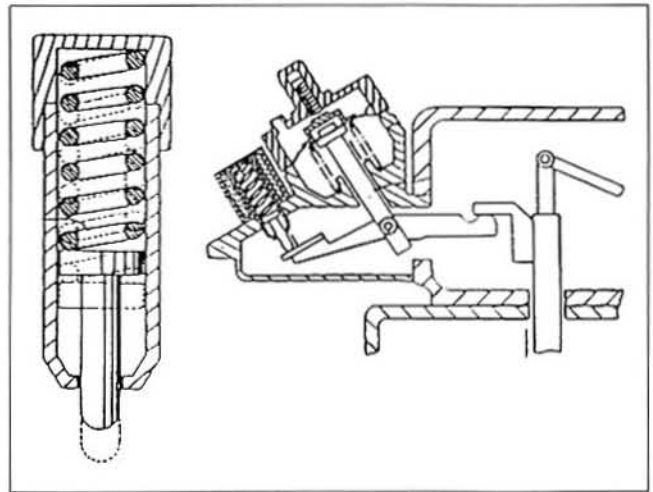


Fig 6 Temperature dependent boost compensator (Reference 1)

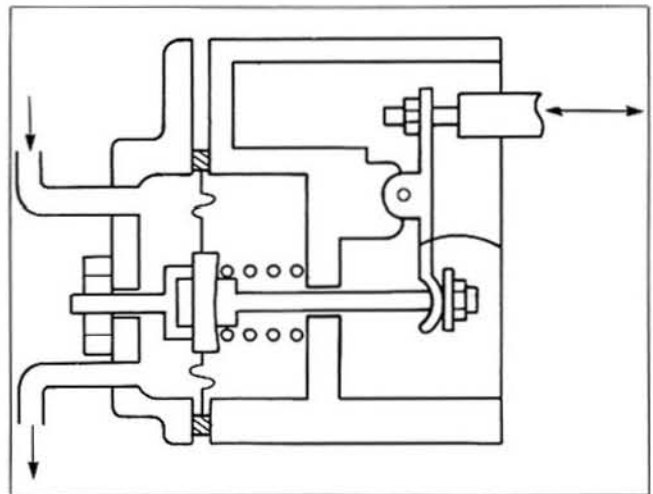


Fig 7 Temperature dependent boost compensator (Reference 2)

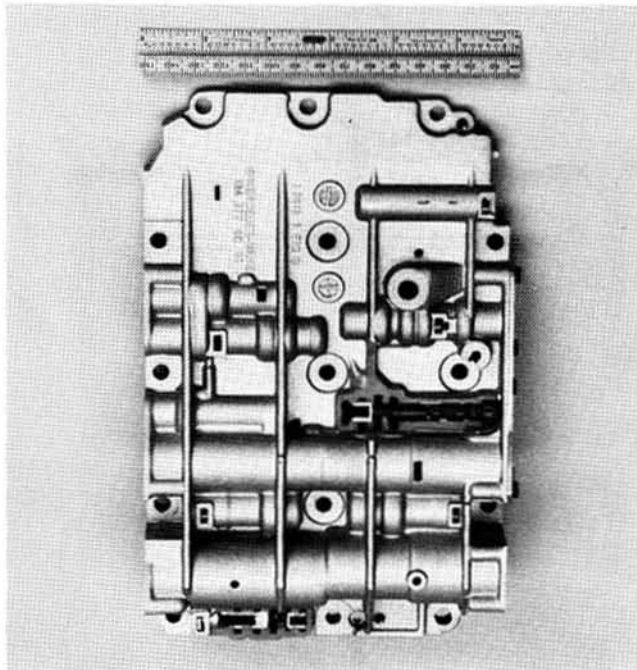


Fig 5 Valve body with two thermal valves (cut-away sections)

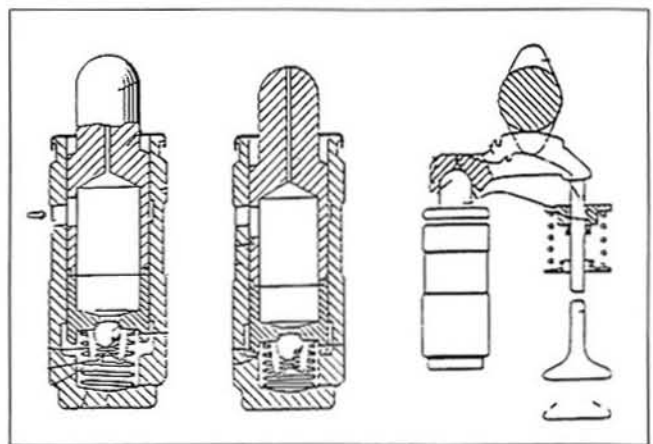


Fig 8 Temperature compensated valve lifter (Reference 3)

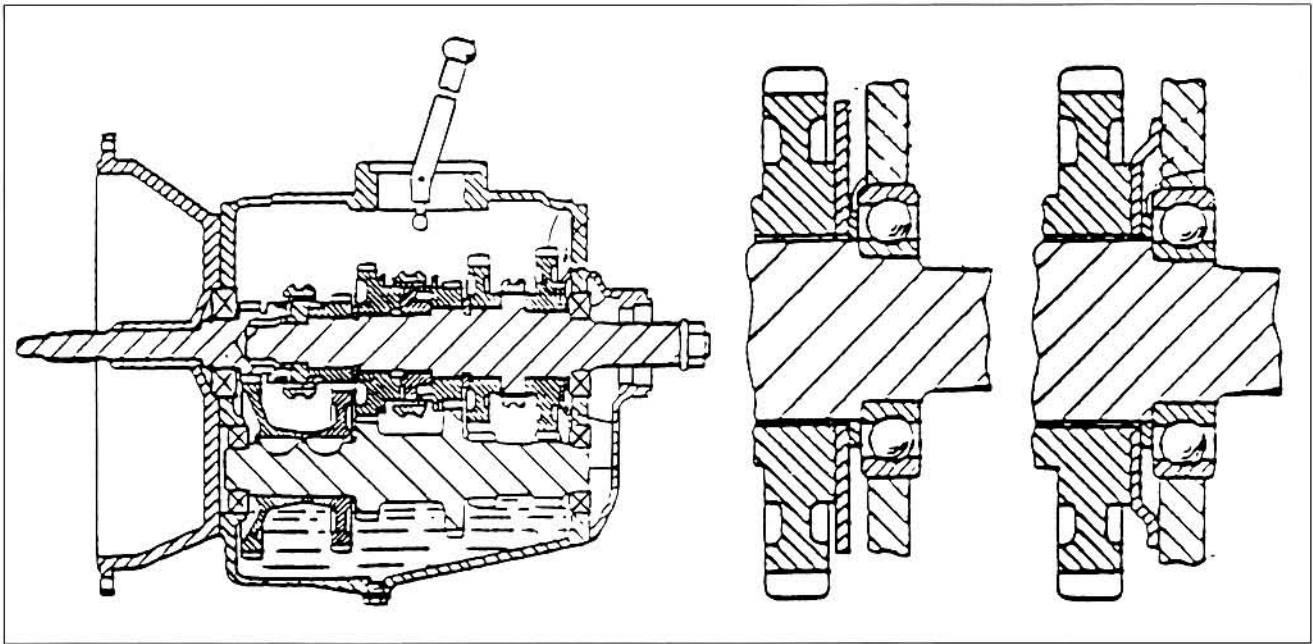


Fig 10 Rattling noise reduction with "Belleville-type" washer (Reference 5)

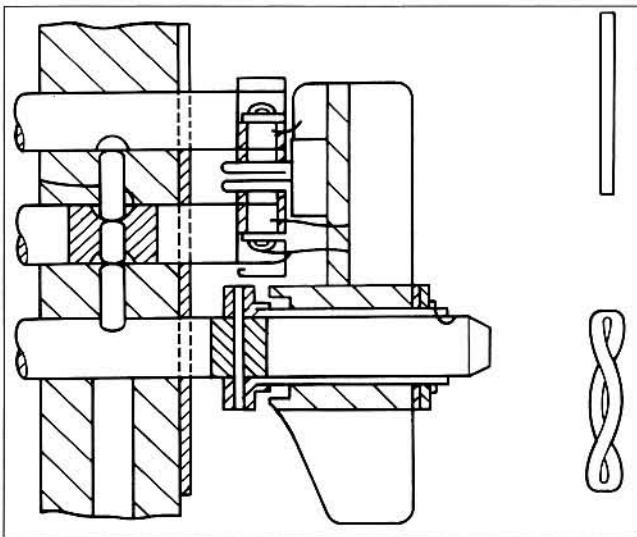


Fig 9 Rattling noise reduction with shape memory wave washer (Reference 4)

Since conventional shock absorbers tend to be too hard at very low temperatures, they don't provide comfortable driving. This is caused by the high viscosity of the oil in the shock absorber, which usually is balanced for the temperature range of 0°C to 100°C. A shape memory washer in the shock absorber's valve (Figure 11), which changes the pressure at low temperatures, compensates for the oil viscosity.

There are many other areas in a car, where shape memory thermal actuators can and will provide significant changes over competing technologies. Some of the benefits are listed:

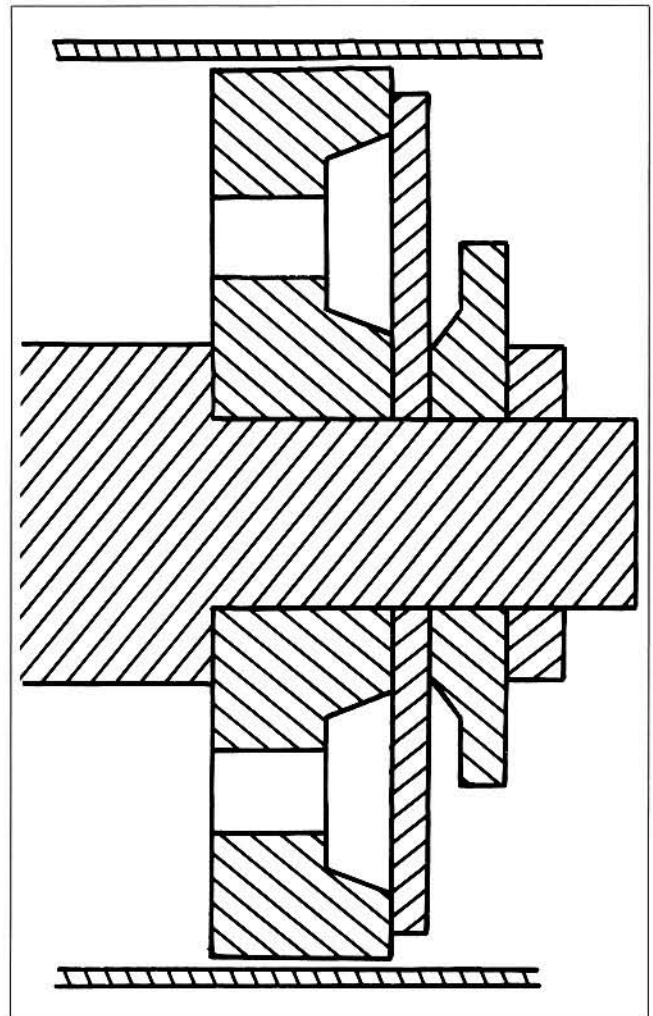


Fig 11 Temperature compensating valve for shock absorbers (Reference 6)

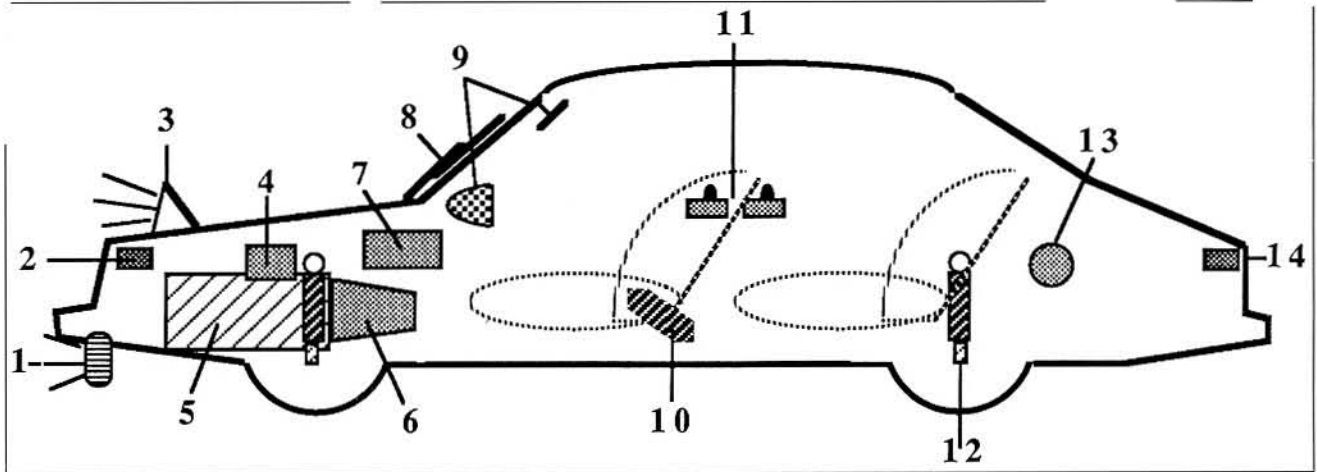


Fig 12 Potential applications for electrical shape memory actuators in automobiles: (1) foglamp louvre; (2) engine hood lock; (3) retractable headlight; (4) fuel management; (5) engine control; (6) transmission control; (7) climate control; (8) wiper pressure control; (9) rear-view mirror adjustment; (10) seat-belt adjustment; (11) central locking system; (12) shock absorber adjustment; (13) filler inlet lock; (14) trunk lock

- size
- high force
- large motion
- high work output
- few mechanical parts
- non-linear characteristic

On the other hand, for certain applications the following limitations have to be taken into account:

- limited range of transformation temperatures
- hysteresis
- non-linear characteristic

Electrical actuators

Electrical actuators are devices which perform a task on demand. The stimulus is any voltage applied to the device, which is usually an electric motor or a solenoid. If electrically heated above A_s , such as by passing current through a wire or spring, Ni-Ti shape memory elements become electrical actuators. They can provide interesting advantages over motors and solenoids like:

- small size
- noiseless operation
- few mechanical parts

Therefore an almost unlimited number of potential applications can be found in the patent literature. Figure 12 schematically shows the areas in a car where electrical shape memory actuators have been suggested. However, few have actually been implemented or seem technically and economically feasible because of the limited range of transformation temperatures of existing shape memory alloys. As shown in Figure 13, the operating temperature range of a car ranges from -40°C to approximately $+100^\circ\text{C}$, with even higher temperatures in under-hood locations. In order to work properly at all temperatures, the shape memory alloy has to have an M_f temperature well above the maximum operating temperature. Today no Ni-Ti alloys with

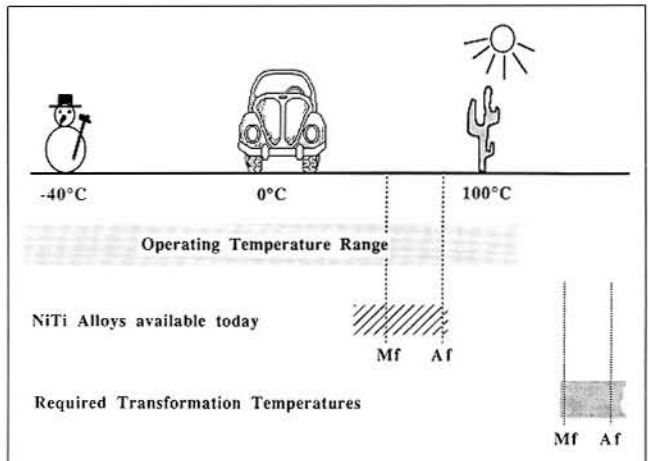


Fig 13 Operating temperature range for automobiles and transformation temperatures of Ni-Ti alloys

transformation temperatures above approximately 80°C are available for cyclic applications. Cu-Al-Ni shape memory alloys have transformation temperatures this high, but they are brittle and unstable. Ti-Pd-Ni alloys remain too expensive for routine applications.

Among those applications that are in production is the remote fog-lamp louvre opening device. A shape memory spring is wired in series with the lamp. Turning on the fog-lamp passes the lamp current through the actuator, which heats up, contracts and opens the louvre (Figure 14). A reset spring closes the louvre when the lamp is turned off. Figure 15 shows the design of the actuator with an integrated over-load spring. The area where fog-lamps are located on a car is usually very well ventilated, so that the low transformation temperature of the actuator ($\sim 65^\circ\text{C}$) is not an issue.

The same applies for windshield wipers. Shape memory actuators could provide an elegant solution for increasing the pressure at high speeds. Figure 16 shows different designs incorporating a Ni-Ti spring or tensile wire into the wiper arm.

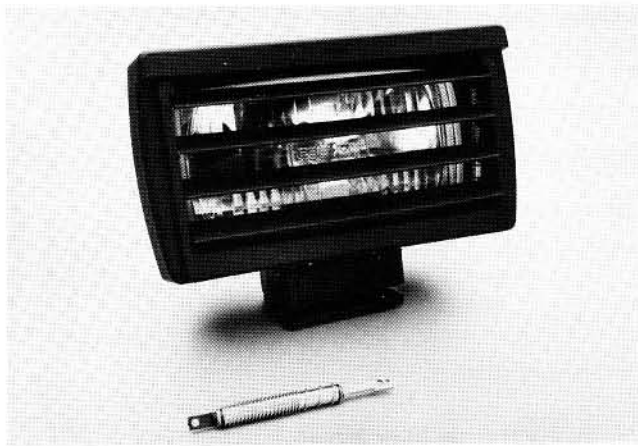


Fig 14 Fog lamp with shape memory electrical actuator

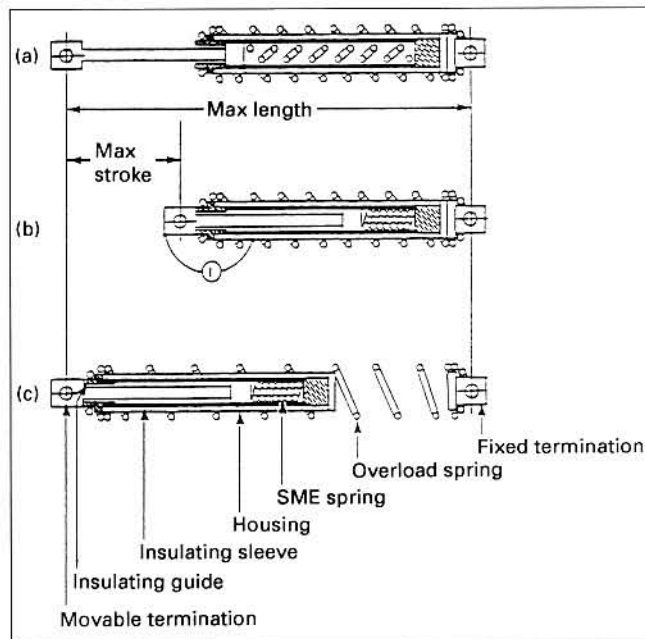


Fig 15 Design example for a linear shape memory actuator

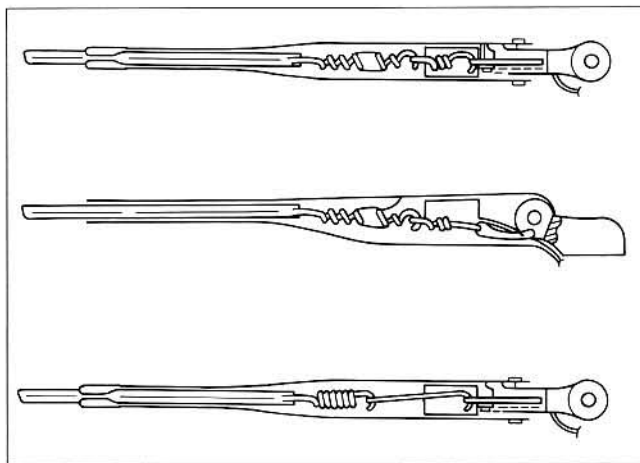


Fig 16 Windshield wiper with shape memory pressure actuator (Reference 7)

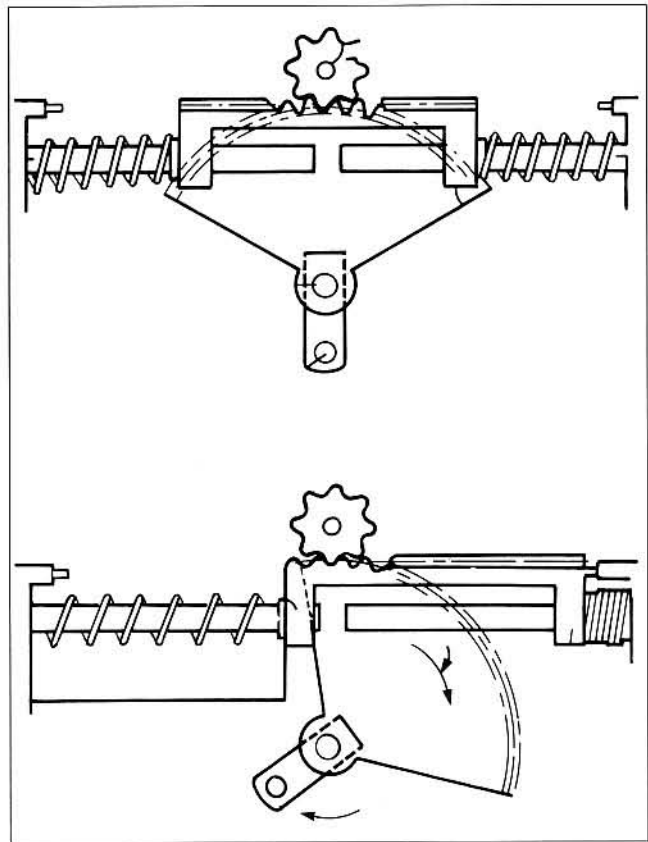


Fig 17 Door locking mechanism with shape memory springs (Reference 8)

Because of their small size and noiseless operation, shape memory actuators have also been suggested for central locking systems (Figure 17), trunk locks and fuel tank cap locks. However, there are serious problems when ambient temperature approaches the transformation temperature of the shape memory alloy, for instance when the car is parked in the sun. In this case, the shape memory actuator could self actuate or fail to reset.

Conclusion

Although shape memory actuators can provide significant advantages over conventional devices in certain areas, they have only slowly been penetrating the automotive market. This is mainly caused by poor information and the lack of engineering data for shape memory alloys. However, with the better understanding of the metallurgy and a more open discussion in the scientific community, shape memory actuators are becoming increasingly popular for automotive applications.

References

- 1 Hino Motor Industry, Kokai No. 63-40543 (1988).
- 2 Nissan Diesel Industry, Kokai No. 62-169230 (1987).
- 3 Mitsubishi Motor, Kokai No. 62-160706 (1987).
- 4 Toyota Motor, Kokai No. 62-50361 (1987).
- 5 Hino Motor Industry.
- 6 Aishin Seiki.
- 7 Mazda, Kokai No. 60-173455 (1985).
- 8 Kokusan Metal Industry, Kokai No. 62-173472 (1987).